JVC

White Paper

Required Grayscale Accuracy in Medical Monitors

Table of Contents

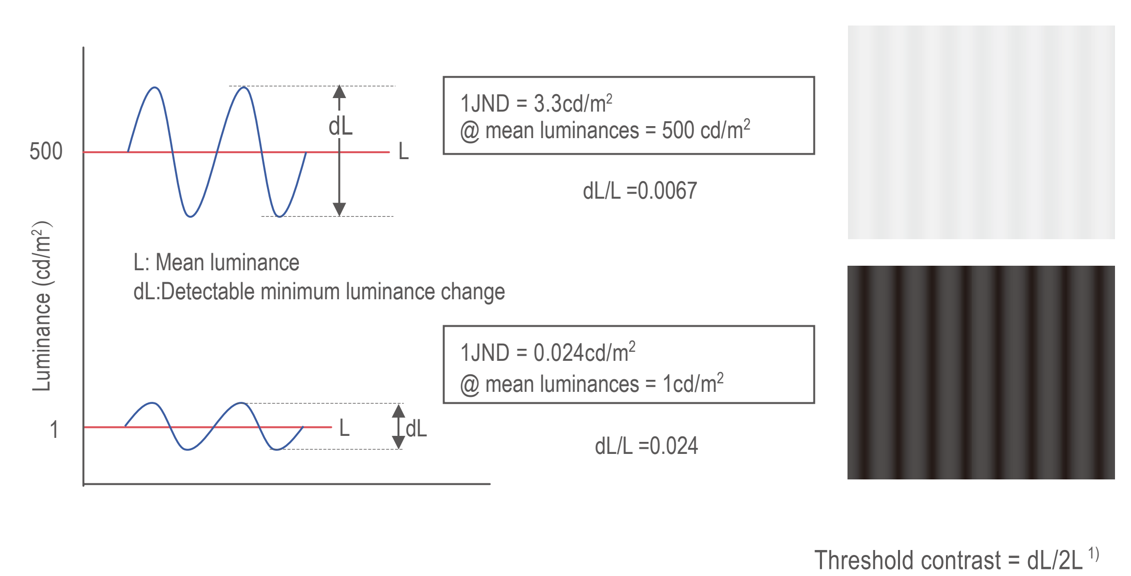
1. Preface

An image monitor used for filmless diagnosis is required to have high gray scale accuracy in displaying monochrome images. Generally, the bit width of the look-up table (LUT) of a monitor is a specification item that represents the capability of the monitor in its catalog. This white paper examines various errors in display systems to find out how the operations of LUTs and differences of input-output bit widths are related to the accuracy in displaying images. It aims to, establish the superiority of JVC display systems and platform-independent approach to multi-shade* display and consequently helps users understand gray-scale performances better.

2. Requirement for Perceptually Linear Display Characteristics

As shown in Figure 1, the minimum luminance difference that can be perceived with human eye in two adjacent areas with different luminances (ΔL) varies depending on the mean luminance of these areas (L). For example, ΔL =0.024cd/m^2 at a low luminance of L=1cd/m^2 and ΔL =3.3cd/m^2 at a high luminance of L=500cd/m^2, demonstrates a large difference. Figure 3 shows the limits of perceivable luminance differences in comparison with mean luminances, which were calculated based on the GSDF.

Figure 1. Minimum perceivable luminance change at mean luminances of 1cd/m^2 and 500cd/m^2



DICOM 3.14 defines the unit of minimum luminance difference that can be perceived with human eye as one JND (Just Notice Difference) and the function of mean luminances and numbers of JNDs as the Grayscale Standard Display Function (GSDF). GSDF, also called the DICOM curve (Figure 2), is used to convert a luminance value to a JND value and vice versa.

*multi-shade : more than 10 bits shades

On the other hand, monitors have widely different grayscale characteristics (commonly called gamma characteristics) depending on manufacturers, models, individual differences, or luminance settings. An image displayed on monitors with different characteristics will naturally look different, significantly interfering with imaging diagnosis. Medical image display systems, therefore, are commonly calibrated according to the grayscale characteristics defined by GSDF (Figure 5).

Figure 2. GSDF (Grayscale Standard Display Function)

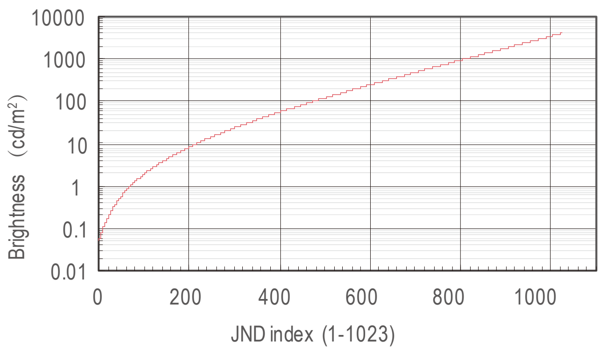


Figure 3. Detectable minimum luminance modulation

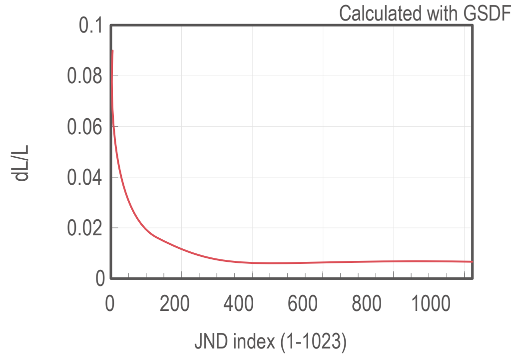


Figure 4 shows the comparison of different grayscale display images due to the difference in monitor display characteristics. This figure shows that, on a monitor with GSDF characteristics, differences between any two shades are perceived as the same degree of change in luminance in the grayscale displayed. On a monitor with gamma 2.2, however, there is a tendency that the shades are emphasized in a low luminance range and compressed in middle and high luminance ranges. In other words, it can be concluded that an image displayed on a monitor with gamma 2.2 will tend to look brighter on the whole than on the other monitor.

Figure 4. Gamma characteristics and displayed grayscale images

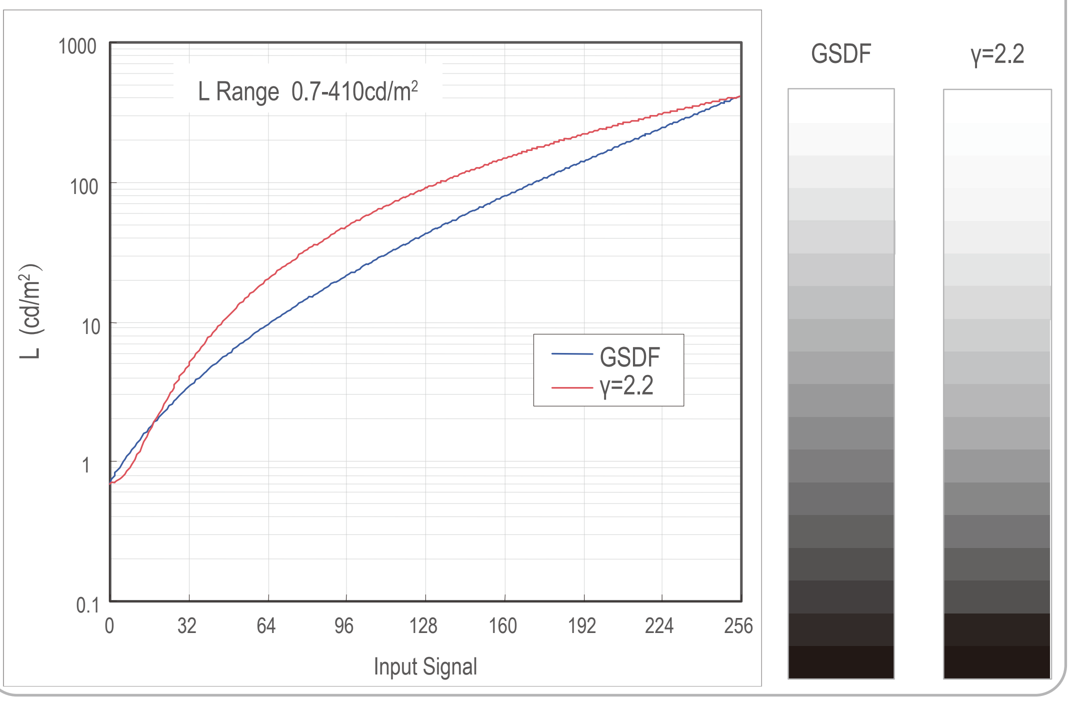
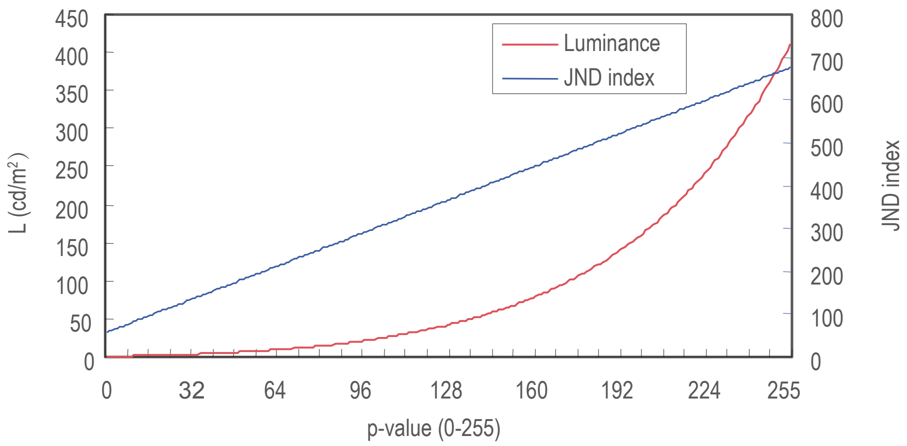


Figure 5. Luminance of an 8-bit monitor calibrated to GSDF



Increments in luminances in relation to increments in p-values are calibrated into perceptually linear.

Figure 5 shows the relationship of the luminance and JND values to input signal levels (p-values) on a GSDF-calibrated monitor. The luminances are shown as a red curve against the left-side vertical axis and the JND values as a blue line against the right-side vertical axis.
This chart shows that, on a GSDF-calibrated monitor, the input signal levels and JND values are in a linear proportionality relation and that increments in the input signal levels and consequent increments in the luminances are displayed as a perceptually linear relationship.

3. Composition of Imaging Display System

Figures 6a and 6b show a composition example of a standard imaging display system.
A look-up table (LUT) used to convert the display-specific shading characteristics to the GSDF is provided in the computer's graphics card on some systems (Figure 6a) and in the monitor on other systems (Figure 6b), the latter of which are increasing due to a widespread use of medical imaging monitors in recent years.
Images transferred from modality system are normally 12 bits wide but are output to the monitor with a bit width downscaled by the computer's operating system, viewer software, or graphics card. The bit width of this output signal represents the maximum number of simultaneously available shades.
On common display systems, the maximum number of simultaneously available shades is limited to 256 because 8-bit viewer software and graphics cards are used. Recently, however, a special approach using color channels was developed to realize a system capable of handling output with a 10-bit width or better on a commercial basis. This system, although not yet standardized like the 8-bit input-output systems, can display 1024 shades or more simultaneously.
How to realize a multi-shade display system is explained in details in Chapter 8.

Figure 6. Image observation display systems

Figure 6a

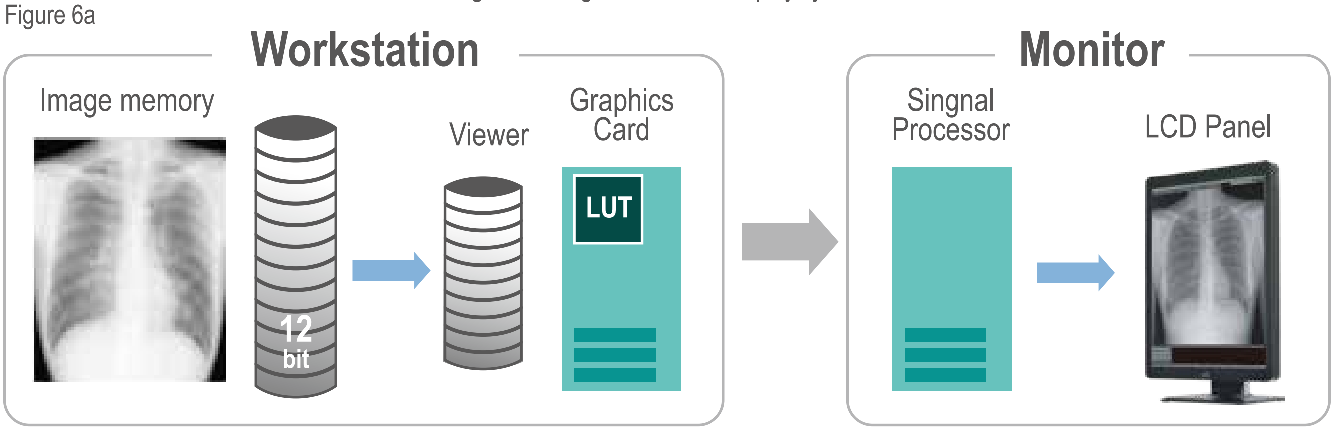
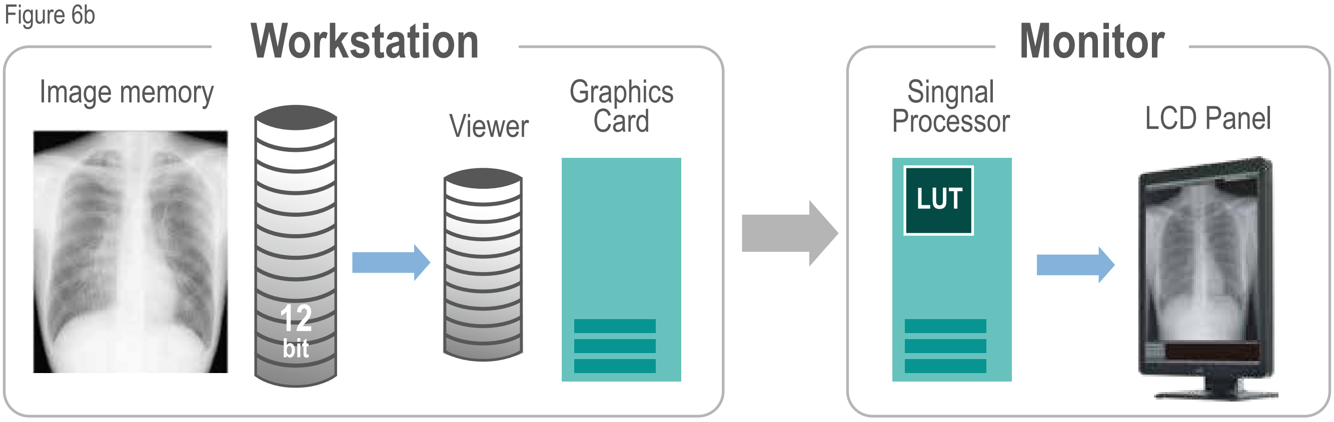


Figure 6b



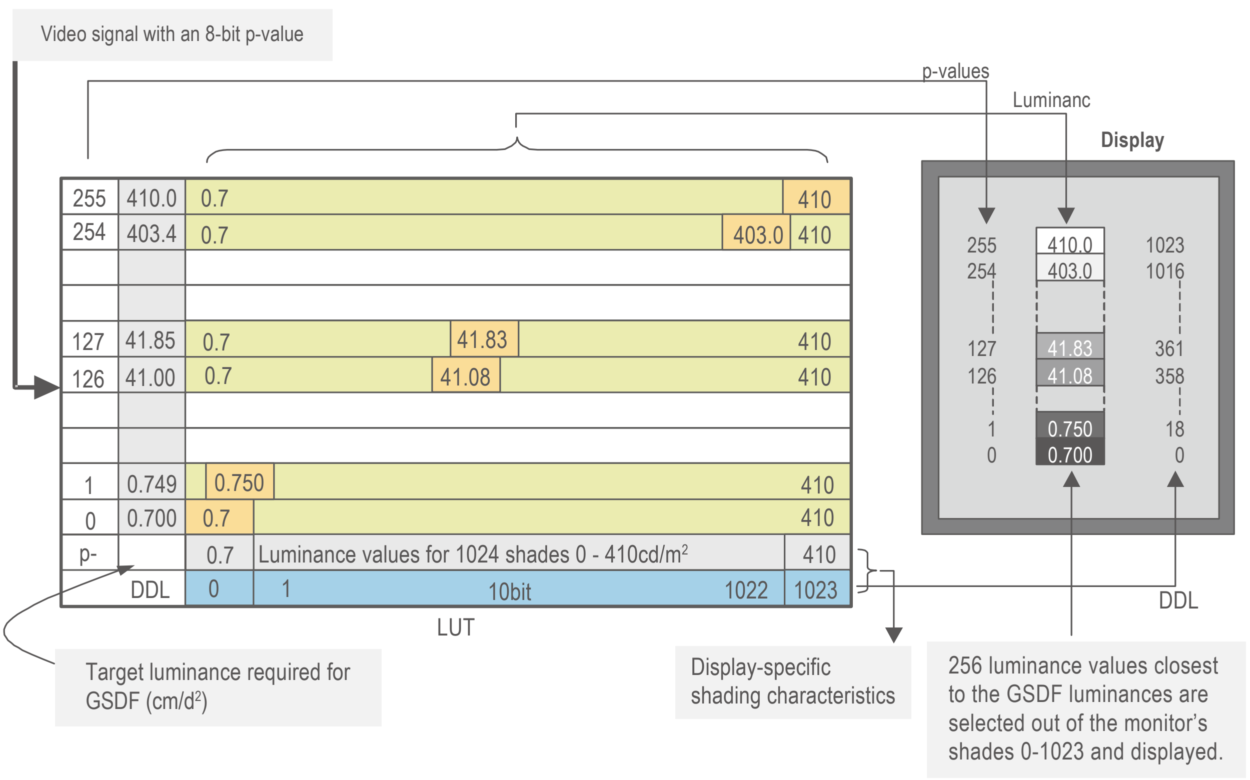
4. Contrast Resolution of Display System

The contrast resolution, if defined as a display system's "ability to display images with finely discriminated luminance changes," corresponds to the bit width of imaging signals that are input to the monitor. More accurately, however, the contrast resolution of a display system should be defined as the "maximum number of shades that can be displayed on the monitor due to input signals" because the number of shades sometimes decreases when grayscale characteristics are converted via the viewer and LUT. The degree of decrease in the number of shades is dependent on the input-output bit width of the LUT, gamma characteristics of the display, and settings of maximum and minimum luminances (Lmax and Lmin) used for calibration.

5. Functions and Operations of LUT

LUT is the memory inserted between the monitor and the imaging signals transmitted as p-values and included in the graphics processing circuit. The LUT has a function of specifying the monitor's digital driving level (DDL) in order to output the shading data of pixels recorded in the video memory as luminance values. Figure 7 shows an example of a monitor with a built-in LUT and a conceptual illustration of operations for 10-bit LUT with 8-bit input-output (8-bit LUT with a 10-bit width).

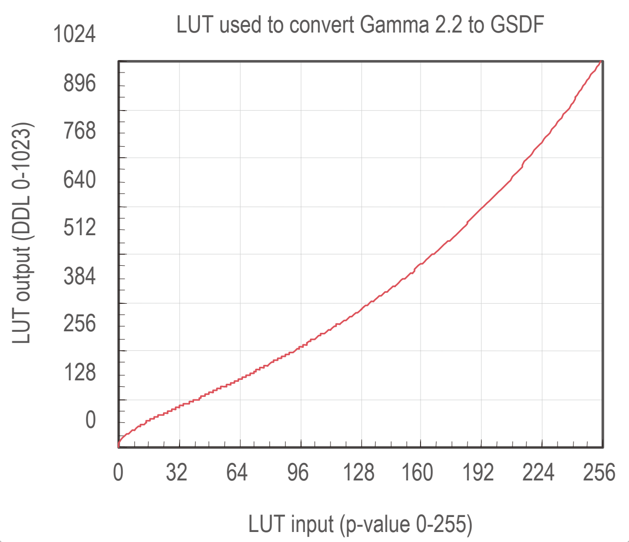
Figure 7. Conceptual illustration of LUT operations on a display system (monitor) with a built-in 10-bit LUT with 8-bit input-output



For the sake of discussion in this paper, a "monitor" means a section between the port of the computer's graphics card that outputs p-values and the unit that receives the signals and displays an image and an "LCD panel" means an internal section of a monitor that converts processed image signals (DDLs) into luminances and displays them.

The vertical axis of the LUT represents pixel data of 8 bits (256 shades). For the sake of more specific explanation, ideal luminance values (target luminances) for the digital values to be displayed in conformity with the GSDF are listed. The horizontal axis represents the LUT output values, which drive a display system capable of simultaneous display of 10-bit data. For the image data that has been input, the LUT is used to select a display luminance closest to the target luminance. The larger output bit width of the LUT, the more finely discriminated the luminances and, consequently, the more the choices and the closer to the target luminances are the displayed images. Figure 8 shows an example of characteristics of a LUT used to convert the display with Gamma 2.2 to the GSDF characteristics.

Figure 8. Example of LUT conversion characteristics



6. Accuracy in Conformance to GSDF Curve

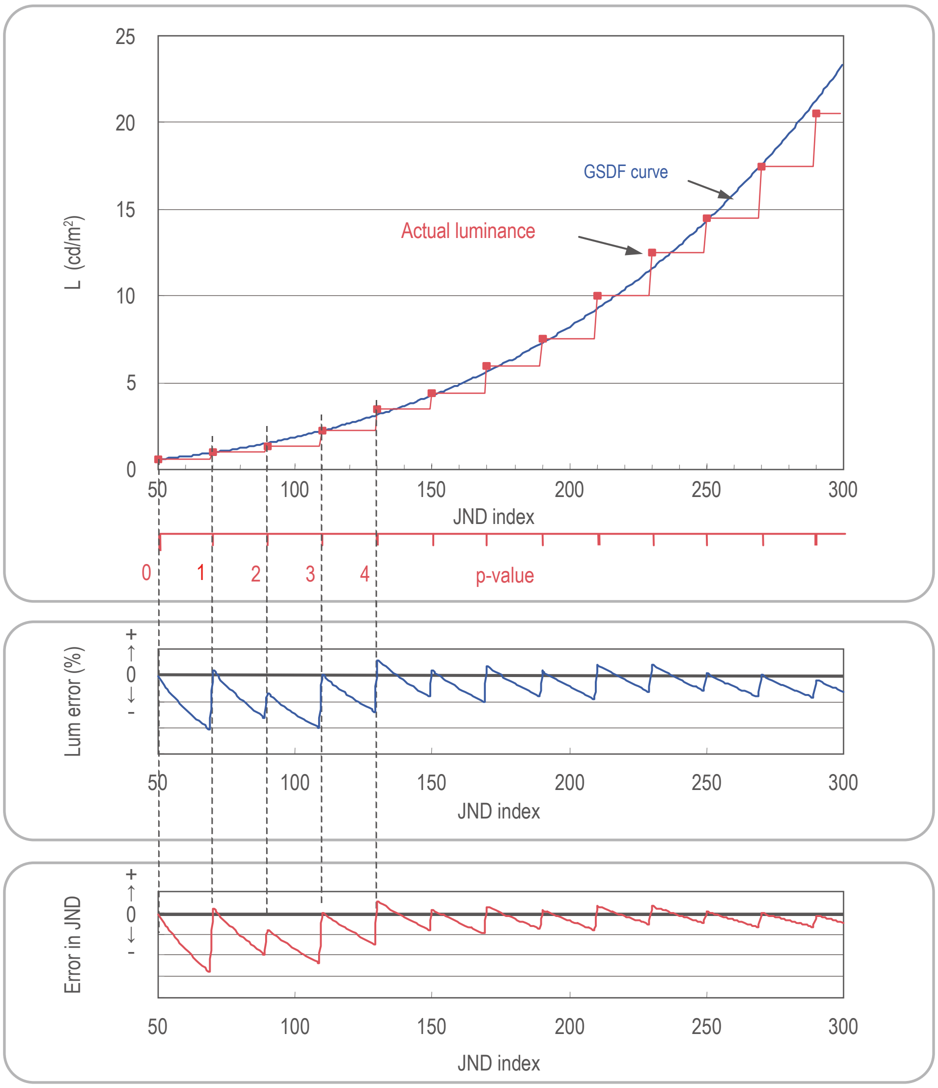
This chapter examines some items concerning the accuracy in conversion of the monitor-specific display characteristics to the GSDF characteristics.

The display luminance accuracy is dependent on the bit width of the LUT, the gamma characteristics, and the luminance range specific to the display system. This section assumes that the display-specific gamma is 2.2 and that the luminance range is 0.7-410 cd/m^2.

6-1. Deviation from GSDF Curve

The GSDF is an analog, continuous curve but, on an actual system driven digitally, the luminance responses of the monitor are in a step-like pattern and, as shown in Figure 9, have errors in comparison with the GSDF curve. The current study is about converting luminance errors into JND values and deriving errors in them in comparison with the ideal JND values. To minimize the calculation errors in sampling, the JND values in the horizontal axis are calculated at 14-bit intervals.

Figure 9. Deviation of luminance responses from the GSDF on a digitally driven monitor



6-2. Errors in Comparison with GSDF (Luminance Errors per Step of p-values)

The figure below shows how accurately the luminance values per step of input signals (e.g., 256-point luminance values for an 8-bit width signal) are displayed in comparison with the luminance values per step defined in the GSDF. The error, expressed as the "number of JNDs," is used as an indicator of the system accuracy performance.

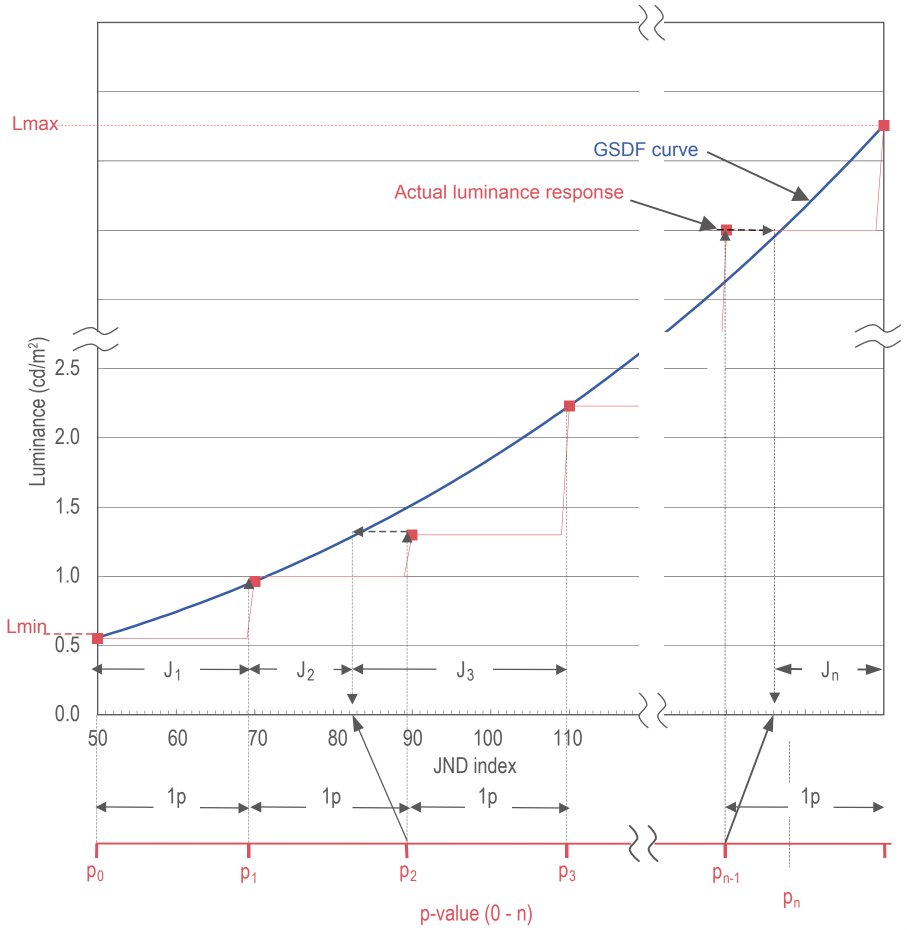
6-3. "Number of JNDs" per Interval of p-values and Deviation (Grayscale Continuity)

On an ideal system, an increment of the display luminance should be one JND per increment of one step of input signal.

However, this condition cannot be easily met on an actual digital system mainly because of a limitation due to the bit width of input signals and quantization errors that occur during grayscale conversion.

If the "number of JNDs" is large per interval between steps of input signals, a discontinuity of luminance is discernable in part of images with gradual luminance changes. To eliminate this discontinuity, you need to decrease the "number of JNDs" per p-value interval to less than one JND. In other words, a small "number of JNDs" per p-value interval as well as a small deviation from the mean "number of JNDs" at all the p-value intervals are the conditions for realizing a smooth grayscale.

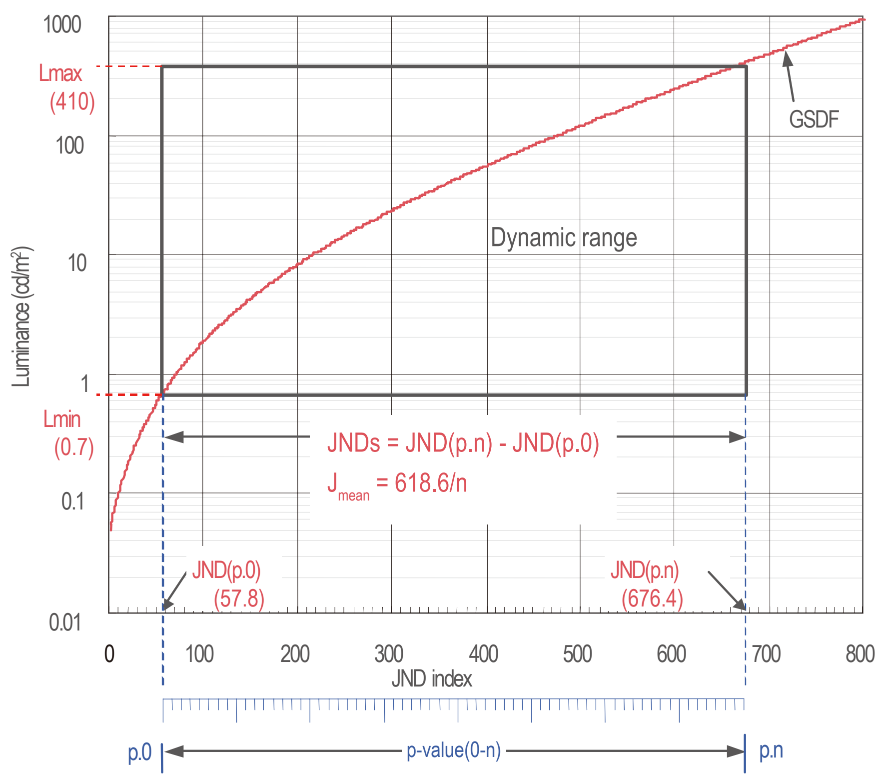
Figure 10. "Number of JNDs" per interval of p-values and deviation from GSDF



On monitors with a display luminance range from 0.7cd/m² to 410cd/m² as shown in Figure 11, for example, the "number of JNDs" existing in this luminance range is 676.4-57.8=618.6. If the input signal is 8 bits wide, the number of steps is 256. The mean value for "numbers of JNDs" per p-value interval (Jmean) is 618.6/255=2.43. Thus, a discontinuity of luminance may be discernable in part of images with gradual luminance changes. If the input signal is 10 bits wide, Jmean is 618.6/1024=0.60, less than one JND. Perceptually, therefore, it can be represented as a continuous luminance change.

The "number of JNDs" per p-value interval has a deviation due to a quantization error that occurs when the gamma specific to the display is converted to the GSDF. This deviation is smaller for a larger output bit width of the LUT.

Figure 11. Calculating the mean value (Jmean) for the "number of JNDs" per interval of p-values



6-4. Contrast Response Error (Contrast per JND associated with GSDF)

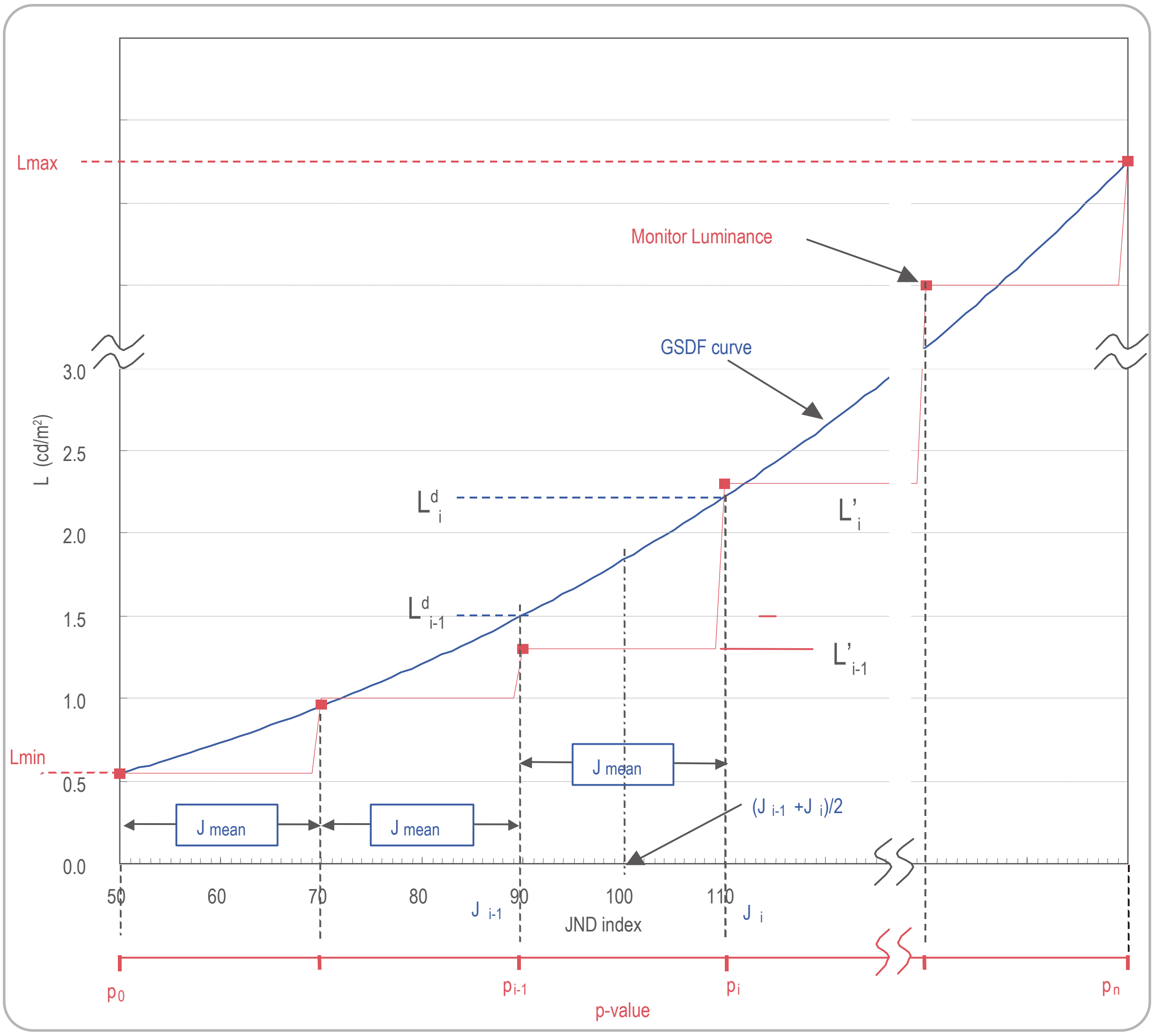
The evaluation of a contrast response error is a method of quantitative and detailed inspection on whether increments in luminances in relation to increments in p-values demonstrate a perceptually linear relationship. This method is defined as the Advanced Evaluation in AAPM-TG18 (American Association of Medical Physicists of Medicine – Task Group 18). As shown in Figure 12, the luminance change rate per p-value interval (dL/L: contrast) is normalized to a value per JND and contrasted with that of the GSDF.

Figures 17D to 23D in Appendix-1 are graphs showing the comparison of the contrast response characteristics of the systems with those in the GSDF.

How much the extent of an error influences the perception needs to be examined in another study. AAPM TG18 recommends that the contrast response evaluated using 18 steps of p-values should be less than ±10% of the GSDF.

In this paper, all the systems are compared under the same condition, a p-value of 256. There is a tendency that, the fewer the p-values to be evaluated, the smaller error value. This is because a larger p-value interval averages out a localized discontinuity.

Figure 12. Calculating the contrast response



In Figure 12, the contrast response at the point with a JND index of (J_{i-1} +J_i)/2 can be defined as follows[7)]:

$$\text{Contrast response of GSDF } \delta_i^d = \frac{2(L_i^d - L_{i-1}^d)}{(L_i^d + L_{i-1}^d)(J_i - J_{i-1})}$$

$$\text{Contrast response of monitor } \delta_i = \frac{2(L_i' - L_{i-1}')}{(L_i' + L_{i-1}')(J_i - J_{i-1})}$$

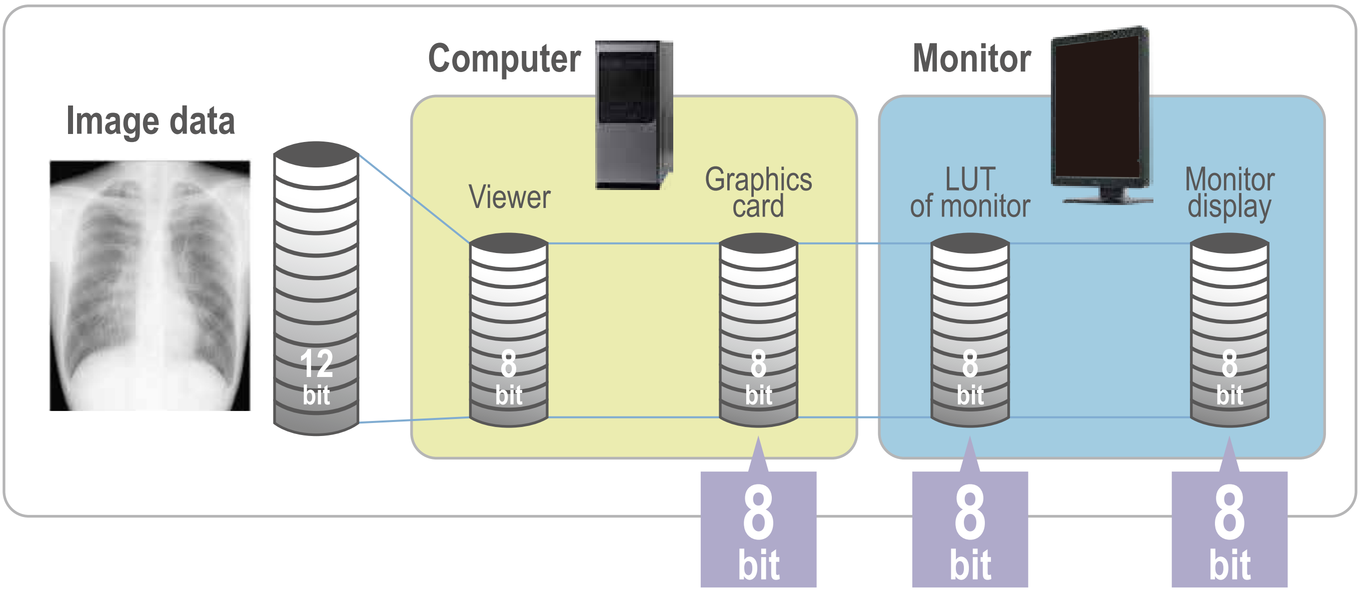
The following section is about the comparison of the GSDF conformance accuracies on specific systems.

7. Comparison of GSDF Accuracies on Specific Systems

7-1. 8-bit Input-Output System (LUT 8, 10, and 12bits)

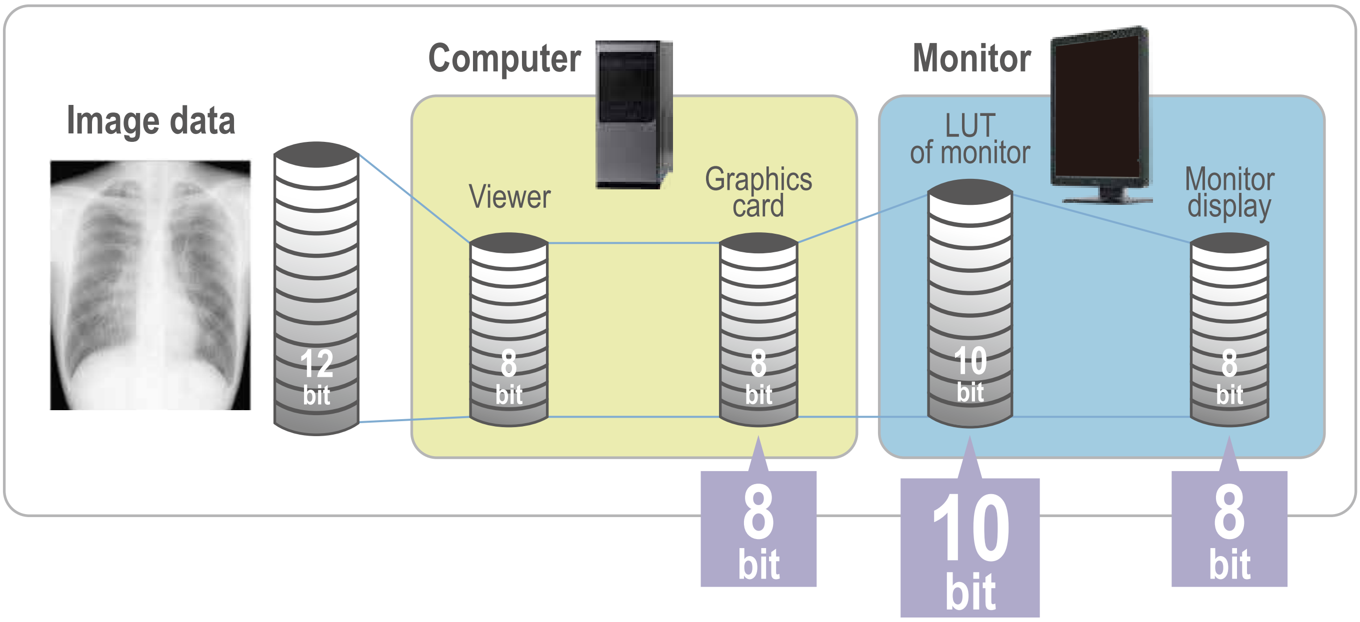
On this system, 12-bit image data stored on a computer is compressed by an 8-bit viewer and a graphics card into image signals with 8-bit, 256-step shades that drive the monitor.
The monitor has a built-in LUT 8 bits wide or better. In generally 8-bit input-output systems have a LUT with an output bit width of 8, 10, or 12 bits. In this paper, we compare the characteristics of these three systems.
Systems with a built-in LUT in the graphics card are handled in the same way as above.

(1) 8-8-8-bit System (Figures 17A-17D in Appendix-1)



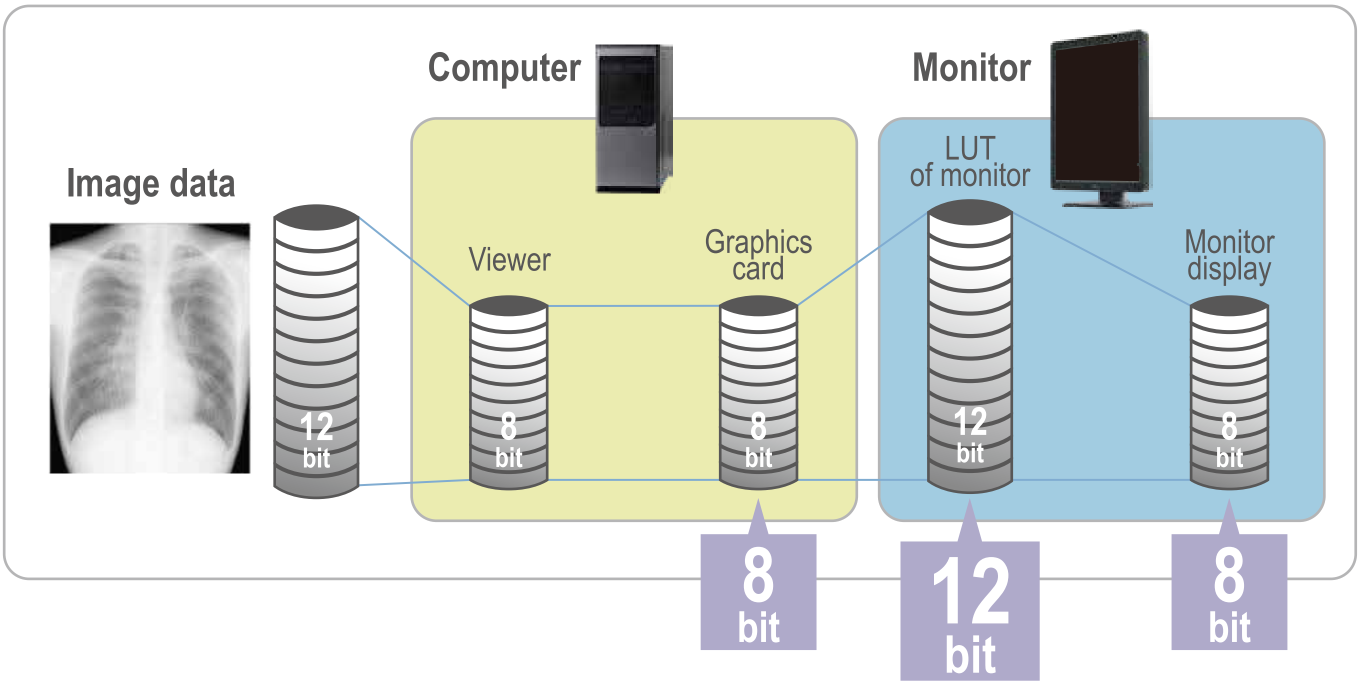
The term "8-8-8-bit system" is used because each of the graphics card output, LUT, and displayed image has a bit depth of 8 bits (this naming convention is used for all the systems described hereafter).
A typical example is a system that includes an ordinary PC monitor. On an 8-8-8-bit system with a few numbers of selectable shades, the error in comparison with the GSDF reaches 2.16 JNDs at the maximum.
Furthermore, the same luminance value is selected for some steps so that there are actually fewer number of shades in the monitor. Under the conditions shown in Table 1, for example, about 44 p-values result in the same luminance values so that the actual number of shades in the display is 256-44=212, making it impossible to display accurate grayscale information.

(2) 8-10-8-bit System (Figures 18A-18D in Appendix-1)



On an 8-10-8-bit system, the monitor has a number of shades as finely discriminated as 1024 and the 256 p-values can be displayed with an error of 0.52 JNDs or less in comparison with the target luminance values of the GSDF. Furthermore, the number of shades in the monitor is maintained so that, actually, 256 shades can be rendered.

(3) 8-12-8-bit System (Figures 19A-19D in Appendix-1)



On an 8-12-8-bit system, the monitor has a larger number of shades of 4096, more finely discriminated, and the 256 p-values can be displayed with an extremely high accuracy, i.e., a maximum error of 0.31 JNDs in comparison with the target luminance values of the GSDF.

(4) Summary of 8-bit Input-Output Systems

Table 1 shows the result obtained from the evaluation of these 8-bit systems concerning the errors in comparison with the GSDF in terms of four perspectives.

Table 1. Comparison of accuracies of 8-bit input-output systems
(Trial calculation assuming Lmin=0.7cd/m², Lmax=410cd/m², and the display-specific gamma =2.2)

	Deviation from GSDF curve (JNDs)		Error in comparison with GSDF (JNDs)		JNDs per step		Contrast response error (%)		Actual number of shades in display
8-8-8-bit system	Max.	4.6	Max.	2.16	Ave.	2.43	Max.	100	212
			p-p	4.11	Ave.	4.76			
8-10-8-bit system	Max.	3.0	Max.	0.52	Ave.	2.43	Max.	30.4	256
			p-p	0.99	Ave.	1.52			
8-12-8-bit system	Max.	2.6	Max.	0.16	Ave.	2.43	Max.	9.8	256
			p-p	0.31	Ave.	0.47			

On an 8-8-8-bit system, the increments in display luminances in relation to increments in p-values present large fluctuation from 0 to 4.76 JNDs. Such a system is not suitable for imaging diagnosis because it is incapable of presenting continuous grayscale representations and have a fewer number of shades that can actually be displayed, causing significant deterioration from an original image.

However, using a LUT with a larger number of output bits can put the 256 luminance points closer to the GSDF target luminances, consequently decreasing the variations of JNDs per step and dramatically improving the display quality.

When seen from a different point of view, this fact proves that a 12-bit LUT has a significantly reduced contrast response error and is capable of smooth grayscale display.

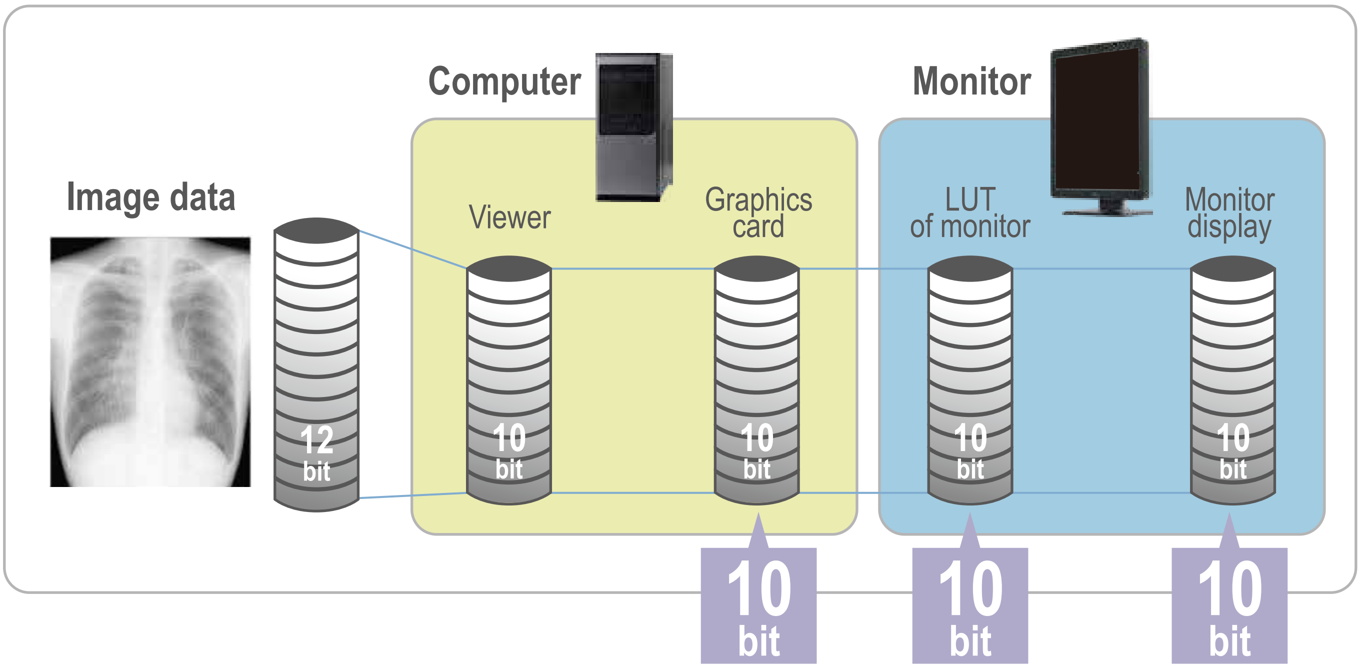
In consideration of the above result, an 8-bit input-output system to be used for imaging diagnosis requires at least a 10-bit LUT and can realize ideal imaging display if a 12-bit LUT is used.

7-2. 10-bit Input-Output System (LUT 10, 11, and 12bits)

On a 10-bit input-output system, 12-bit original image data is compressed into 10-bit image signals that drive the monitor. Concerning this group of systems, this section compares systems with LUTs with output bit widths of 10, 11, and 12 bits.

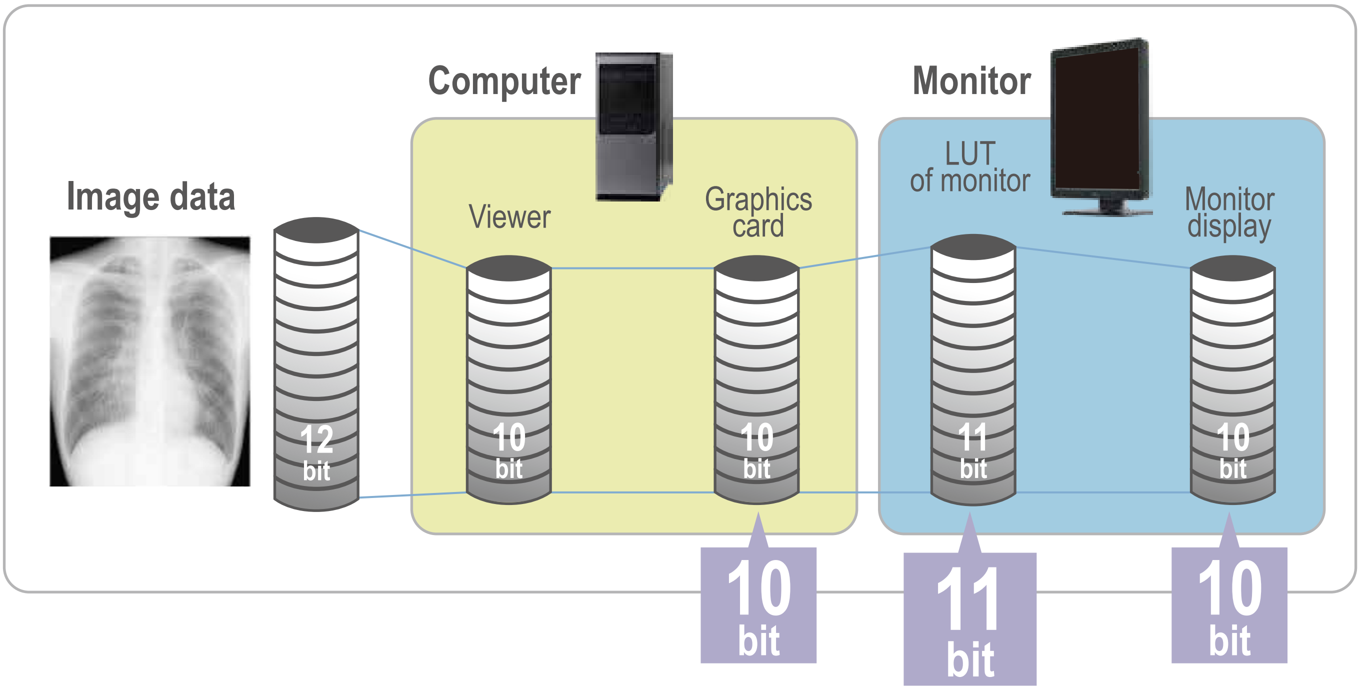
These systems are ready for input image signals with four times as many shades as an 8-bit input-output system, which result in about one-fourths of deviations from the GSDF curve and come closer to more analogous representations. Since the mean value of JNDs per step is also improved to less than one JND, an even smoother grayscale representation can be realized.

(1) 10-10-10-bit System (Figures 20A-20D in Appendix-1)



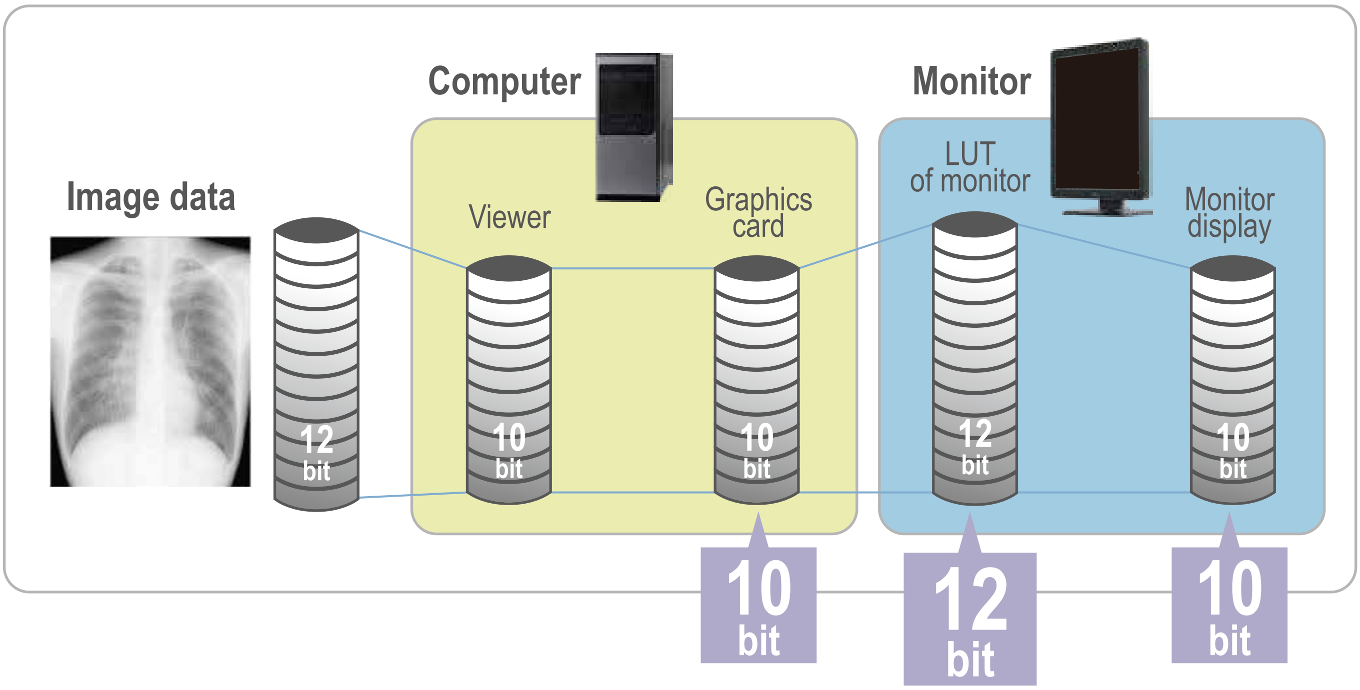
On a 10-10-10-bit system, 1024 p-values are used to select values closest to the GSDF target values out of the 1024 luminance values determined according to the monitor's own display characteristics. As described before, the LUTs have the same number of input-output bits so that the tonal expression is lost during conversion of display characteristics and consequently there are a fewer number of shades that can actually be displayed. On the other hand, this system build in wider bit LUT, so that an error in comparison with the GSDF in each shade of gray can be limited to 0.54 JNDs at the maximum.
Since the variation of JNDs per step reaches 1.19 JNDs at the maximum, the discontinuity of tonal representations is discernable in part of images with gradual luminance changes.

(2) 10-11-10-bit System (Figures 21A-21D in Appendix-1)



On a 10-11-10-bit system, there are 2048 choices of luminance values that are available on the monitor for 1024 p-values so that the steps of input signals can be brought closer to the GSDF target values.
When the errors in comparison with the GSDF are considered, the deviation from the GSDF curve is 0.87 JNDs, the error of each shade in comparison with the GSDF is 0.28 JNDs, and the variation of JNDs per step is 0.76 JNDs. Since all of these errors are less than one JND, assumed to be the limit of average human perception, more or less satisfactory display quality can be obtained.

(3) 10-12-10-bit System (Figures 22A-22D in Appendix-1)



On a 10-12-10-bit system, there are 4096 choices of luminances that are available on the monitor so that the each input signals match the GSDF target values very accurately.

When the errors in comparison with the GSDF are considered, the deviation from the GSDF curve is 0.76 JNDs, the error of each shade in comparison with the GSDF is 0.17 JNDs, and the variation of JNDs per step is 0.45 JND. This system has an ideal performance as a 10-bit input-output system.

(4) Summary of 10-bit Input-Output Systems

Table 2 shows the summary of evaluations of 10-bit input-output systems.

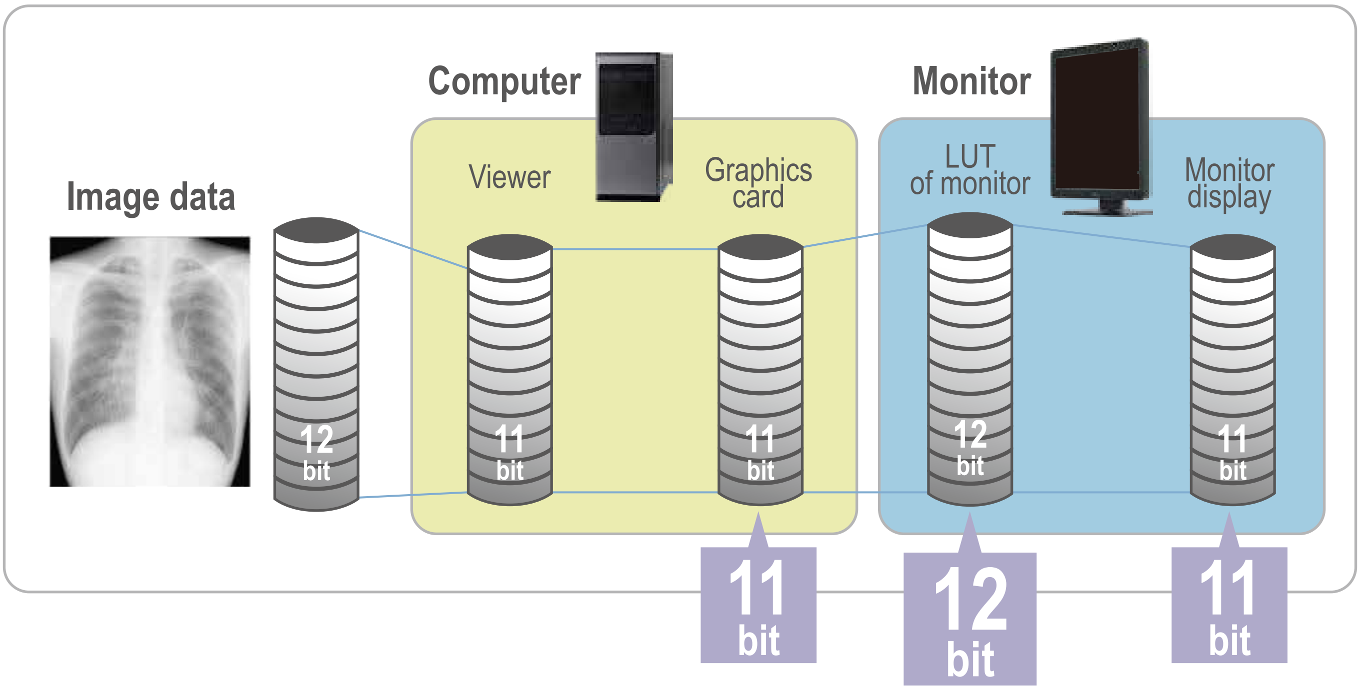
Table 2. Comparison of accuracies of 10-bit input-output systems
(Trial calculation assuming Lmin=0.7cd/m^2, Lmax=410cd/m^2, and the display-specific gamma =2.2)

	Deviation from GSDF curve (JNDs)		Error in comparison with GSDF (JNDs)		JNDs per step		Contrast response error (%)		Actual number of shades in display
10-10-10-bit system	Max.	1.10	Max.	0.54	Ave.	0.60	Max.	31.8	849
			p-p	1.05	Ave.	1.19			
10-11-10-bit system	Max.	0.87	Max.	0.28	Ave.	0.60	Max.	19.7	1024
			p-p	0.55	Ave.	0.76			
10-12-10-bit system	Max.	0.76	Max.	0.17	Ave.	0.60	Max.	9.3	1024
			p-p	0.32	Ave.	0.45			

A 10-bit input-output system is ready for handling four times as much shading information as an 8-bit input-output system. With the deviation from the GSDF curve about one-third of that of an 8-bit input-output system, a 10-bit input-output system can display images more similar to an analog system.

Generally speaking, a 10-bit input-output system is far superior to an 8-bit input-output system. However, a 10-10-10-bit input-output system, with its actual number of shades in the display significantly decreased, cannot prove its worth as a 10-bit input-output system. A 10-bit input-output system needs to have at least an 11-bit or better LUT and, if provided with a 12-bit LUT, can deliver a more sophisticated display performance.

7-3. 11-12-11-bit System (Figures 23A-23D in Appendix-1)



On an 11-bit input-output system, 12-bit original image data is compressed into 11-bit image signals that drive the monitor.

It can simultaneously display 2048 shades, twice as many as a 10-bit input-output system.

Table 3 shows the superiority of an 11-12-11-bit system to a 10-12-10-bit system.

Table 3. Comparison of accuracies of 11-12-11-bit and 10-12-10-bit input-output systems
(Trial calculation assuming Lmin=0.7cd/m^2, Lmax=410cd/m^2, and the display-specific gamma =2.2)

	Deviation from GSDF curve (JNDs)		Error in comparison with GSDF (JNDs)		JNDs per step		Contrast response error (%)		Actual number of shades in display
10-12-10-bit system	Max.	0.76	Max.	0.17	Ave.	0.60	Max.	9.3	1024
			p-p	0.32	Ave.	0.45			
11-12-11-bit system	Max.	0.45	Max.	0.17	Ave.	0.30	Max.	9.7	2048
			p-p	0.32	Ave.	0.42			

As is apparent from this table, an 11-12-11 system is advantageous even to a 10-12-10-bit system whose high fidelity to the GSDF curve was confirmed in the previous section in terms of performance indicated by the deviation from the GSDF curve and JNDs per step. Although the limit of average human perception is allegedly one JND, there are variations among individuals and a radiologist with great sensitivity may be able to perceive a contrast of less than one JND.

Therefore, this system that can achieve 50% or less of one JND ranks as a top-of-the-line medical imaging display monitor.

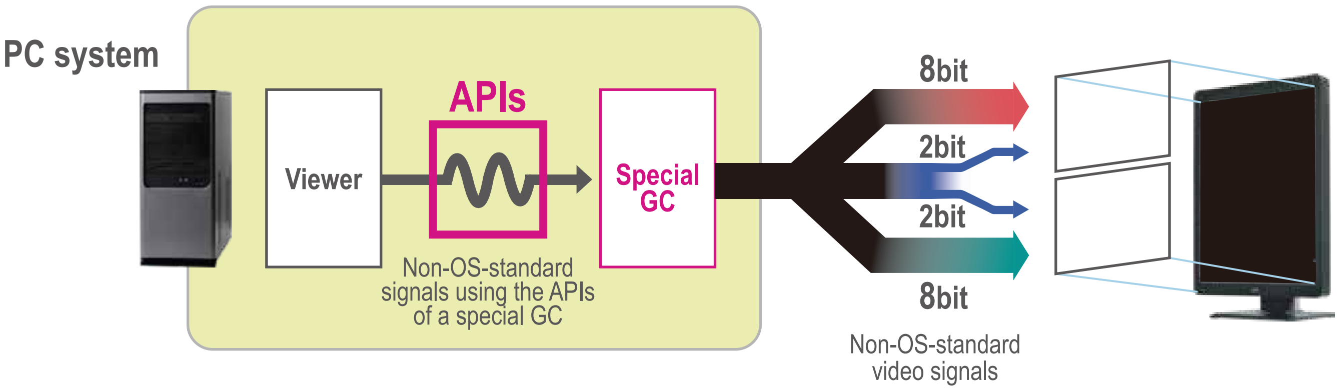
8. Realization of Multi-shade System

Then, how is it possible to realize a multi-shade system with a high fidelity to the GSDF curve, which was concluded to be the best above?

8-1. Realization through Combination of Viewer, GC, and Monitor (Figure 13)

This section explains an approach to realization with a focus on the transmission of digital image signals for an LCD monitor.
The commonly used operating systems (OS) such as Windows, MacOS, SUN Solaris, and Linux are specified to transmit image signals through three channels R, G, and B, covering 8 bits each and 24 bits in total.
Although a monochromatic system needs only single-color signals and thus uses only one channel, it cannot perform over-8-bit data transfer due to the above reason, i.e., a limitation of the OS.
A medical display system, as shown in the figure 13, realizes over-8-bit data transfer by sending monochromatic image data via all of the R, G, and B channels. For example, 8-bit data and 2-bit data are transferred via the R-channel and B-channel, respectively, to half of the screen and thus 10-bit data is used to drive the monitor. For the remaining half of the screen, 8-bit data and 2-bit data are transferred via the G-channel and B-channel, respectively, to half of the screen and thus 10-bit data is used to drive the monitor. Therefore, 10-bit display is realized for the entire screen.
Since this signal transfer system is not a specified for the hardware or operating system, the driver software for the graphics card must be provided with special software (an application program interface or API). In other words, this software allows 10-bit signals in an application to be converted on the graphics card to special output.

Figure 13. Example of a conventional multi-shade display system



This system has the following difficulties:

(1) Since the multi-shade transmission system is not a standardized for specified the hardware or operating system, an API must be prepared for each graphics card (GC) or operating system (OS).

(2) Since there is no standard way for deciding which channel should be the main one for the multi-shade transmission system or which bit of which channel should be the multi-shade bit, the input-output interface of an LCD monitor should conform to the interface of a GC.

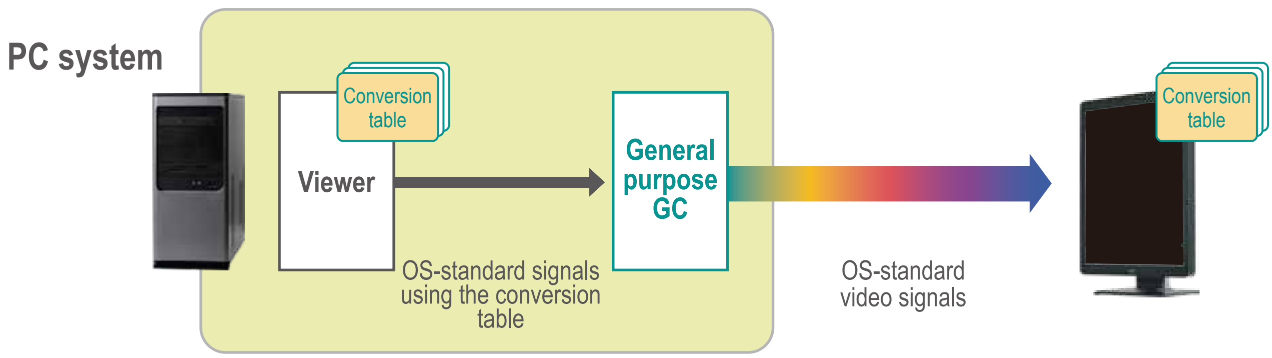
(3) The system will not be compatible at all with an ordinary 8-bit system or common 32-bit mode.

An unexpected problem may occur if you try to run a general application such as Web browser in addition to the viewer. In sum, this system is not versatile due to its many restrictions.

8-2. Realization through Combination of Viewer and Monitor (Figure 14)

This system, based on a general 32-bit color mode (24-bit signal transmission mode), encodes monochromatic multi-shade signals into color signals when transmitting them and decodes the signals in the monitor to realize multi-shade display.

Figure 14. Example of a conventional multi-shade display system



Specifically, this system transmits multi-shade signals using a table that converts monochromatic shades into color signals, R, G, and B. Theoretically, representation of about 16 million shades is possible because there are 24-bit signal lines including R, G, and B with 8 bits each. However, only about 4,000 shades (12 bits) are actually necessary at the most and therefore about half of these signal lines are required to transmit a necessary and sufficient number of shades of gray.

This system has the following advantages:

(1) The use of a standard image signal transmission system (24-bit full-color transmission) of Windows or other OS (such as MacOS and Linux) eliminates the need of special APIs dependent on the graphics card.

(2) The installation of a monochrome-to-color conversion table into an application easily realizes this system.

(3) The adoption of an OS standard video output enables the use of a general-purpose graphics card and eliminates dependence on graphics card manufacturers.

(4) A possible increase in the number of shades from 10-bit, 11-bit, 12-bit, and so on can be dealt with only by modifying the conversion table, a table used to assign combinations of color signals to shades of monochromatic signals, eliminating the need of rewriting other software or upgrading of hardware, etc. in principle.

In comparison of the above two systems, the latter JVC system is dependent only on the viewer and monitor and thus apparently advantageous to the other.

9. Summary

This paper compared the relationships between the LUT input-output bit width and the GSDF accuracy that can be theoretically achieved on each of 8-bit, 10-bit, and 11-bit systems assuming the monitor's displayable range as 0.7-410cd/m^2 and the display native gamma as 2.2. The following summarizes what is described in previous chapters and examines evaluation items and results for grayscale accuracy required for medical imaging monitor.

"JNDs per step" means:

"Increments in luminances in relation to increments per step of input signals." Ideally, it is desirable that both the mean value and variation of "JNDs per step" should be no more than one JND, which is the limit of human perception. The mean value, dependent on the input signal bit width, is 2.4 JNDs for an 8-bit input-output system, 0.6 JNDs for a 10-bit input-output system, and 0.3 JNDs for an 11-bit input-output system. The variation decreases if the output bit width of the LUT increases.

"Deviation from the GSDF Curve" means:

"An error resulting in loss of shades due to sampling." In other words, this term means how much error an original image is finally displayed with on the monitor if the original image is assumed to be analog. It is desirable that this error should be no more than one JND to reproduce an image with sufficient fidelity to the original image.

"Error in comparison with the GSDF" means:

"An error that represents a difference between the luminance values of all the steps of input signals and the luminance values defined in the GSDF (target luminances)." In this paper, an error is expressed not as a percent error of a luminance value but converted to a "number of JNDs" because the expression as a perceptually linear scale enables comparison actually by numbers and facilitates understanding. Note that there is a significant difference in terms of perception between 1% in a low-luminance area and 1% in a high-luminance area, as described in Chapter 2.

"Contrast response error" means:
"How much error the increment in luminance per increment in input signals (contrast) has in comparison with the value defined in the GSDF." In other words, this means how much error a contrast between all the neighboring steps of input signals (the luminance difference divided by the mean luminance) has in comparison with the value in the GSDF. This parameter can be used to strictly evaluate the conformity to the GSDF.
The performances of the systems described in this paper can be compared in terms of the above four perspectives as follows:

8-bit Input-Output System
Has discernable boundaries of shades in part of images with gradual luminance changes because the "mean value of JNDs per step" is 2.4 JNDs. An 8-bit LUT, in particular, makes the variation so wide that it causes significant jumps and drops in shades of gray, which may adversely influence diagnosis. The use of a 10-bit LUT considerably reduces the variation and makes few jumps and drops so that the system is in a range of practical use. The use of a 12-bit LUT makes a necessary and sufficient monitor for an 8-bit input-output system.

10-bit input-output system
Is a desirable system because the "mean value of JNDs per step" is 0.6 JNDs and the increment of luminance per step is less than the limit of perception. However, a 10-bit LUT, which will cause jumps and drops in shades of gray, is insufficient for a 10-bit input-output system. It needs to be equipped with at least an 11-bit LUT. The use of a 12-bit LUT allows you to make the 10-bit input-output system to deliver its best performance.

11-bit input-output system
Is a desirable system because the "mean value of JNDs per step" is 0.3 JNDs and the increment of luminance per step is less than the limit of perception. It is an ideal imaging display system because the deviation from the GSDF is not more than half of one JND, which is considered a limit of perception, and thus it provides image representation with extremely high fidelity to an original image.

The grayscale accuracy required of an imaging display system depends on the type of diagnosis image, image reading environment, luminance range of the monitor, or depth of sensitivity of the radiologist. Generally, however, it is desirable that a 1- to 2-megapixel monitor is at least provided with an "8-10-8 bit system" and that a 3- to 5-megapixel monitor is provided with at least an "8-12-8-bit system" or ideally an "11-12-11-bit system."

JVC, based on the above result, realized an 8-10-8-bit system for 1-megapixel resolutions and an 11-12-11-bit system for 2- to 6-megapixel resolutions, thus providing an ideal solution for each of these resolutions from the perspective of accurate medical imaging monitor.

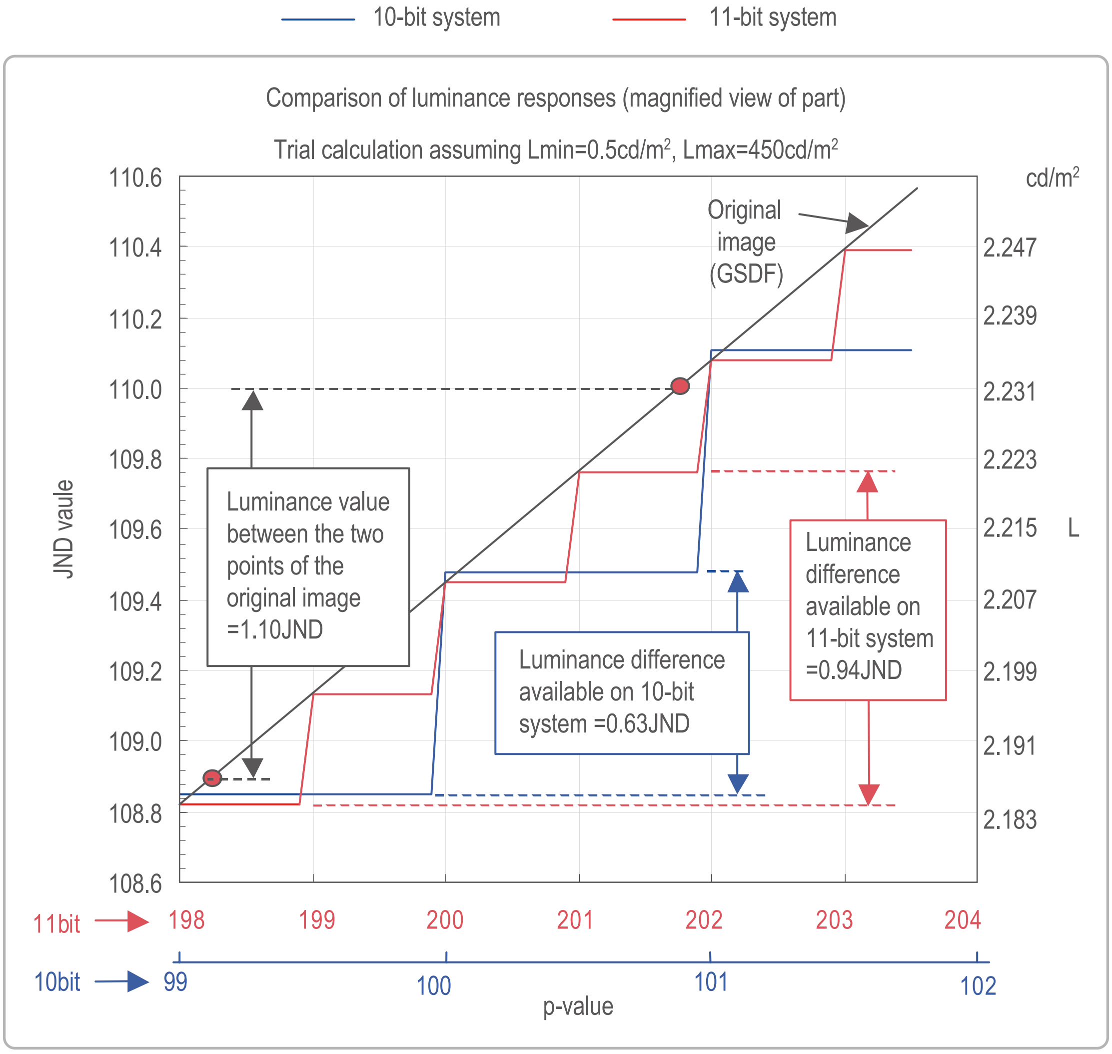
Furthermore, a research paper was published to report that, as a result of carrying out psychological and physical evaluation by human observers on monitor systems supporting 8-bit-plus multi-shade imaging, they were able to make out on an 11-bit system some images that they could not on an 8-bit system.

With these facts considered, it can be concluded that the ideal theoretical accuracy of a display system should be targeted at no less than one-half JND.

Lastly, let us examine the superiority of an 11-bit system. For example, a 0.5-450cd/m^2 monitor, when the performance is converted to a "number of JNDs," can display about 644 JNDs. Some people claim that, on a 10-bit input-output system with a p-value of 1024 and thus more than 644 JNDs, no system with a higher number of bits is necessary. Let us, then, examine whether a 10-bit-plus system is really unnecessary. A digital display system has an error close to the "mean number of JNDs" per step at the maximum due to a quantization error. Figure 16 shows a close-up view of part of the luminance response characteristics of 10-bit and 11-bit input-output systems. The black line represents the grayscale of an original image and the two stepped lines represent the luminance responses of 10-bit and 11-bit input-output systems, respectively. This chart shows, in specific values, how a low-contrast luminance difference existing in the original image is represented on the above two systems when an original image with sufficient grayscale information close to an analog counterpart is displayed. The luminance difference between the two red dots shown in this figure is 1.10 JNDs. The luminance difference between the two areas, therefore, is perceivable on a display system that can reproduce the image with fidelity. If this original image is displayed on 10-bit and 11-bit input-output systems, the luminance difference between the two areas will be 0.63 JNDs and 0.94 JNDs, respectively.

From this figure, it can be concluded that 11bit system is a superior to 10 bit input-output system.

Figure 15. Comparison of 10-bit and 11-bit systems



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Appendix-1

Accuracy Calculation Results

8-8-8-bit system

Figure 17A Shows the deviation from the GSDF curve on an 8-8-8-bit system by the "numbers of JNDs."

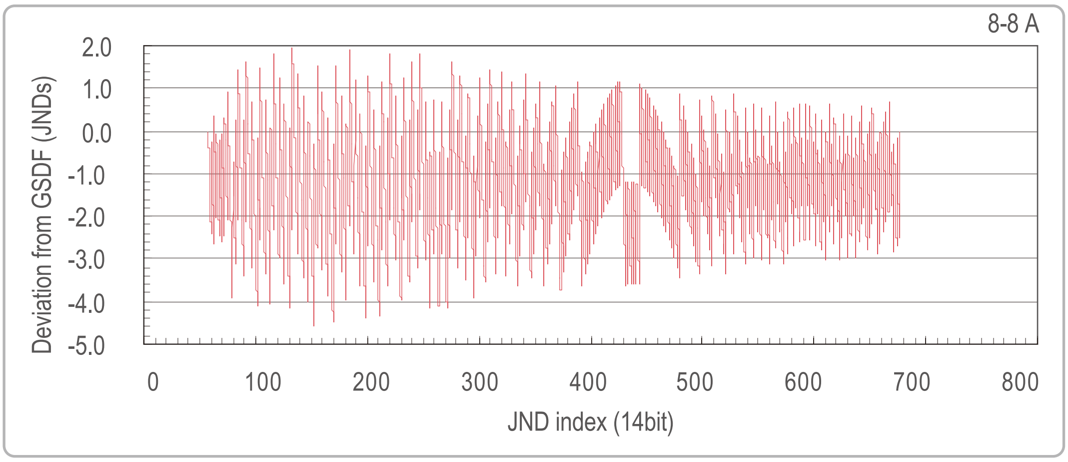


Figure 17B Shows the luminance error in comparison with the GSDF on an 8-8-8-bit system by the "numbers of JNDs."

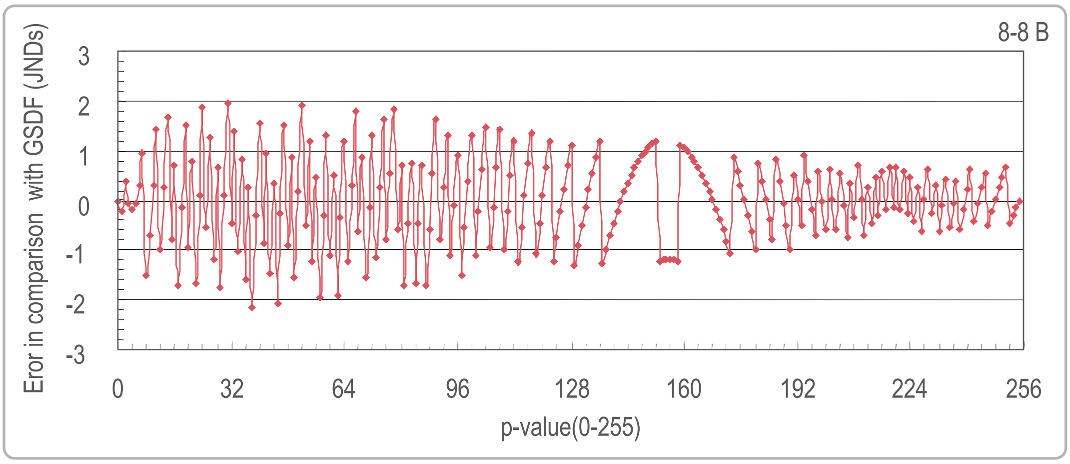


Figure 17C Shows the "numbers of JNDs" per p-value interval on an 8-8-8-bit system.

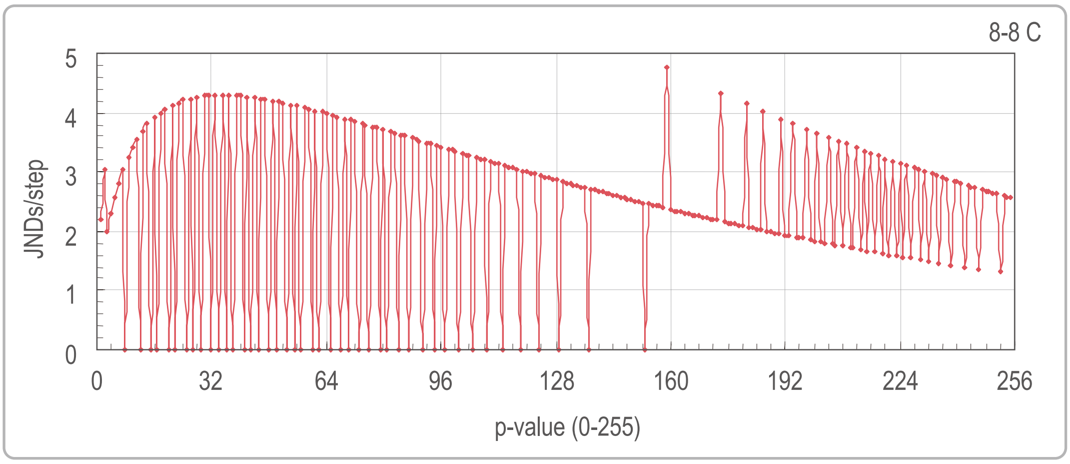
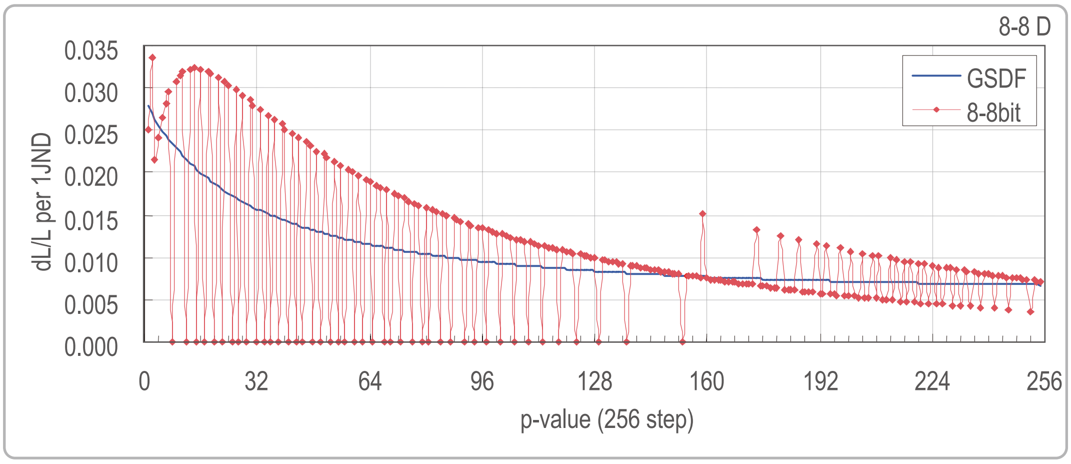


Figure 17D Shows the contrast per JND on an 8-8-8-bit system.
The values evaluated using 256 steps of p-values are shown.



8-10-8-bit system

Figure 18A Shows the deviation from the GSDF curve on an
8-10-8-bit system by the numbers of JNDs.

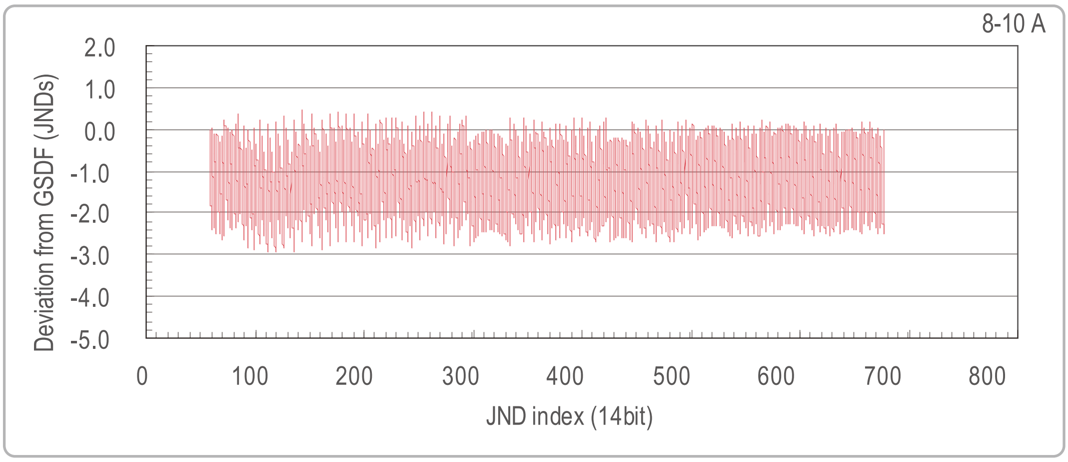


Figure 18B Shows the luminance error in comparison with the GSDF on an
8-10-8-bit system by the "numbers of JNDs."

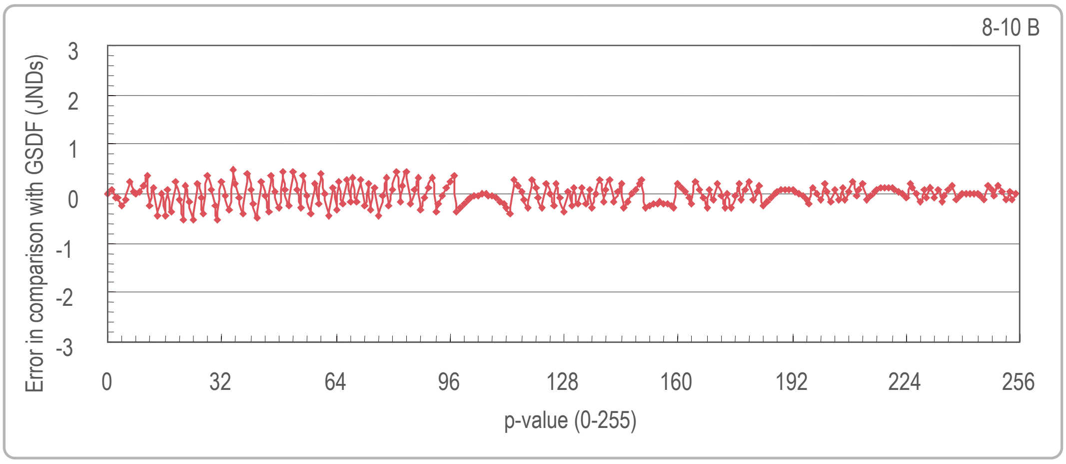


Figure 18C Shows the "numbers of JNDs" per p-value interval on an 8-10-8-bit system.

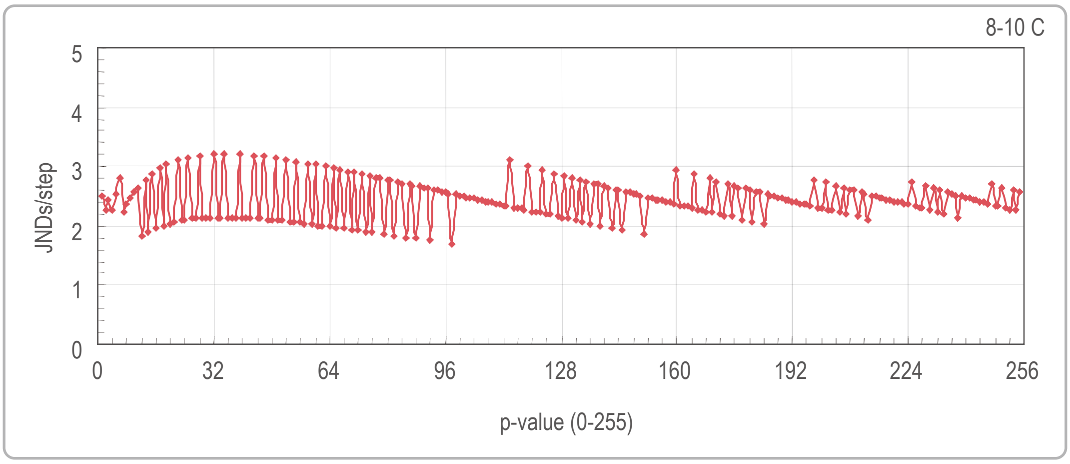
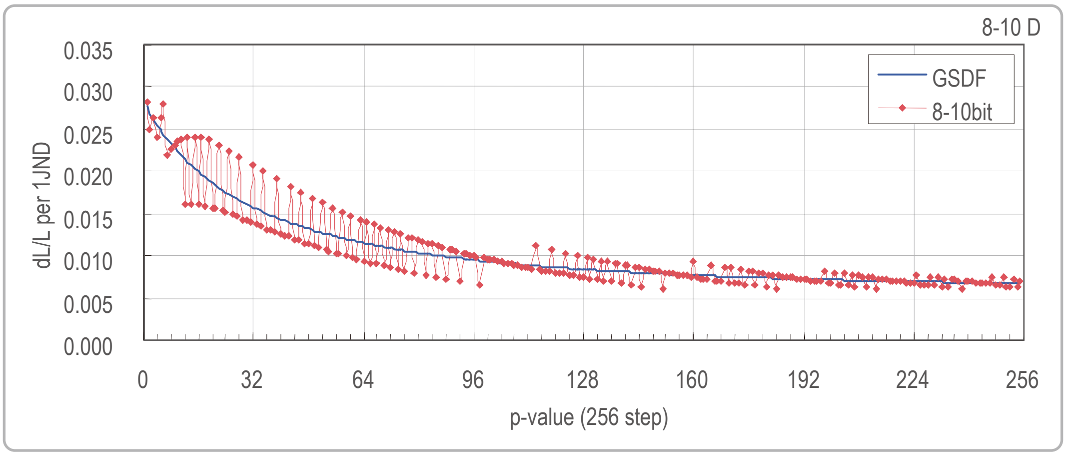


Figure 18D Shows the contrast per JND on an 8-10-8-bit system.
The values evaluated using 256 steps of p-values are shown.



8-12-8-bit system

Figure 19A Shows the deviation from the GSDF curve on an
8-12-8-bit system by the "numbers of JNDs."

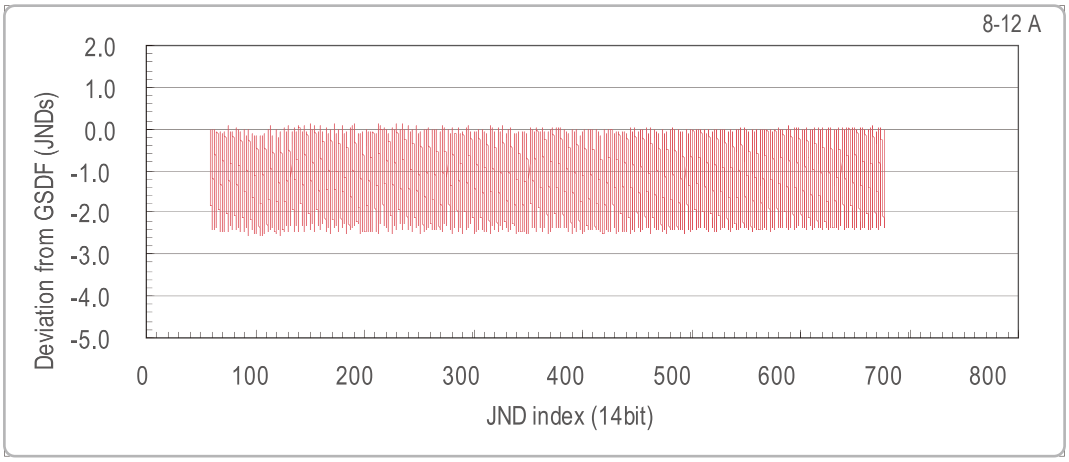


Figure 19B Shows the luminance error in comparison with the GSDF on an 8-12-8-bit system by the "numbers of JNDs."

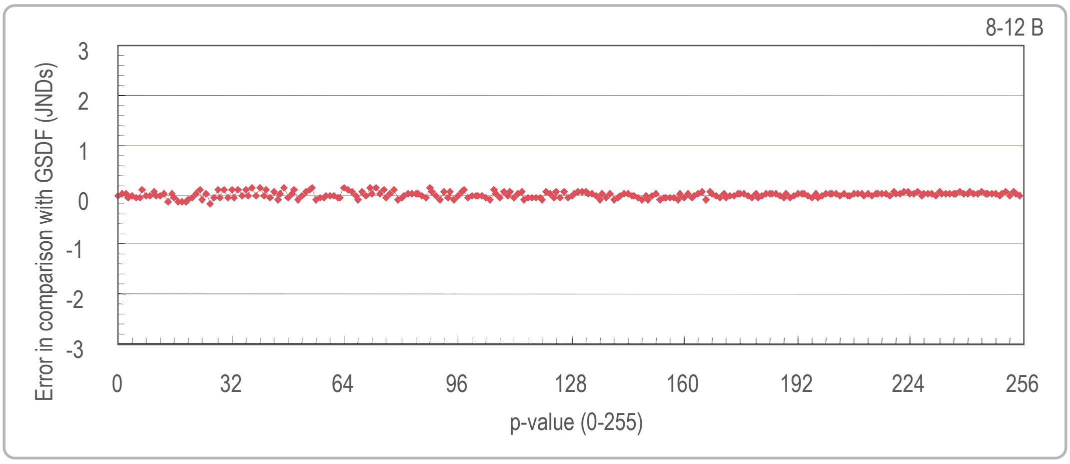


Figure 19C Shows the "numbers of JNDs" per p-value interval on an 8-12-8-bit system.

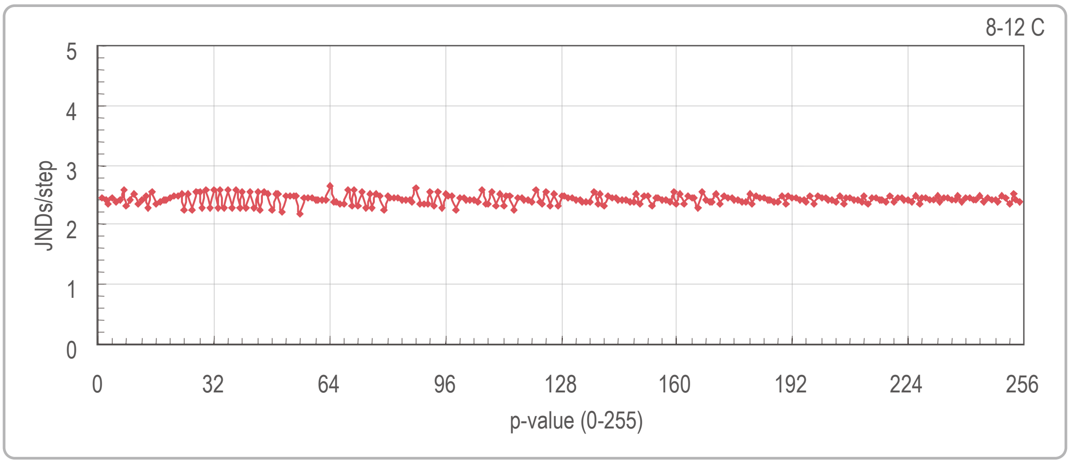
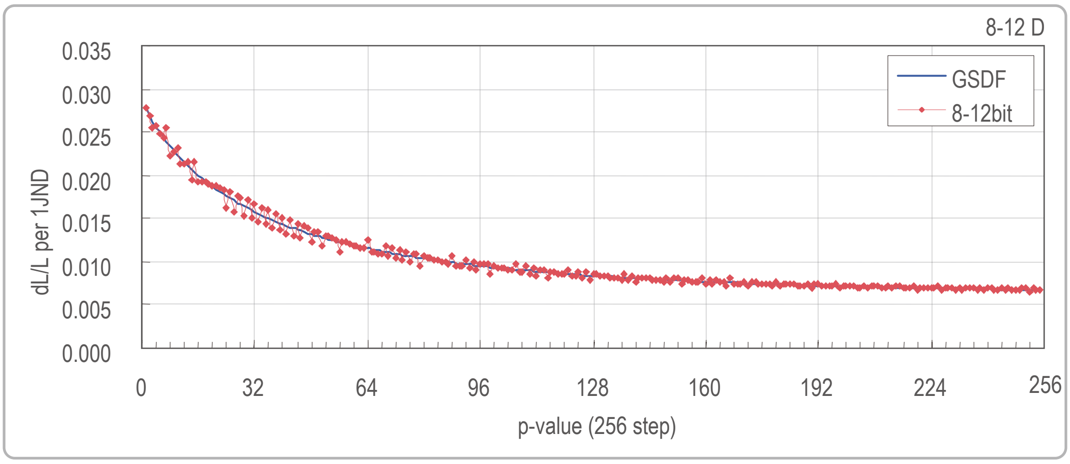


Figure 19D Shows the contrast per JND on an 8-12-8-bit system. The values evaluated using 256 steps of p-values are shown.



10-10-10-bit system

Figure 20A Shows the deviation from the GSDF curve on a
10-10-10-bit system by the "numbers of JNDs."

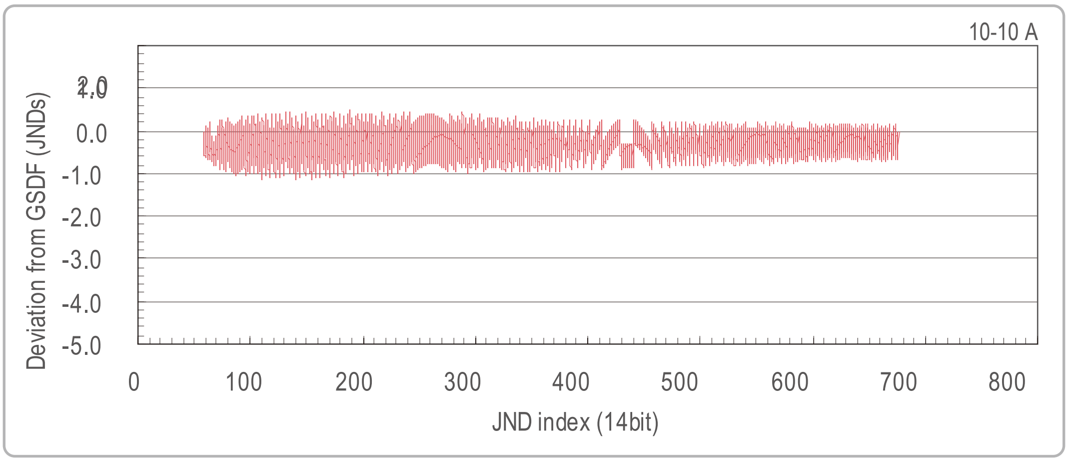


Figure 20B Shows the luminance error in comparison with the GSDF on a
10-10-10-bit system by the "numbers of JNDs."

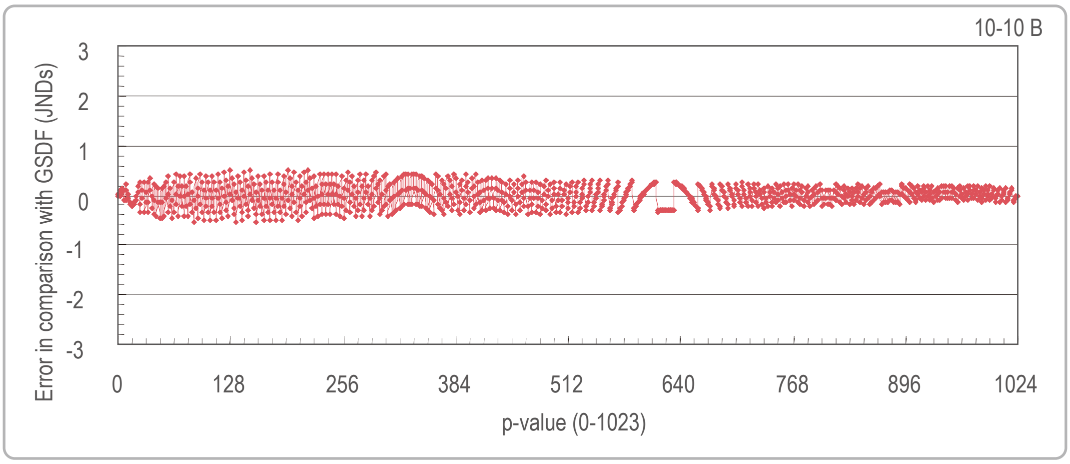


Figure 20C Shows the "numbers of JNDs" per p-value interval on a 10-10-10-bit system.

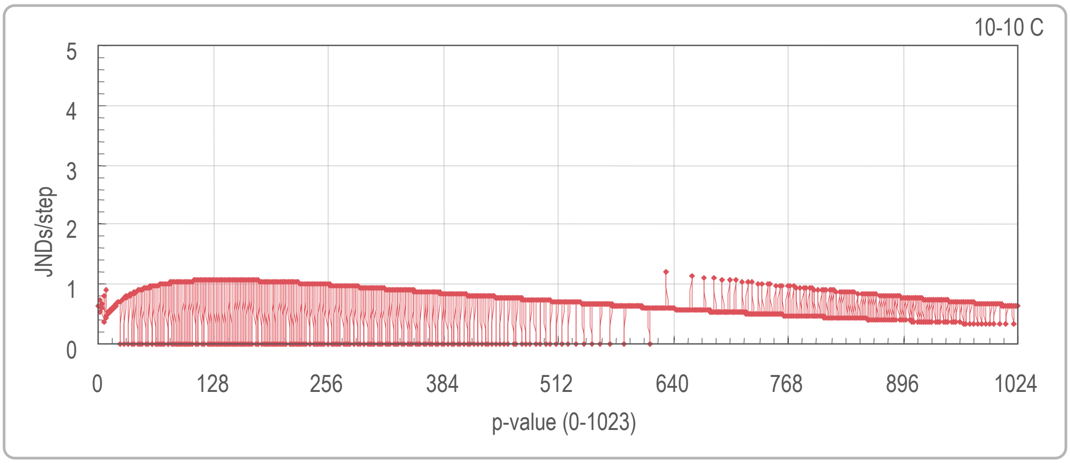
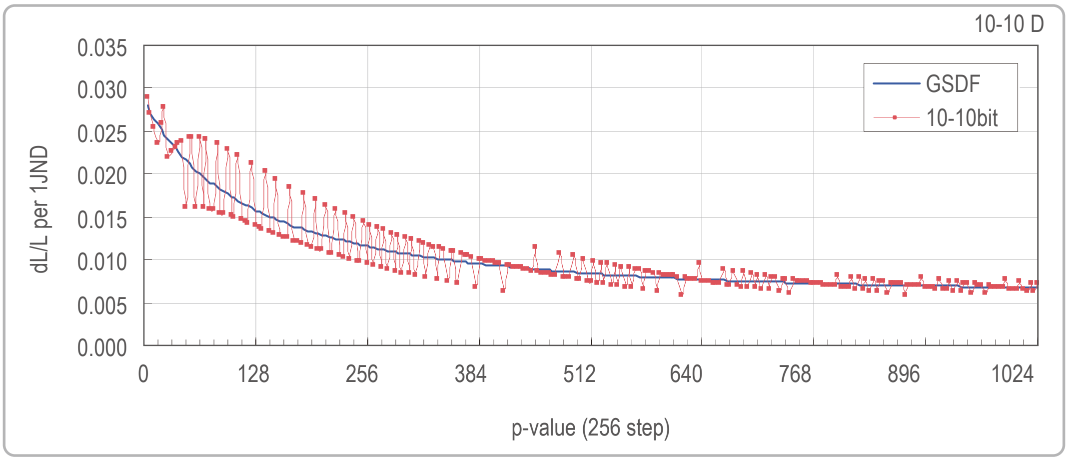


Figure 20D Shows the contrast per JND on a 10-10-10-bit system.
The values evaluated using 256 steps of p-values are shown.



10-11-10-bit system

Figure 21A Shows the deviation from the GSDF curve on a 10-11-10-bit system by the "numbers of JNDs."

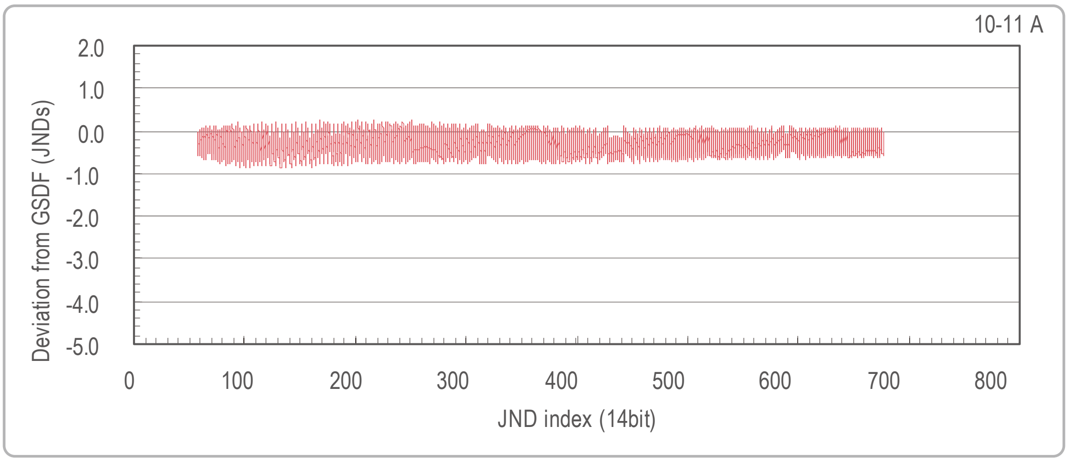


Figure 21B Shows the luminance error in comparison with the GSDF on a 10-11-10-bit system by the "numbers of JNDs."

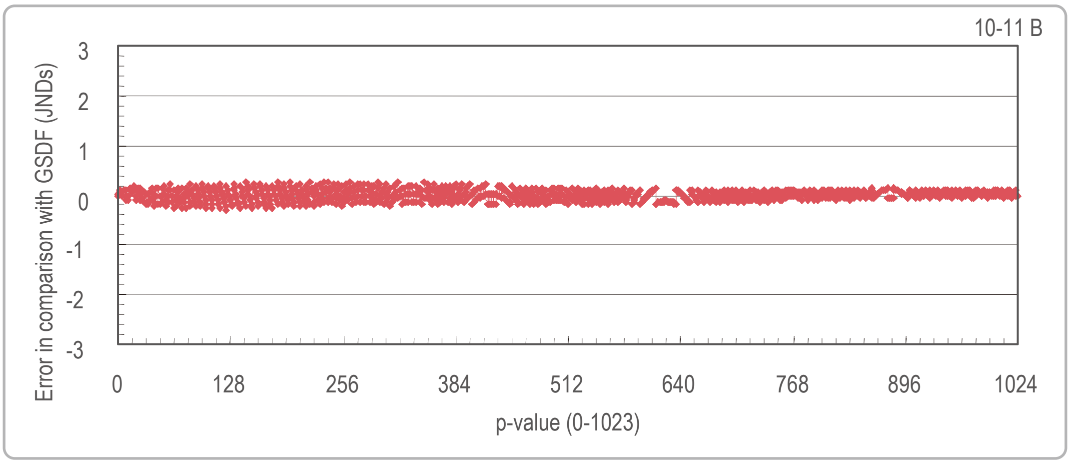


Figure 21C Shows the "numbers of JNDs" per p-value interval on a 10-11-10-bit system.

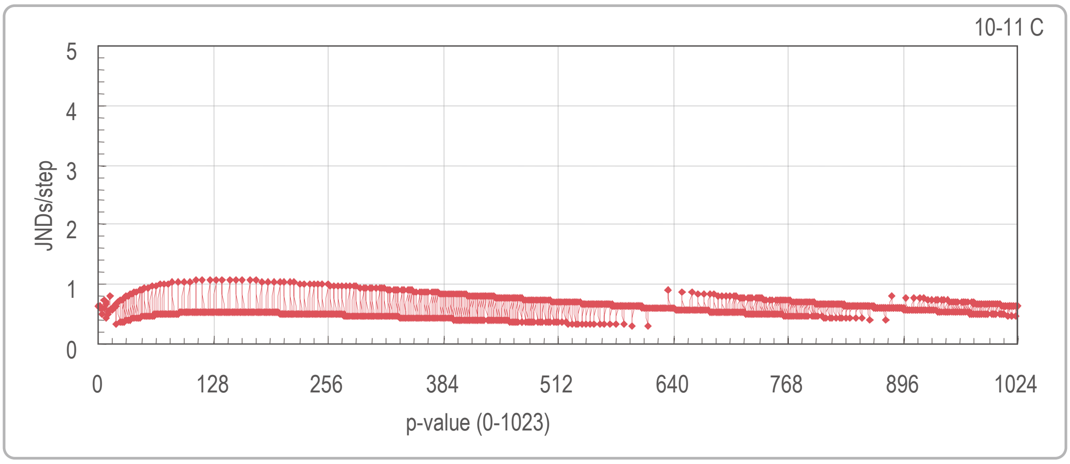
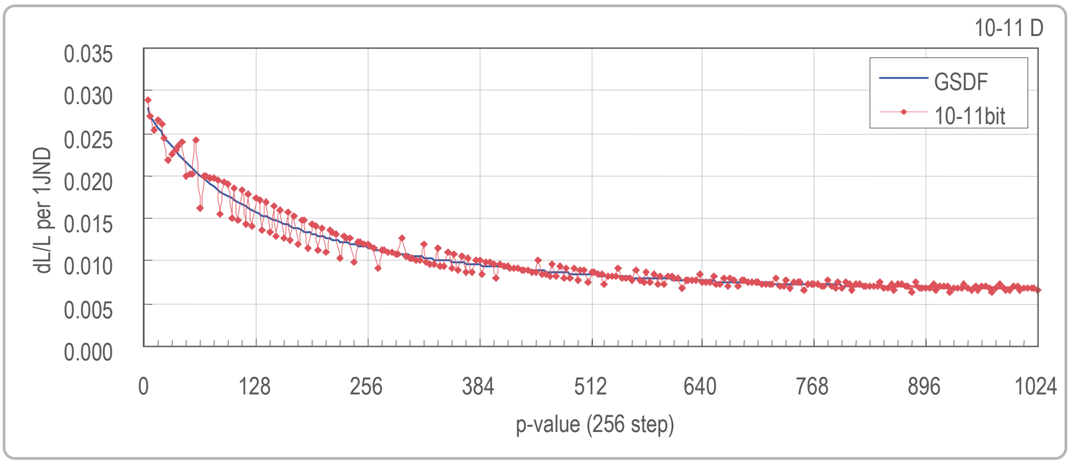


Figure 21D Shows the contrast per JND on a 10-11-10-bit system.
The values evaluated using 256 steps of p-values are shown.



10-12-10-bit system

Figure 22A Shows the deviation from the GSDF curve on a
10-12-10-bit system by the "numbers of JNDs."

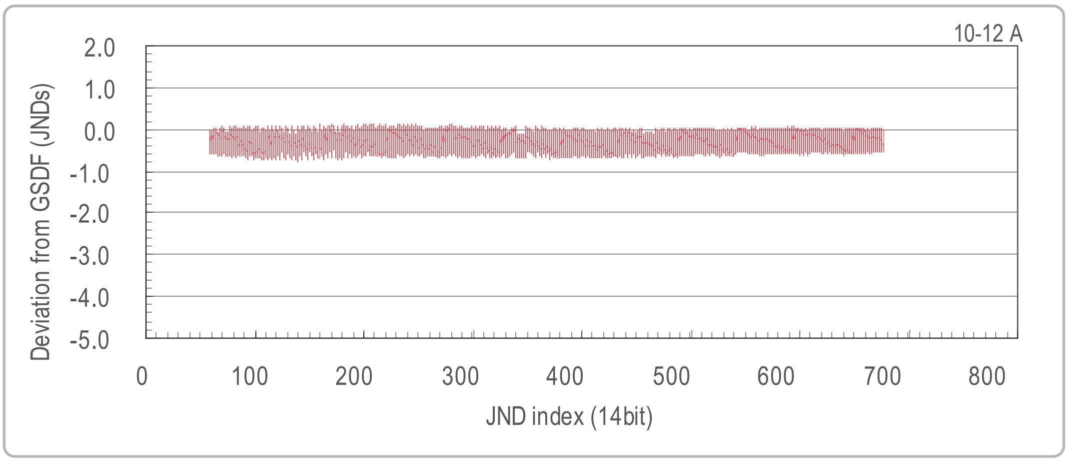


Figure 22B Shows the luminance error in comparison with the GSDF on a 10-12-10-bit system by the "numbers of JNDs."

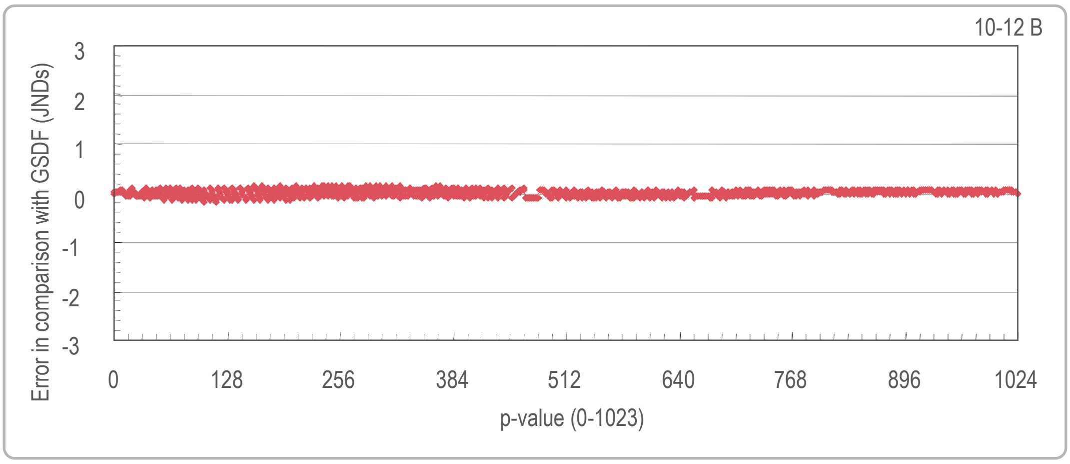


Figure 22C Shows the "numbers of JNDs" per p-value interval on a 10-12-10-bit system.

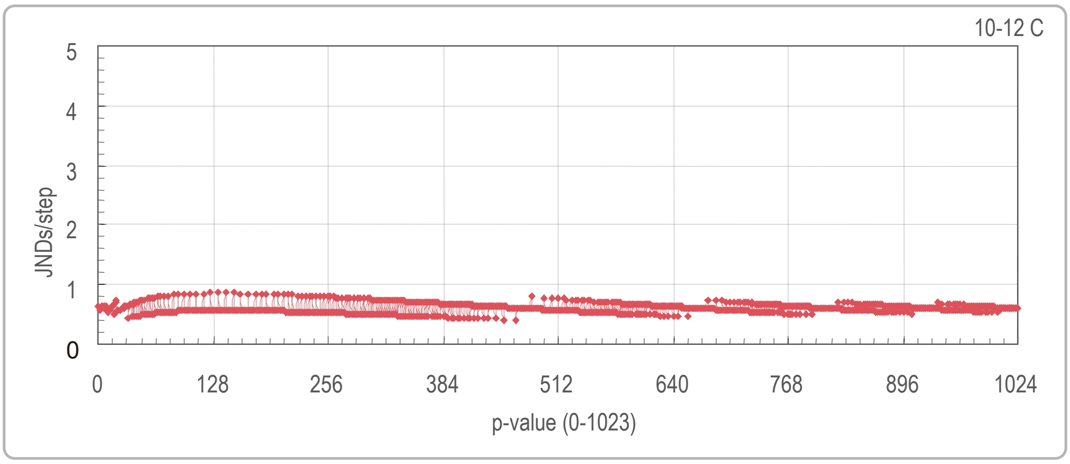
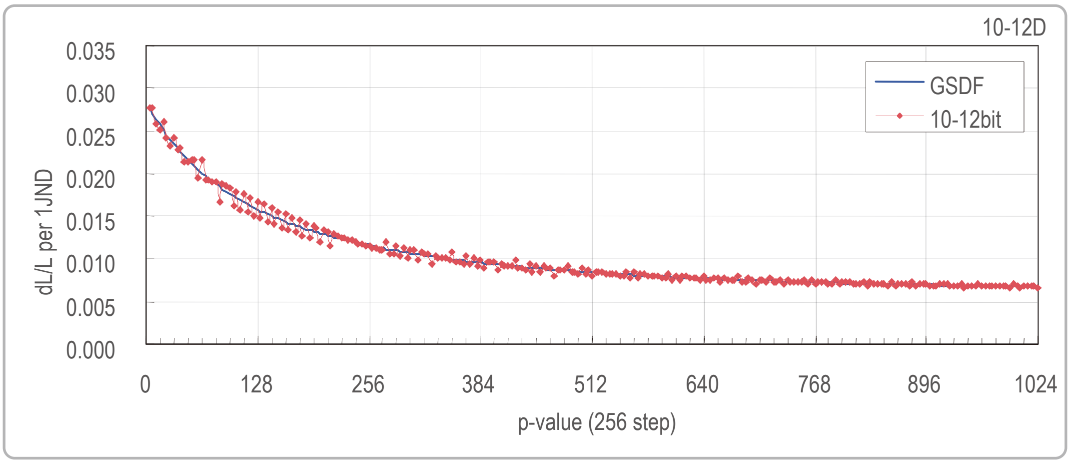


Figure 22D Shows the contrast per JND on a 10-12-10-bit system.
The values evaluated using 256 steps of p-values are shown.



11-12-11-bit system

Figure 23A Shows the deviation from the GSDF curve on an 11-12-11-bit system by the "numbers of JNDs."

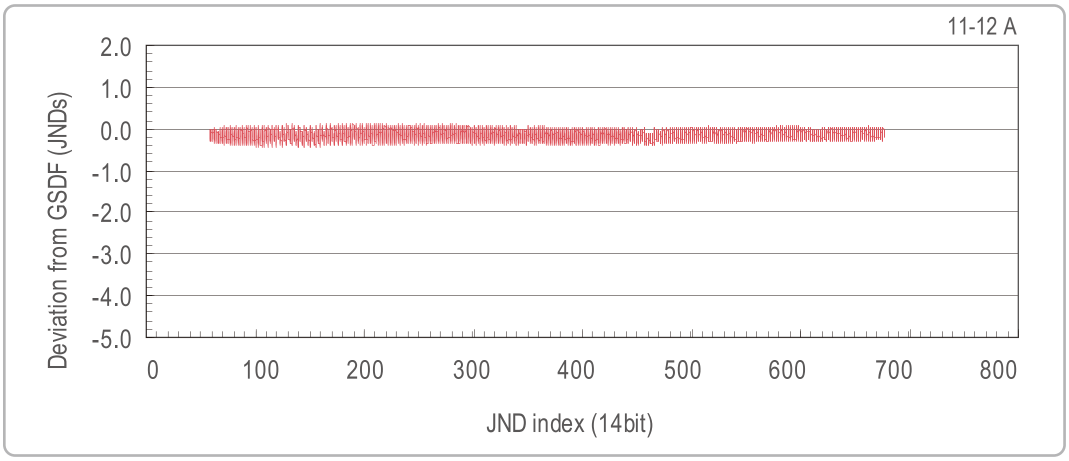


Figure 23B Shows the luminance error in comparison with the GSDF on an 11-12 11-bit system by the "numbers of JNDs."

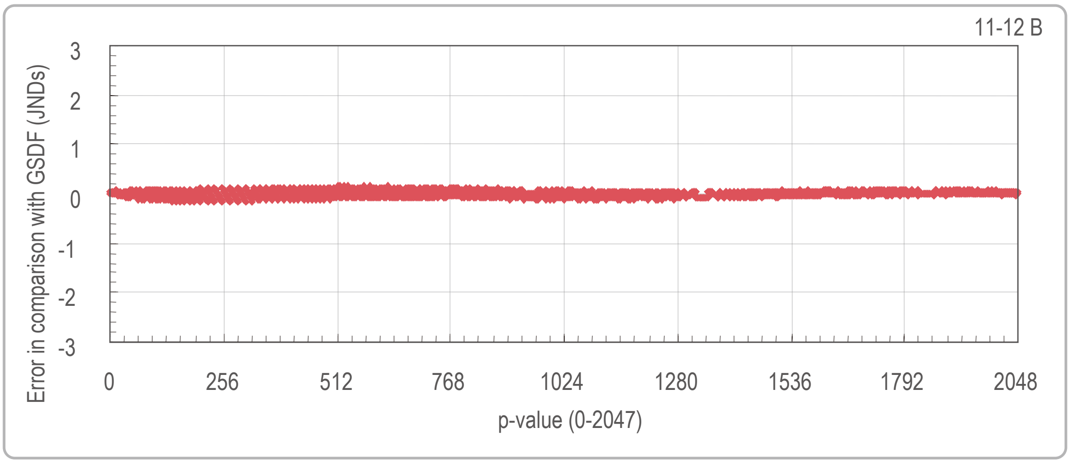


Figure 23C Shows the "numbers of JNDs" per p-value interval on an 11-12-11-bit system.

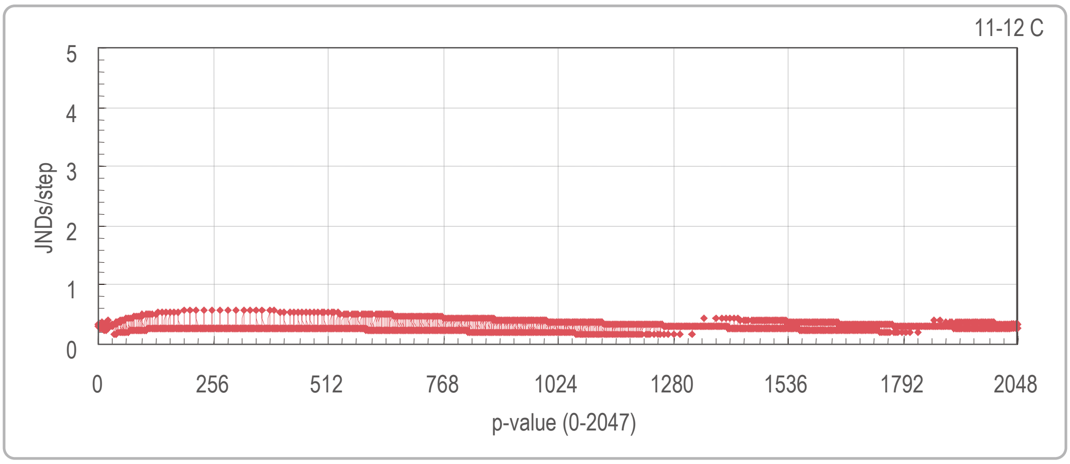
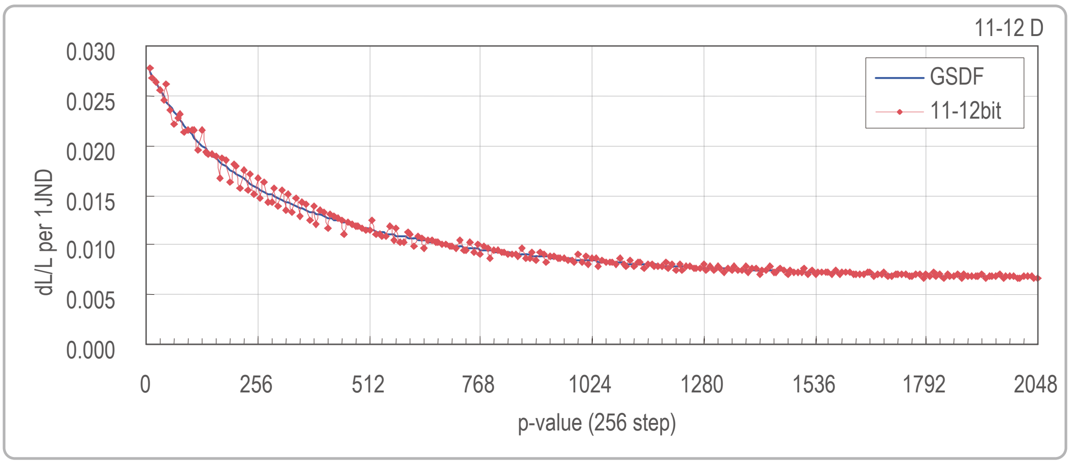


Figure 23D Shows the contrast per JND on an 11-12-11-bit system.
The values are evaluated using 256 steps of p-values.



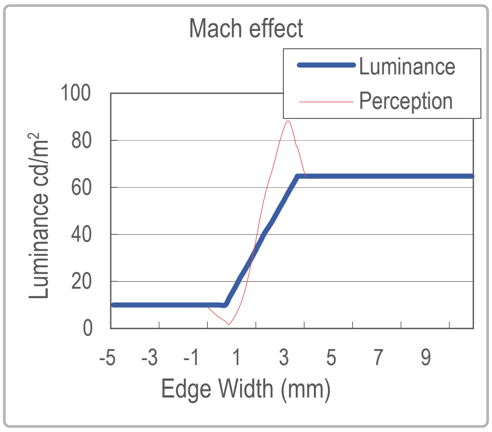
Appendix-2

Psychology affect caused by human visual systems

People do not always perceive figures exactly as their physical existence. This appendix shows some examples.

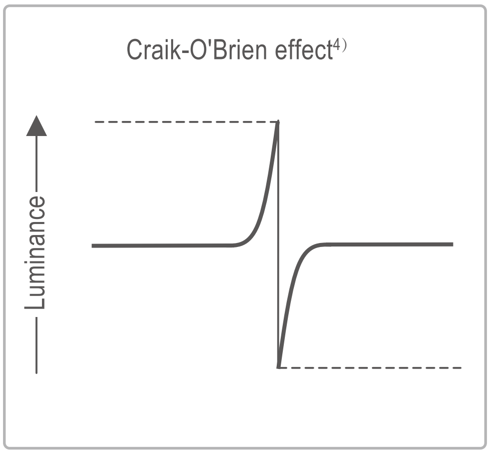
1. Mach Effect[4)]

Around a spatial boundary between step patterns of shading, the light side looks lighter and the dark side looks darker.



2. Craik-O'Brien Effect[4)]

In the figure on the right, for example, both the sides of a vertical line in the center, having exactly the same luminance, look as if they have a difference in shading, as shown by dotted lines, if there is a gradient of shading between them.



3. Spatial Frequency Characteristics of Human Eyes[5)]

When a pattern with luminance modulation is seen, the luminance differences are perceived with different sensitivities depending on the spacing of light and dark stripes. In the entire visual system, the peak threshold value is around four cycles per visual angle (the spacing of one shading cycle is about 1.3 mm if the pattern is observed from a distance of 30 cm). If the stripes are narrower or broader than this value, the sensitivity to perception of light and dark stripes declines.

The visual system's sensitivity to contrast depends on
the spatial frequency (cycle per degree)

4. Adaptation[6)]

The visibility is different between photopic and scotopic visions. Between images with high and low mean luminances, the differences of luminances in the images are perceived with different sensitivities. Refer to other papers for more information on visual characteristics, which are not the aim of this paper.

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