Bit Depth Needed for High Image Quality TV-Evaluation Using Color Distribution Index

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***Abstract*—In this paper, we proposed a new image quality evaluation index—Color Distribution Index (CDI). It considers color gamut, contrast ratio, maximum luminance, gamma characteristics, and Just Noticeable Difference (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, luminance JND was $\Delta L/L = 0.01$ and chromaticity JND was $\Delta u'v' = 0.001$. We used these with unit CDI cell and evaluated bit depth needed for high image quality without any visible false contour. We clarified that 12 bit is needed for necessary and sufficient condition to reproduce high image quality with TV set designed based on BT.709. Also, we clarified that color gamut, contrast ratio, maximum luminance, 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.**

***Index Terms*—Bit depth, color distribution index, image quality, Just Noticeable Difference (JND), TV.**

I. Introduction

THE SENSE of a person who watches a TV set radically depends on the adaptation luminance level in surroundings. The level of adaptation luminance depends on illuminance, diffuse reflectance of display surface, and minimum luminance of a display. In low adaptation luminance, viewers can tell a little change of luminance.

Currently, the TV set is required to reproduce not only HDTV images but also digital cinema which demands over 12 bit and xvYCC standard which can represent over 10 bit [1]. Color gamut of digital cinema and xvYCC is wider than HDTV. In addition, the requirement for reproducing visually smooth gradation is more difficult than before, because the diffuse reflectance of the flat panel display (FPD) TV is about 1/10 of cathode ray tube (CRT) TV, and minimum luminance of FPD TV in bright room is lower than CRT TV.

According to these surroundings, 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 the latest LCD TV, the maximum luminance and contrast ratio are 450 cd/m^2 and 3000:1, respectively [2]. Furthermore, the LCD TV with contrast ratio is over 100 000:1 is developed [3]. LCD TV, whose color gamut is much wider than HDTV, is commercialized [4], maximum luminance and contrast ratio is 3000 cd/m^2 and 50 000:1, respectively, is being developed as high dynamic range (HDR) display [5].

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 reveal the bit depth which is necessary to distribute reproduced colors perceptually evenly 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 bit depth, the investigation by Just Noticeable Difference (JND) which use uniform color space ($L^*a^*b^*$ color space or Munsell color space) and $\Delta Eab*$ is performed [6], [7]. Yoshida [8] revealed bit depth for LCD TV by subjective evaluation under various condition of adaptation luminance. In case of evaluation of display based on $L^*a^*b^*$, he indicated that 100% white should be set as reference and it was difficult to apply their result to the case of severe condition, like observing low average picture level (APL) images in dark room. So, he indicated that JND should be evaluated using absolute luminance level.

In this paper, we assume that colors are needed to be reproduced under JND in all region of reproducible color gamut. First, we investigate bit depth needed for high image quality TV considering luminance JND. Then as an index for evaluating image quality considering luminance and chromaticity JND, we propose Color Distribution Index; CDI. For calculating CDI, JND is the important index. There are many researches on JND [9]. But we inspect it again with the newest instruments and we inspect the suitability of luminance JND from Weber Fraction and chromaticity JND from subjective evaluations.

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

In this paper, we use CIE $u'v'$ and $Lu'v'$ (L: absolute luminance) color space because display primary chromaticity coordinates are usually selected to cover a target chromaticity triangle in the CIE $u'v'$ chromaticity diagram and we consider absolute luminance L.

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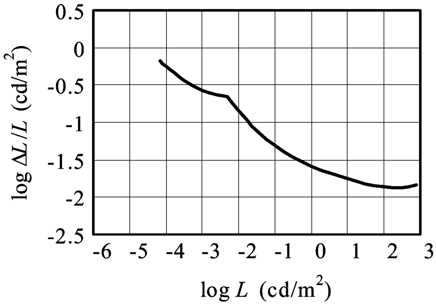

Fig. 1. Relation between stimulus and luminance JND; $\Delta L/L$, Wyszecki and Stiles [12].

II. Bit Depth by Weber Fraction

A. Verification of Weber Fraction

Weber fraction in Fig. 1 is well known as luminance JND [10]. Characteristics between luminance of background as adaptation luminance; L and Luminance JND; ΔL is, when $\log L > 1$ ($L > 10$ cd/m^2), then $\log \Delta L/L \approx -2$ (constant), 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, and $\log \Delta L/L = -0.7$ (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. 1 gained the data from experiments in aperture color. It needs to be confirmed that Weber Fraction is also effective on FPD TV. In this research, we conducted the experiments to confirm the characteristics of Weber fraction by subjective evaluation using LCD TV.

1) Methodology: We displayed the square window pattern of same color and 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 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 over 8 bit, digital halftoning processing was used to create 12-bit image. Luminance and chromaticity point were measured by spectro photometer, SR-UL1R (Topcon Technohouse Corporation). Color difference between window and background, $\Delta u'v'$ was less than 0.0005.

Luminance of background was set to 0.5, 1, 10, 100 cd/m^2, respectively. Colors patterns were gray, red, green, and blue. Chromaticity points of red, green, and blue patterns were set almost same as primary colors of BT.709 [11]. The subjective evaluation was performed in a darkroom. Visual distance was 3H which is three times of absolute display height, horizontal visual angle was 35 degree, and the size of window was 10% of whole display (8.5 deg at visual angle). Observers were 20–30 years old, 14 male. They took 100 hue test and were confirmed they had normal sense of color vision.

2) Result: The results are shown in Fig. 2(a) and (b). Fig. 2(a) shows the result of achromatic color pattern and Fig. 2(b) shows the result of chromatic colors. In the figure the result of Wyszecki and Stiles is shown with a solid line [10]. In this experiment we regarded the pattern which over half the number of subjects could recognize as "perceptible" and pointed "◯" in Fig. 2(a) and 2(b). We assumed that observers

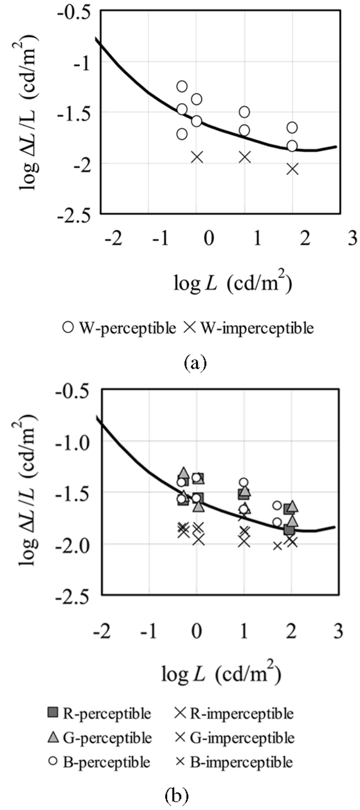

Fig. 2. Result of subjective evaluation on luminance JND. (a) Achromatic color. (b) Chromatic colors.

completely adapted to the luminance of background and compared our result with Fig. 2 regarding luminance of background as adaptation luminance.

From Fig. 2(a) when 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 with the result of Wyszecki and Stiles [10] well. Also from Fig. 2(b) the result of chromatic color showed almost the same result with achromatic color. Wyszecki and Stiles said that the result did not change in chromatic colors or achromatic colors. We got the same result, the result of chromatic color and achromatic color did not show difference and agreed with Weber Fraction 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 luminance JND could be used independently of chromaticity.

B. Bit Depth Considering Luminance JND

Considering only luminance JND, from the result of subjective evaluation we calculated bit depth needed for high image quality TV sets. We set luminance JND to Weber fraction, and calculated minimum number of bit depth which luminance difference of one gradation step of the display fulfill the JND. We regarded the number of bit depth as the bit depth needed for high image quality TV reproducing smooth pictures without any false contour.

TV sets quantized the input signal (evenly assign the input signal level from minimum to maximum luminance of TV set by bit depth), and controlled the output to be gamma characteristic. So the luminance difference between two gradation steps depends on maximum luminance and contrast ratio of TV set.

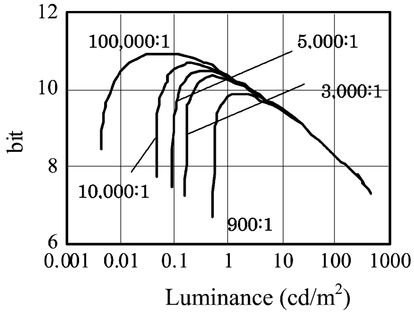

Fig. 3. Bit depth needed for high image quality TV considering luminance JND. Result to each contrast ratio under the condition which is constant maximum luminance; 450 cd/m^2.

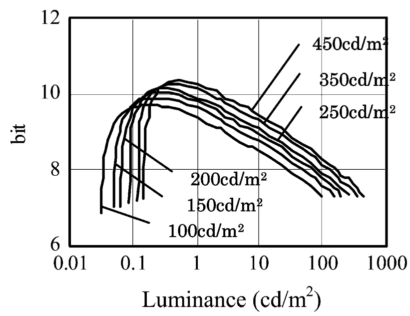

Fig. 4. Bit depth to be needed to TV considering luminance JND. Result to each maximum luminance under the condition which is constant contrast ratio; 3000:1.

Therefore, we set the maximum luminance and contrast ratio as a parameter for calculation. Gamma characteristic of TV sets were gamma 2.2 because the TV set was designed to be based on BT.709 or sRGB. The value of Weber fraction is $\Delta L/L$ value from Fig. 1. We assumed that observers completely adapted to the luminance of TV sets and analyzed results regarding luminance of TV sets as adaptation luminance.

Fig. 3 shows the results of each contrast ratio under the condition of maximum luminance 450 cd/m^2. Fig. 4 shows the result of each maximum luminance under the condition of contrast ratio 3000:1. From Fig. 3, bit depth needed for high image quality TV tends to increase as the contrast ratio increases. Also from Fig. 4, the bit depth for high image quality TV tends to increase as the maximum luminance increases. When adaptation luminance was 0.1 or a few cd/m^2, 10 bit was needed for high image quality TV sets whose maximum luminance and contrast ratio were 450 cd/m^2 and 3000:1, respectively. As a result it was revealed that maximum luminance and contrast ratio influence ability to reproduce smooth images without any false contours seriously.

III. Bit Depth Considering Luminance and Color

A. Color Distribution Index—CDI

Up to now evaluations of color reproduction system have performed with color difference (ΔEab^*) in $L^*a^*b^*$ color space. 100% white had to be 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 [8].

If the reproduced colors distribute in narrow region in color space, the value of color difference will be small, but large ΔEab^* might appear in a part of region in color space which

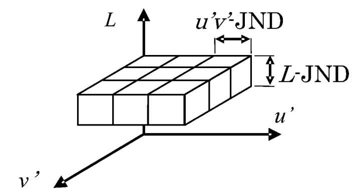

Fig. 5. CDI cell.

TV set can reproduce. Therefore there was a possibility that the ratio of large value of ΔEab^* decreased though the system had not enough color reproduction ability for reproducing visually smooth gradation. As a result the actual image quality might not agree with evaluation by color difference.

Considering these problems, TV sets for reproducing visually smooth need to have sufficiently small color difference between adjoining colors and reproduced colors distribute evenly in reproducible color gamut. So in this paper, we proposed Color Distribution Index; CDI which does not set 100% reference white, it is an evaluation method using absolute luminance value. The purpose of CDI is to evaluate the distribution of colors which TV set can reproduce in 3D color space.

Fig. 5 shows the CDI cell. First, the reproducible color gamut is divided by luminance JND and chromaticity JND and each cell is checked whether it includes one or more reproduced color or not. Second, CDI is defined as the percentage of the cells which include reproduced colors. If all cells include reproduced colors, the system has ability to reproduce high image quality without any false contours. In this paper, Weber fraction, which we inspected in Section II, was set as luminance JND, and we used $Lu'v'$ color space (luminance; L and chromaticity; $u'v'$).

B. Further Validation of Chromaticity JND

In this research, we set the $Lu'v'$ color space for CDI calculation. From MacAdam ellipsis it is obvious that chromaticity JND changes its tendency by saturation and hue. Then the minimum JND in CIE $u'v'$ color space was set as the width of chromaticity JND of CDI cell. To confirm the JND we performed subjective evaluations.

1) Methodology: The window in the pattern which we used for subjective evaluations had same luminance as background, and different chromaticity. The criterion of evaluation was observers could distinguish the window from background or not. Conditions (observers and instruments) were same as experiment of Section II.

The pattern colors were gray, red, green, and blue. The adaptation luminance (luminance of patterns) was 10 cd/m^2. The luminance difference $\log(\Delta L/L)$ between window and background was less than -2.5 which was lower than luminance JND.

2) Result: The result is shown in Fig. 6. The patterns which more than half of observers could distinguish were regarded as "perceptible." The distance in Fig. 6 indicated 10 times of distance in chromaticity diagram. The result agreed well with distribution of MacAdam ellipsis because chromaticity JND of hue direction was smaller than chromaticity JND of saturation direction. In $u'v'$ chromaticity diagram, the chromaticity JND $(\Delta u'v')$ of hue direction was about $\Delta u'v' = 0.002$ in hue of red-green, about $\Delta u'v' = 0.001$ in hue of blue and gray. In addition we performed experiments which the luminance of pat-

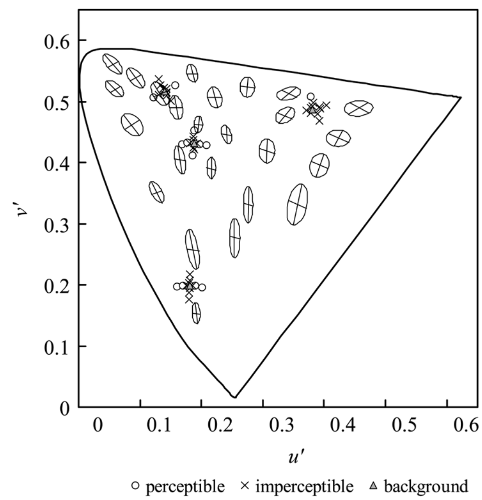

Fig. 6. Result of subjective evaluations for chromatic JND.

tern was changed to 1, 10, and 50 cd/m^2. It was revealed that JND was almost constant, did not depend on luminance. So we defined chromaticity JND as $\Delta u'v' = 0.001$ for the CDI calculation.

C. Structure of CDI Cells

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

- Luminance JND was almost constant ($\Delta L/L = 0.01$), when the luminance was over 0.5 cd/m^2.
- Chromatic JND was almost constant ($\Delta u'v' = 0.001$), when the luminance was over 1 cd/m^2.

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

From the relation between ΔL and $\Delta L/L$ in Fig. 1, the characteristic indicates sensitivity of cones and rods for human vision. When adaptation luminance is over 10 cd/m^2, cones work mainly. When 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 [10]. When evaluation on color reproduction ability is performed, the evaluation should be performed in the luminance range which cones are active. So under the case of adaptation luminance over 10 cd/m^2, the result of evaluation which gratify CDI $= 100\%$ was the first step to reproduce high image quality without any false contour. That was, we defined this as the necessary condition to reproduce high image quality. Secondly, the result of evaluation which gratifies CDI $= 100\%$ when 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.

IV. Evaluation of Relationship Between Image Quality and Bit Depth Using CDI

A. TV Set Designed Based on BT.709

First we investigated the bit depth needed for TV set designed based on BT.709 [11] for reproducing visually smooth gradation without any false contours using CDI. From Figs. 4 and 5, it was expected that extremely high bit depth was needed in dark images, because the value of ΔL from Weber fraction decreased as adaptation luminance decreased. So we investigated the relation between CDI and adaptation luminance for each bit depth.

We used the specifications of TV set for investigations as follows. The gamma characteristic of TV set was 2.2. The color gamut was same as BT.709 standard. Maximum luminance and contrast ratio was 450 cd/m^2 and 3000:1, respectively, as latest LCD TV.

Examples of the result, shown in Fig. 9(a)–(c), shows distribution of reproducible colors for CDI cells for 8 bit, 10 bit, and 12 bit at 1 cd/m^2 TV set 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.

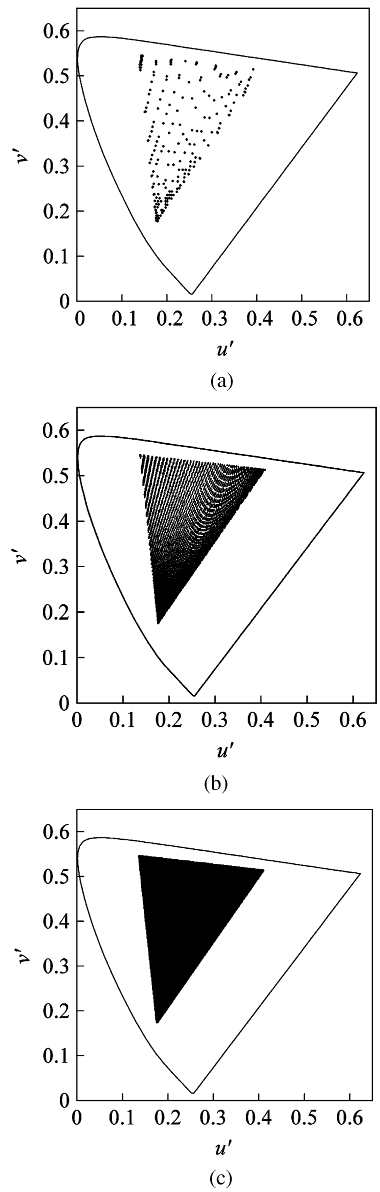

Fig. 7. Distribution of reproducible colors for CDI cells for (a) 8 bit, (b) 10 bit and (c) 12 bit in adaptation luminance 1 cd/m^2.

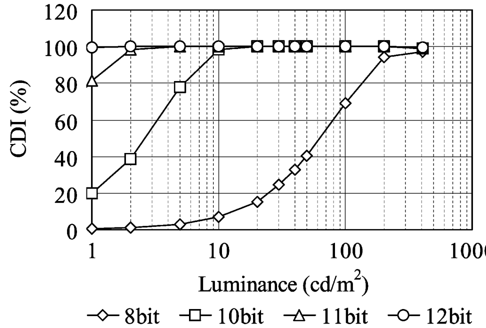

Fig. 8. Relation between CDI and adaptation luminance for each bit depth (8, 10, 11, 12 bit). Color gamut; BT.709, Maximum luminance; 450 cd/m^2, Contrast ratio; 3000: 1.

From Fig. 7, the ability for reproducing visually smooth gradation could be confirmed considering luminance and chromaticity of TV sets. In case of 8 bit, reproduced colors distributed roughly at 1 cd/m^2. Also, reproduced colors distributed still roughly at 10 bit. At 12 bit, reproduced colors ware dense in $u'v'$ color space.

Fig. 8 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 3000:1 contrast ratio. From Fig. 8, it was revealed that 8-bit ability of reproducing visually smooth gradation was not sufficient at all 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 signal was processed in 11 bit CDI value decreased under 5 cd/m^2.

As a result 12 bit was necessary for reproducing visually smooth gradation at all luminance. This value of 12 bit was 2 bit higher than the result of Fig. 5 which considered only luminance JND. So the bit depth needed for high image quality TV increased when chromaticity was considered. Thus both luminance and chromaticity need to be considered in case of evaluating reproducing gradation for image quality evaluation.

B. *Influence of Expanding Color Gamut*

From the result above, color gamut influence the ability for reproducing gradation. TV set with wide color gamut is being developed eagerly. They may need higher bit depth than the TV sets designed based on BT.709. So we investigated the relation between bit depth needed for high image quality TV and CDI in the TV sets using TV sets with NTSC primaries which has wider color gamut than that of BT.709. From our previous research [12], the color gamut with 3 primaries near spectrum locus was needed to reproduce the whole real-world surface colors under D65. So we also investigated the relation between the bit depth and CDI using TV sets which has a very wide color gamut to reproduce the whole real-world surface colors. Table I shows primaries of TV sets used for our investigation. Calculation was done using the maximum luminance and the contrast ratio were fixed to 450 cd/m^2 and 3000:1.

Fig. 9 shows the relation between the adaptation luminance and CDI of each TV set with bit depth and 3 primaries shown

TABLE I
PRIMARIES OF TV SETS USED FOR INVESTIGATIONS

	R	G	B	W
	u' v'	u' v'	u' v'	u' v'
BT.709	0.451 0.523	0.125 0.563	0.175 0.158	0.198 0.468
NTSC	0.477 0.528	0.076 0.576	0.152 0.196	0.198 0.468
Wide gamut	0.556 0.517	0.023 0.584	0.144 0.151	0.198 0.468

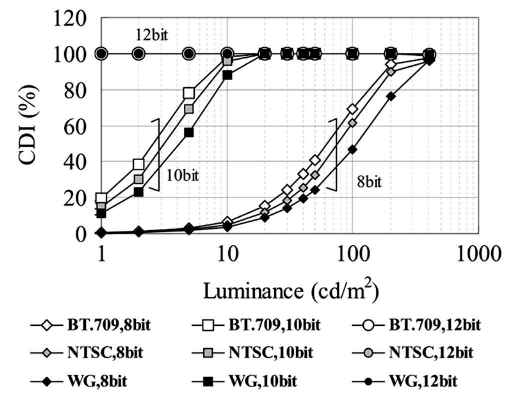

Fig. 9. CDI(%) of 8, 10, and 12 bit in each adaptation luminance level. Influence by color gamut. The maximum luminance; 450 cd/m^2 and contrast ratio;3000:1.

Table I. When the color gamut expands at constant maximum luminance and contrast ratio, CDI tends to decrease. From Fig. 9, from the viewpoint of assuming CDI $=$ 100% with 10 cd/m^2 or more which was the necessary condition for the high image quality TV sets, 10 bit was not enough for TV sets with color gamut which includes all the real-world surface colors though 10 bit became a necessary condition for BT.709 and NTSC.

On the other hand, 10 bit was insufficient for BT.709 and NTSC from the viewpoint of the sufficient condition of CDI $=$ 100% even for 1 cd/m^2 for high image quality. With 12 bit, we can see that TV sets with three kinds of primaries we investigated satisfy the sufficient condition. Thus, if a TV set was 12-bit display with characteristics of gamma 2.2, maximum luminance 450 cd/m^2, and contrast ratio 3000:1, we say that there was no decrease in the ability for reproducing smooth gradation even if the color gamut was expanded to the area where whole real-world surface colors are included.

C. *Influence by Contrast Ratio*

Next, we investigated the influence of contrast ratio to the ability for reproducing gradation of the TV sets. The relation between the bit depth and CDI when setting contrast ratio 3000:1, and 10 000:1, 100 000:1 is shown in Fig. 10 using the TV sets with gamma 2.2, BT.709 color gamut, and 450 cd/m^2 maximum luminance.

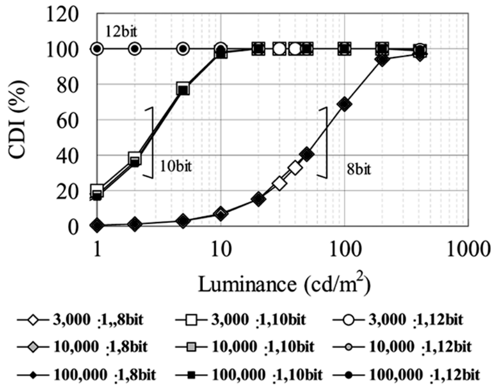

Fig. 10. CDI(%) of 8, 10, and 12 bit in each adaptation luminance level. Influence by contrast ratio. The maximum luminance; 450 cd/m^2, and display gamut; BT.709.

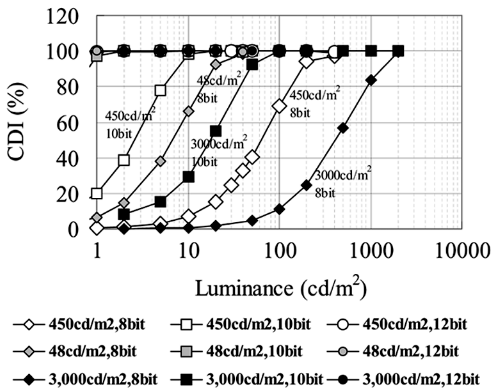

Fig. 11. CDI(%) of 8, 10, and 12 bit in each adaptation luminance level. Influence by maximum luminance. Contrast ratio; 3000:1, display color gamut; BT.709.

Even if the contrast ratio became from 3000:1 to 100 000:1, CDI of 10 cd/m^2 or more was not changed. For the TV sets with contrast ratio 3000:1, 10 000:1, and 100 000:1, the condition of $\mathrm{CDI} = 100\%$ with 10 cd/m^2 or more which is the necessary condition for the high image quality is 10 bit. Even if CDI in the adaptation luminance of 1 cd/m^2 was seen, there was no influence by a contrast ratio increase, and 12 bit was sufficient condition in the TV sets with maximum luminance 450 cd/m^2 and the BT.709 color gamut.

D. Influence of Maximum Luminance of Display

The maximum luminance level exerts a big influence on the performance of the TV sets (ability for reproducing visually smooth gradation) as shown in Fig. 4. In this section, we investigated the influence that the maximum luminance of display exerted on the ability for reproducing visually smooth gradation. The relation between bit depth and CDI for the maximum luminance level of 48, 450 cd/m^2, and 3000 cd/m^2 which is maximum luminance level of HDR display is shown in Fig. 11 with gamma 2.2, BT.709 color gamut and contrast ratio 3000:1.

CDI showed the tendency to increase when the maximum luminance level of display was low as well as Fig. 4, and the bit depth that became $\mathrm{CDI} = 100\%$ in adaptation luminance 10 cd/m^2 was about 9 bit for 48 cd/m^2. When the maximum luminance increased, CDI decreased oppositely. With 3000 cd/m^2, the CDI of 10 bit became about $\mathrm{CDI} = 30\%$, and it was clear that 11 bit was needed for the necessary condition for $\mathrm{CDI} = 100\%$. However, with the contrast ratio 3000:1, the minimum luminance level elevates and bit depth which satisfies the sufficient condition of the high image quality was 12 bit, which is similar to TV sets of 450 cd/m^2.

Next, the result of investigation of the TV sets with contrast ratio 100 000:1, maximum luminance level 3000 cd/m^2 is shown in Fig. 12. There was no change in CDI in adaptation luminance 10 cd/m^2. But CDI in 1 cd/m^2 decreased to about 40% even in 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 that the color gamut, contrast ratio, and the maximum luminance exerted on the ability of reproducing visually smooth gradation in the TV sets of gamma 2.2. As a result, when the color gamut, contrast ratio, and the maximum luminance increased, it was clarified that the ability of reproducing visually smooth gradation decreased. Also when the color gamut volume in $Lu'v'$ color space increases, the bit depth for the necessary and sufficient condition for reproducing visually smooth gradation without any false contours increases. These indicate that even if only one of color gamut, contrast ratio, or the maximum luminance is improved, it is insufficient from the viewpoint of reproducing visually smooth gradation. From the viewpoint of the total image quality improvement, color, contrast ratio, the maximum luminance, and the bit depth should be balanced to achieve the TV sets of high image quality.

Considering from the viewpoint of the design of an actual TV sets, CDI, that is, the ability for reproducing visually smooth gradation is greatly influenced in 10 bit or less when assuming color gamut volume, contrast ratio and the maximum luminance as a parameter like in Figs. 10–12. It is unaffected when bit depth is 12 bit. From these, we can say that the target of the bit depth in the TV sets design whose gamma characteristic is 2.2 is 12 bit.

V. Influence of Gamma Charactteristics

Above these, we have been investigating on the assumption of gamma 2.2 based on a general LCD TV sets. Finally, we investigated the influence of the gamma characteristic on the ability of reproducing visually smooth gradation.

Recently, instead of CRT, the TV sets with LCD, PDP, and DMD device have appeared. The device for TV sets has a peculiar gamma characteristic respectively.

Because the LCD device controls the state of the distribution of the liquid crystal molecule according to the voltage, the gamma characteristic can be set arbitrarily. Generally, as we have been investigating so far, it is designed to be gamma 2.2 which is same as BT.709 or sRGB. On the other hand, because DMD controls the mirror at high-speed by a digital signal, the gamma characteristic is set to linear (gamma 1.0) [13]. In this section, considering such gamma characteristic peculiar to the device, we investigated required bit depth for reproducing visually smooth gradation without any false contour with linear gamma characteristic. The characteristic of the TV sets used for calculation was gamma 1.0, maximum luminance 450 cd/m^2, contrast ratio 3000:1 and color gamut BT.709.

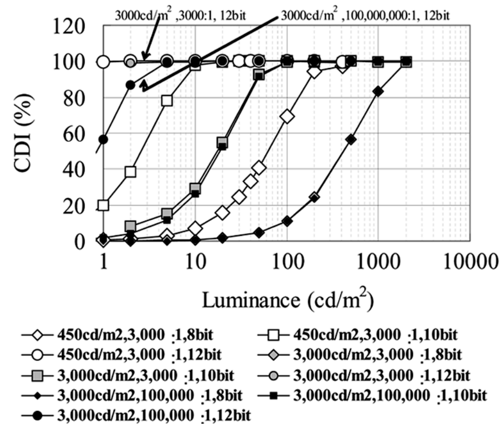

Fig. 12. CDI(%) of 8, 10, and 12 bit in each adaptation luminance level. Influence by maximum luminance and contrast ratio. color gamut; BT.709.

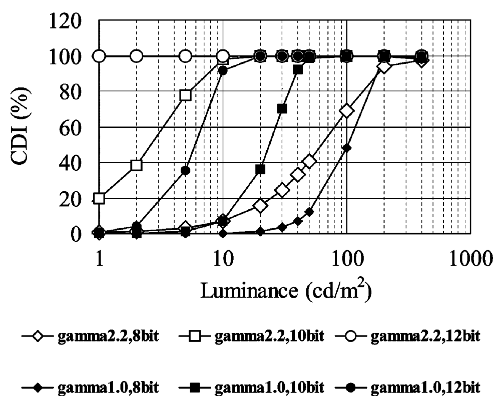

Fig. 13. CDI(%) of 8, 10, and 12 bit in each adaptation luminance level. Influence by gamma characteristics. maximum luminance 450 cd/m^2, contrast ratio 3000:1, display color gamut; BT.709.

Fig. 13 shows CDI of 8, 10, 12 bit, respectively. When the gamma characteristic changed from 2.2 to 1.0, CDI of all 8, 10, and 12 bit at low adaptation luminance level was greatly deteriorated. For TV sets of gamma 1.0, 12 bit was needed from the viewpoint of assuming CDI $= 100\%$ with 10 cd/m^2 or more which was 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 necessary condition, so 2 bit or more should be needed compared with the TV sets of gamma 2.2.

New image quality evaluation index CDI is proposed in this research. It is an evaluation index that considers the main factor of high image quality, maximum luminance, contrast ratio, color gamut, gamma characteristics, and bit depth of TV sets. It is a useful index for evaluation of image quality as covers the overall characteristic of TV sets.

VI. Conclusion

In this paper, we proposed new image quality evaluation index , CDI. It considers color gamut, contrast ratio, maximum luminance, gamma characteristics, 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, luminance JND was $\Delta L/L = 0.01$, chromaticity JND was $\Delta u'v' = 0.001$. We used these with unit CDI cell and evaluated bit depth needed for high image quality without any visible false contour. We clarified 12 bit is needed for necessary and sufficient condition to reproduce high image quality which has the ability of reproducing visibly smooth gradation without any false contour with TV set designed based on BT.709.

We found out that the expansion of color gamut, higher contrast ration, and the increasing of the maximum luminance have a big influence on the ability for reproducing visually smooth gradation. It indicated that even if only one of color gamut, contrast ratio, or the maximum luminance we improved, it was insufficient. Color gamut, 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. Also we evaluated the influence of gamma characteristics using CDI. New image quality evaluation index CDI proposed in this research was an evaluation index that considers the main factor of high image quality, maximum luminance, contrast ratio, color gamut, and bit depth of TV sets. It is a useful image quality evaluation index as it covers the overall characteristic of the TV sets.

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