

# Evaluation of an organic light-emitting diode display for precise visual stimulation

**Hiroyuki Ito**

Faculty of Design,  
Research Center for Applied Perceptual Science,  
Kyushu University, Fukuoka, Japan



**Masaki Ogawa**

Graduate School of Design, Kyushu University,  
Fukuoka, Japan



**Shoji Sunaga**

Faculty of Design,  
Research Center for Applied Perceptual Science,  
Kyushu University, Fukuoka, Japan



**A new type of visual display for presentation of a visual stimulus with high quality was assessed. The characteristics of an organic light-emitting diode (OLED) display (Sony PVM-2541, 24.5 in.; Sony Corporation, Tokyo, Japan) were measured in detail from the viewpoint of its applicability to visual psychophysics. We found the new display to be superior to other display types in terms of spatial uniformity, color gamut, and contrast ratio. Changes in the intensity of luminance were sharper on the OLED display than those on a liquid crystal display. Therefore, such OLED displays could replace conventional cathode ray tube displays in vision research for high quality stimulus presentation. Benefits of using OLED displays in vision research were especially apparent in the fields of low-level vision, where precise control and description of the stimulus are needed, e.g., in mesopic or scotopic vision, color vision, and motion perception.**

to CRTs in many respects, e.g., they save space, possess flat screens, and exhibit no image deformation and little perceived flicker. However, LCDs are inferior to CRTs in certain aspects that are critical for specific types of research. For example, in general, LCDs have a slow response, motion smear, low contrast, leaking back-light in presenting black, and viewing angle dependence in color/luminance.

The rapid development of LCD techniques, however, has enabled vision researchers to use LCDs to display stimuli in experiments where fine control of the temporal properties or complete uniformity of color and luminance are not critical. Some reports state that recent LCD products are better than CRTs from the perspective of timing control of stimulus presentation (Wang & Nikolic, 2011). In some experimental paradigms, e.g., the attentional blink and metacontrast masking paradigms, where a duration change by a single display frame could affect the phenomenon, the results acquired from CRT displays and LCDs were comparable (Kihara, Kawahara, & Takeda, 2010). Lagroix, Yanko, and Spalek (2012) even showed CRT inferiority, demonstrating that “display persistence,” in which a visual stimulus is still perceived on the screen after the stimulus offset is signaled from a computer, is virtually nonexistent in LCDs. In contrast, a bright vertical or horizontal bar against a black background could be discriminated for about 3 s after the stimulus offset using a CRT for dark-adapted observers (their CRT contained P22 phosphor, which is common in computer monitors and gives a temporal property classified as “medium-short persistence”). Also, because the CRT is a raster scan display, horizontal lines

## Introduction

Computer-driven visual displays have become the workhorse for vision research. In the 20th century, this function was carried out primarily by the cathode ray tube (CRT). However, in the 21st century, new flat panel displays (mainly liquid crystal displays, or LCDs) have completely replaced CRTs in the consumer marketplace. As a result, it has become difficult to acquire high-quality CRT displays in good condition. Existing CRT units will degrade in the near future, so vision researchers must now consider replacing their CRT displays with other equipment. LCDs are superior

Citation: Ito, H., Ogawa, M., & Sunaga, S. (2013). Evaluation of an organic light-emitting diode display for precise visual stimulation. *Journal of Vision*, 13(7):6, 1–21, <http://www.journalofvision.org/content/13/7/6>, doi:10.1167/13.7.6.

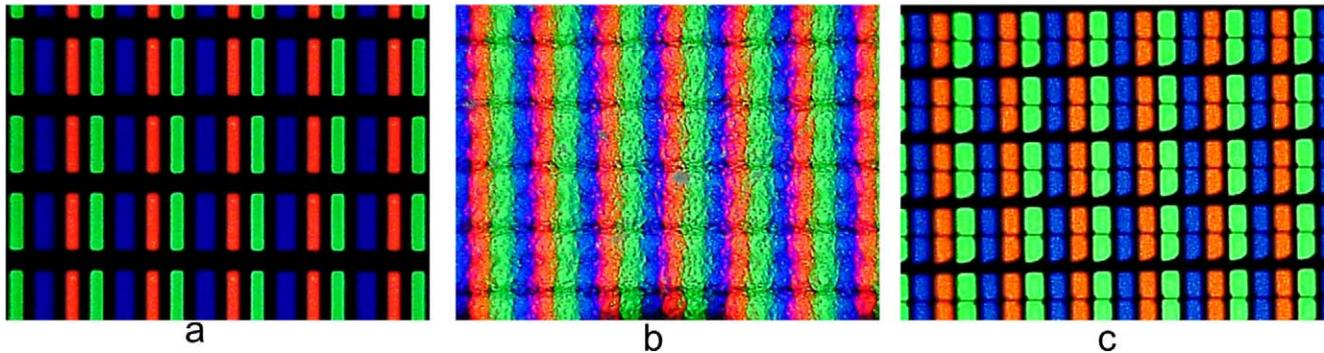


Figure 1. Magnified images of screen surfaces, taken with a digital microscope: (a) OLED; (b) “nonglare” LCD; (c) “glare” LCD.

presented on the screen are usually much brighter than vertical ones (Pelli, 1997). Wang and Nikolic (2011) showed that the luminance of stripes that were one pixel wide with a vertical orientation on a CRT (displaying  $1280 \times 1024$  pixels at a refresh rate of 120 Hz) was less than 50% of that of the same stripes with a horizontal orientation. Some studies have been performed with CRT units tilted at  $45^\circ$  to cancel out luminance artifacts caused by the orientation of the stimulus (e.g., Bach & Meigen, 1992).

Despite these problems with CRTs (Bach, Meigen, & Strasburger, 1997), some researchers still hesitate to use LCDs in their experiments because there is little evidence of the validity or reproducibility of results compared to the data accumulated from experiments using CRTs. In fact, problems persist with regard to low luminance contrast and apparent color shifts at lower luminance levels, or because of changes in observation directions (locations on the screen), even for modern LCDs. Also, although the rise/fall times of recent LCDs are quite rapid, they still have problems with presenting a single-frame stimulus and achieving independent luminance between frames. However, a new type of display has become available that can solve most of the problems noted above.

In this paper, the characteristics of an organic light-emitting diode (OLED) display are measured and compared with those of LCDs and/or CRT displays. OLED panels are sometimes used as illumination devices because they are energy-efficient and can emit light from planar surfaces. At present, OLEDs are most commonly used for small displays such as mobile phones and head-mounted displays. They are not popular for relatively large displays because of current difficulties in producing large size OLEDs and their relatively high cost. If large enough, OLED displays are considered to be ideal for vision research because they provide self-illumination, rapid rise/fall luminance level performance, and high contrast images. The Sony PVM and BVM series of monitors are the only OLED models readily available on the market at present.

Here, we test a Sony PVM-2541 OLED display with a 24.5-in. screen that consists of a  $1920 \times 1080$  pixel matrix. Figure 1a shows a magnified picture of the screen surface of the OLED display, which was taken with a digital microscope (Sanwa Supply, 400-CAM010). As we see in Figure 1a, each pixel on the OLED display consists of three subpixels emitting red, green, or blue light just like that on an LCD panel (i.e., Figure 1b; a “nonglare” LCD panel [Eizo, FlexScan S2410W] or Figure 1c; a “glare” LCD panel [Apple MacBook Pro]). Blue subpixels are wider than red and green ones. Unlike a light-emitting diode (LED) backlight used in recent LCDs, light emission from each pixel (and each subpixel) is independent. Although OLED displays are self-emitting like CRTs, the present display uses additional color filters to purify each of the three color primaries.

Krantz (2000) suggested that a computer monitor is a sampling device working in four dimensions: spatial, temporal, luminance, and chromatic. Here, we describe the characteristics of an OLED display with reference to these four dimensions and discuss the advantages (and disadvantages) of the display and its suitability as an experimental device for vision research applications in particular. This is the first comprehensive report measuring the properties of an OLED display for use as an apparatus for psychophysical experiments.

## Initial setting of the display

Images on the OLED display could be controlled by manipulating parameters through a pop-up menu appearing on the screen when the Menu button is pushed or by buttons on the front panel. The pop-up menu includes adjustment of colors, selection of color space (off, EBU, ITU-709, or SMPTE-C), selection of color temperature presets (D65 or D93), and “bias” and “gain” controls for each of the three color primaries. “Gamma” can be selected from 2.2, 2.6, or “CRT simulation.” “Aperture” and “brightness” are

also in the menu. Aperture determines the effect of the low-pass spatial filter as noted later. Through the brightness parameter, an offset to the input RGB values can be set. Brightness is also accessible by a button on the front panel. The gamma changes through brightness manipulation are described later. “Contrast” and “chroma” can be manipulated by the buttons on the front panel. Contrast is an important parameter for the display when used in an experiment, so we describe it in detail later. In the present study, we did not test the chroma parameter, which is used to control the saturation of colors and might not often be used for vision experiments. When the chroma is set to 0, all colors appear as shades of gray.

We tested the display basically in the default conditions for brightness (i.e., 0 for the onscreen menu and 50 in the front button manipulation) and contrast (i.e., 80). The color space was set to off, enabling us to access the full device gamut. The color temperature was set at 6500 K. We set gamma at 2.2. A computer (Dell XPS 8300) supplied video signals in 8-bit depth for each color primary through a digital visual interface (DVI) to high-definition multimedia interface (HDMI) cable. The HDMI setting of the display was “full,” which indicated that the display received signals in a 0–255 RGB range. It is noteworthy that many computers that have an HDMI connector output signals in a “limited” RGB range of 16–235. In that case, the HDMI setting of the display should be set at limited. When one uses an HDMI output from a computer, sometimes the display scaling may need to be adjusted using utility software of the graphic card to achieve dot-by-dot presentation. The luminance, color, and spectral distribution of the display were measured using a colorimeter (Minolta, CS-100A) or a spectral radiometer (Konica Minolta, CS2000) from a distance of 57 cm.

Before obtaining the main measurements, we tested the luminance and color stability of the display for 30 min from power-on by measuring a white square in the center of the screen once per minute on two different days. We found that the luminance and color of the white square (RGB [255, 255, 255]) in the center of the screen was constant for the 60 measurements of the CIE 1931  $xy$  chromaticity (luminance range: 193–196  $\text{cd/m}^2$ ,  $x$  range: 0.323–0.325,  $y$  range: 0.352–0.354, measured with the CS100A colorimeter). In a room at a comfortable temperature, the display could be used as a stimulus display just 3 min after power-on for almost all psychological experiments with regard to luminance and color stability. Even for fine psychophysical experiments, 15 min seems to be sufficient warm-up time, because after that no measurable change in luminance was observed using the CS-100A colorimeter. This is a great advantage over existing CRT displays, which sometimes require warming up for 45

min to eliminate luminance and color changes. As noted later, the measured values changed little after four months from the initial measurement. However, the stability of the PVM-2541 may be accomplished by strict color control because it is a professional video monitor, so such control is inherent in this model. We are not certain that this property will apply to other models of OLED displays.

## Luminance gradation

The PVM-2541 has three gamma presets, i.e., 2.2, 2.6, and “CRT simulation,” which seems to have a gamma value of approximately 2.4 and a slightly floating black level. Unfortunately, gamma 1.0 was not available, which vision researchers sometimes hope to use. For our measurements, we selected gamma 2.2. First, we measured the luminance/color of a white square ( $2^\circ \times 2^\circ$ ) positioned at the center of the screen on a black background with RGB values of (0, 0, 0); we call this the “small area condition.” We changed the luminance of this white square from the RGB values of (0, 0, 0) to (255, 255, 255), red from the RGB values of (0, 0, 0) to (255, 0, 0), green from (0, 0, 0) to (0, 255, 0) and blue from (0, 0, 0) to (0, 0, 255).

Figure 2a shows the results obtained for the small area condition. The curves are generally smooth and the measured luminance exhibits a monotonic increase for each color throughout the RGB values of 0–255. The measured luminance ( $M$ ) at an RGB level ( $L$ ) obeys  $M = 0.0012L^{2.1839}$ . One of the most impressive properties of the OLED display is the deep black production. When the RGB values were (0, 0, 0), the measured luminance was  $0.00003725 \text{ cd/m}^2$  (measured with a spectral radiometer [CS2000]). The luminance level seems to be under the typical ambient light level of starlight (cf. figure 1 in Stockman & Sharpe, 2006) and also under the cone threshold calculated according to Haig (1941); that is,  $0.010948554$  photopic troland and  $0.000284637 \text{ cd/m}^2$  in photopic luminance, assuming a pupil diameter of 7 mm. We could not find any correlation between the spectral distributions of RGB (0, 0, 0) and each level of gray. Thus, the luminance level of RGB (0, 0, 0) measured here may be caused by stray light in the room or instrument noise. In contrast, the spectral distribution of red or green in the lowest level, i.e., RGB (1, 0, 0) or RGB (0, 1, 0), correlated with that of RGB (255, 0, 0) or RGB (0, 255, 0), respectively. As for blue, spectral distributions of RGB (0, 0, 3) and RGB (0, 0, 255) were correlated, while no correlation was found for RGB (0, 0, 1) or RGB (0, 0, 2) with RGB (0, 0, 255). These results are consistent with Figure 11, which shows that the  $xy$ -values in the

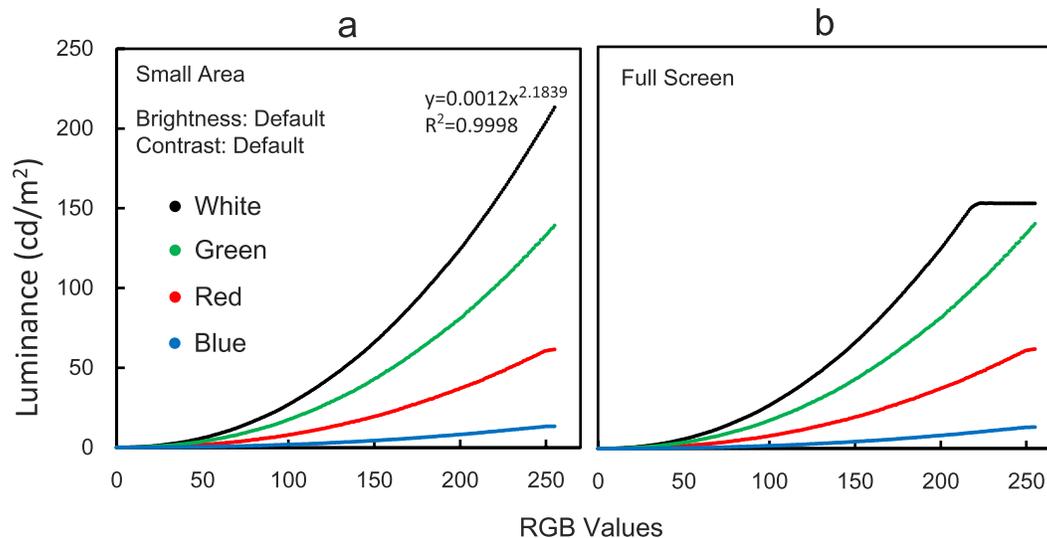


Figure 2. Gamma curves for white, green, red, and blue colors measured with a spectral radiometer (CS2000). The gamma preset was set at 2.2. (a) shows the luminance measured at a small square in the center of the screen with a black background (small area condition). (b) shows the luminance measured at the center of the full-screen color field (full-screen condition).

lowest levels of blue shift considerably from blue, whereas those of red and green are relatively stable.

We could not perceive any light, and the screen could not be detected in a totally darkened room when the full screen of RGB (0, 0, 0) was displayed. However, even in the darkest region, some luminance gradation is perceivable. Under the small area condition, when the RGB values were (1, 1, 1) for gray or (0, 1, 0) for green, all five observers detected the square on the black background. Two of the observers detected (1, 0, 0) for red. The reddish, greenish, and bluish colors of the squares for red (2, 0, 0), green (0, 2, 0), and blue (0, 0, 2) were perceived by two of the observers. The others could see all of the squares but could only perceive the reddish and greenish colors. This display produces fine gradation in a dark region and visible color differences, even if the luminance is under the colorimeter threshold, for example, 0.01 cd/m<sup>2</sup> for the CS100A colorimeter. However, when the whole screen displayed an image (denoted the “full-screen condition”) with RGB values of (1, 1, 1), some unevenness in brightness that looked like sand paper was perceived.

We next measured gamma under the full-screen condition. As shown in Figure 2b, when we presented a white field that filled the whole screen, the gamma curve was not the same as that acquired under the small area condition. When the RGB values were more than (220, 220, 220), the luminance was constant at 153 cd/m<sup>2</sup> (measured with the CS2000 spectral radiometer). For red, green, and blue, as shown in Figure 2b, no limit was observed when each color was displayed separately, even when the entire screen was filled (however, blue luminance is saturated at 13.3 cd/m<sup>2</sup> when the B value is over 250). The same kind of luminance behavior is

observed for CRT displays because of their beam-current limitations. We actually acquired a similar result from a CRT (Mitsubishi RDF193H) when the contrast parameter was high. This difference in luminance limitations between the small area and full screen conditions does not exist in an LCD because the luminance of the back light is constant, and each pixel is independently controlled. We measured the luminance at various RGB values on the PVM-2541 while changing the area of the white rectangle (target) relative to the screen size. As shown in Figure 3a, when the RGB values in the target area were (216, 216, 216), the luminance was identical irrespective of the proportion of the target. However, when the target RGB values exceeded (220, 220, 220) and the area of the target was greater than 40% of the screen, the luminance reduced systematically as if the display was limiting the brightness of the entire screen. This characteristic may stem from the strict luminance control inherent in this model (PVM-2541), and may not be typical of other OLED displays. Conversely, when the proportion of the target was below 40%, the full luminance range was available.

The luminance of a visual stimulus should be constant if there is no change in the software parameters, even when the luminance of other parts of the screen changes. We then measured how the luminance of a small square at the center of the screen (target) was affected by the luminance of the surrounding area. Luminance values of the target area for five levels of RGB values were measured while changing the surrounding (background) luminance. As shown in Figure 3b, when the RGB values of the surrounding area were more than (220, 220, 220), the

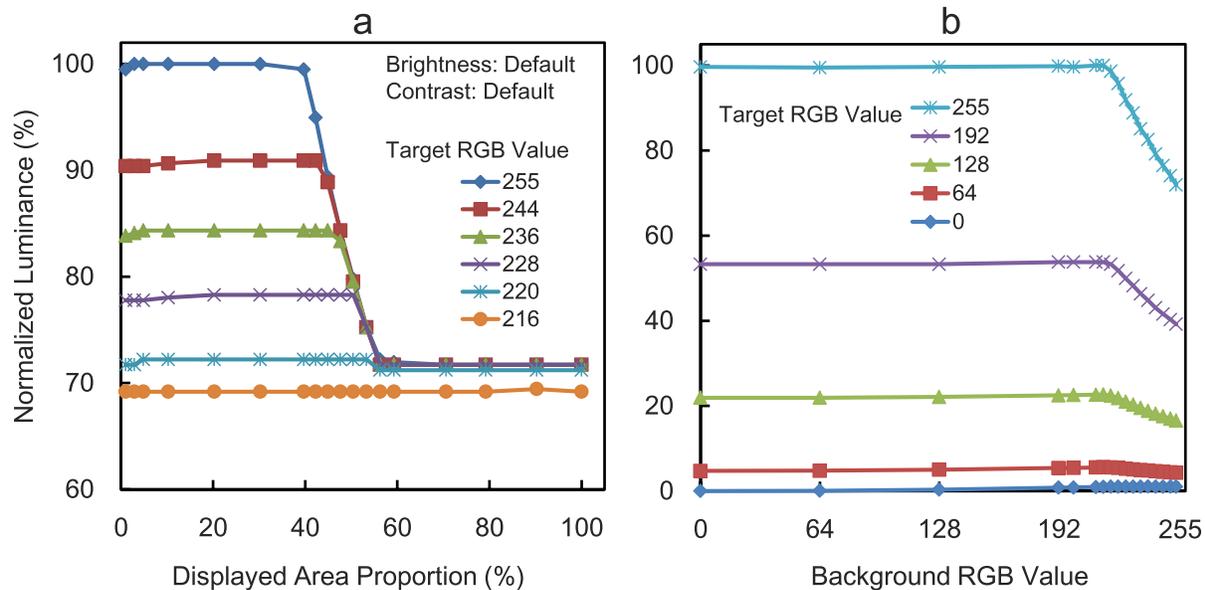


Figure 3. Normalized luminance changes relative to area proportion and the luminance of the surrounding area measured with a CS100A colorimeter. The luminance of a rectangle (i.e., target) was measured while changing its proportion relative to the area of the full screen (a), and while changing the luminance in the surrounding field and keeping the target area fixed (b).

luminance of the target area in each RGB value gradually decreased to approximately 73% of each initial luminance. Even when the RGB values in the target area were (40, 40, 40), the target luminance was affected. Thus, exceeding the RGB values of (220, 220, 220) over a wide area results in a decrease in the luminance of the whole image, while maintaining the image contrast.

We tried to adjust the display to maintain constant image luminance irrespective of the displayed image size and the RGB levels in the surround by manipulating brightness and contrast settings. As noted above, brightness is accessible from a button on the front panel or menu screen. Brightness ranges from 0 to 100 with a minimum step of 1, and the default value is 50 when manipulated using the front panel button. In the pop-up screen menu appearing when the menu button is pushed, it ranges from  $-10$  to 10 with a minimum step of 1 and a default value of 0. In this paper, we manipulated the brightness in the pop-up menu and kept the front panel brightness at 50. The 11 curves in Figure 4 represent the luminance under each brightness setting in the pop-up menu. As shown in Figure 4a, when the brightness is positive, the maximum luminance increases for an image with a small area. The curves simply move left (or right) in the graph when the brightness parameter increases (or decreases). Increasing by 1 in brightness corresponds approximately to a shift of 3 in RGB values.

For the full-screen condition, the upper luminance limit (i.e.,  $153 \text{ cd/m}^2$  [CS2000]) remains irrespective of changes in “brightness” (see Figure 4b). However, when the brightness is  $-10$ , the difference in luminance

between the small-area and full-screen conditions is relatively small. Below RGB values of (240, 240, 240), the luminance values are nearly the same for both conditions. In contrast, under a brightness of  $-10$ , RGB values of (32, 32, 32) produce dark gray under  $0.01 \text{ cd/m}^2$ , i.e., very low RGB values (e.g., under [30, 30, 30]) may not produce enough practical luminance gradation for standard psychological experiments.

In short, when the brightness parameter of the PVM-2541 is positive, the upper limit of luminance is extended if the image is small. However, at the same time, the black level also increases. Also, the difference in luminance between the small area and full-screen conditions increases. In contrast, when the “brightness” parameter is negative, the difference in luminance between the small-area and full-screen conditions decreases. However, low RGB values lose gradation in luminance for practical use. Thus, the number of steps in luminance actually available does not increase for the full-screen image under a negative brightness setting.

Figure 5 shows the results of adjusting luminance by changing the contrast, which is accessible with a button on the front panel of the display. The contrast can be set within a range of 0–100 and the default value is 80. Changing the contrast value compresses/decompresses the gamma curves in the vertical (luminance) dimension, whereas changing the brightness shifts the curve in the horizontal dimension. It is noteworthy that the contrast parameter does not really change the contrast of an image but instead changes the mid-gray because the parameter amplifies the signal about the black point. This is quite different from the traditional

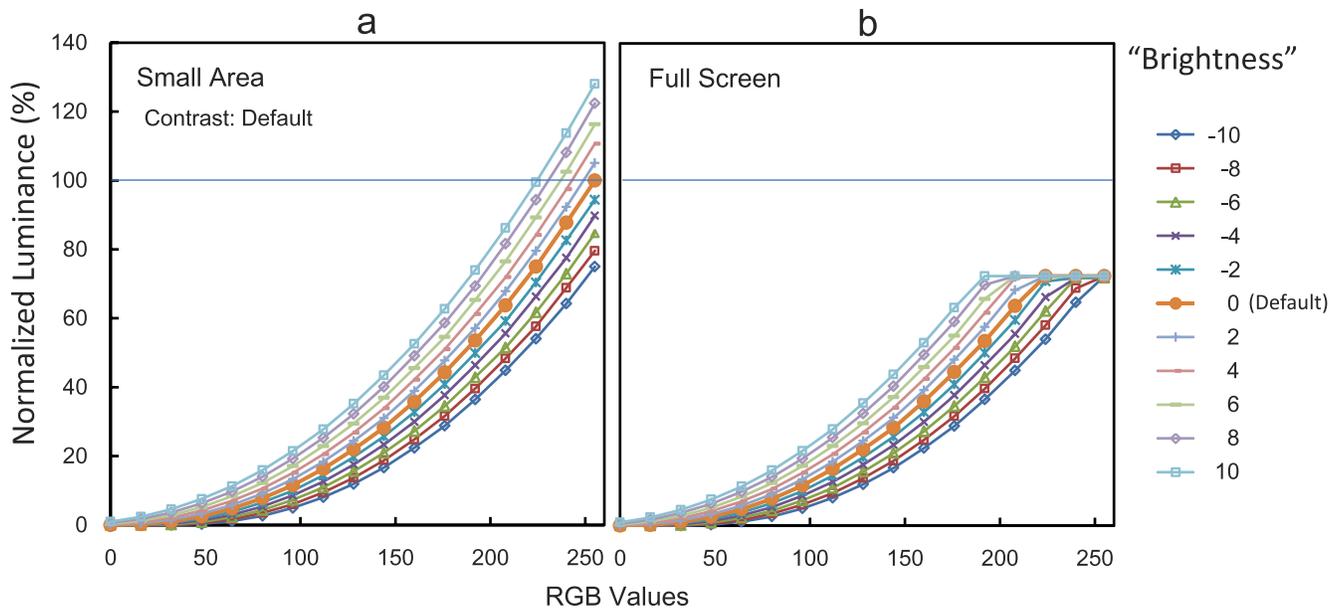


Figure 4. Changes in luminance using brightness settings. 100% indicates luminance in the small area condition with a brightness of 0 (default). (a) shows the results for the small-area condition, and (b) shows the results for the full-screen condition. The luminance was measured with a CS100A colorimeter.

concept of a contrast parameter, which amplifies the signal about the mid-gray without changing the mid-gray level.

As in the case of brightness, for the full-screen condition, an upper luminance limit (i.e., 153 cd/m<sup>2</sup> [CS2000]) remains irrespective of the contrast. However, when the contrast value is under 70, the curves in both panels look similar. Figure 6 shows the gamma curves

under a contrast value of 67 measured with the CS2000 spectral radiometer. There is no difference in luminance between the small-area and full-screen conditions, so setting the contrast at 67 may be suitable for research except that luminance of red and blue saturated at an RGB value of around 253. The maximum luminance under a contrast of 67 is 147 cd/m<sup>2</sup> (CS2000), which is comparable to that of a typical CRT display.

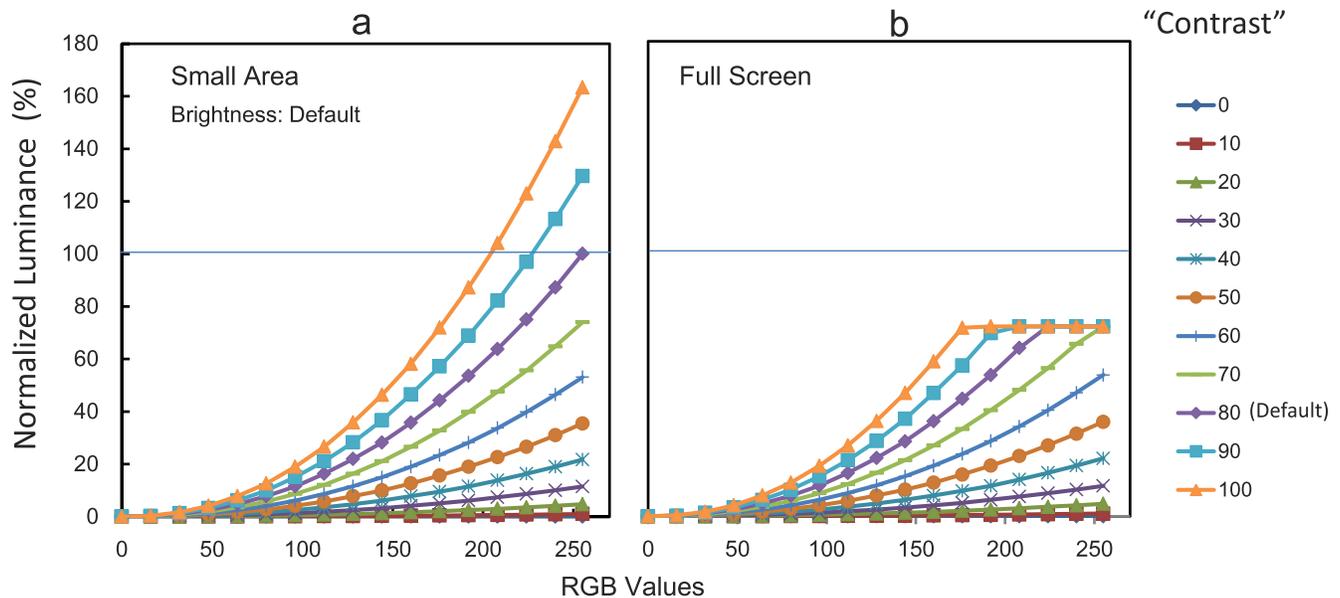


Figure 5. Changes in luminance using contrast settings. 100% indicates luminance in the small area condition with a contrast of 80 (default). (a) shows the results for the small-area condition, and (b) shows the results for the full-screen condition. The luminance was measured with a CS100A colorimeter.

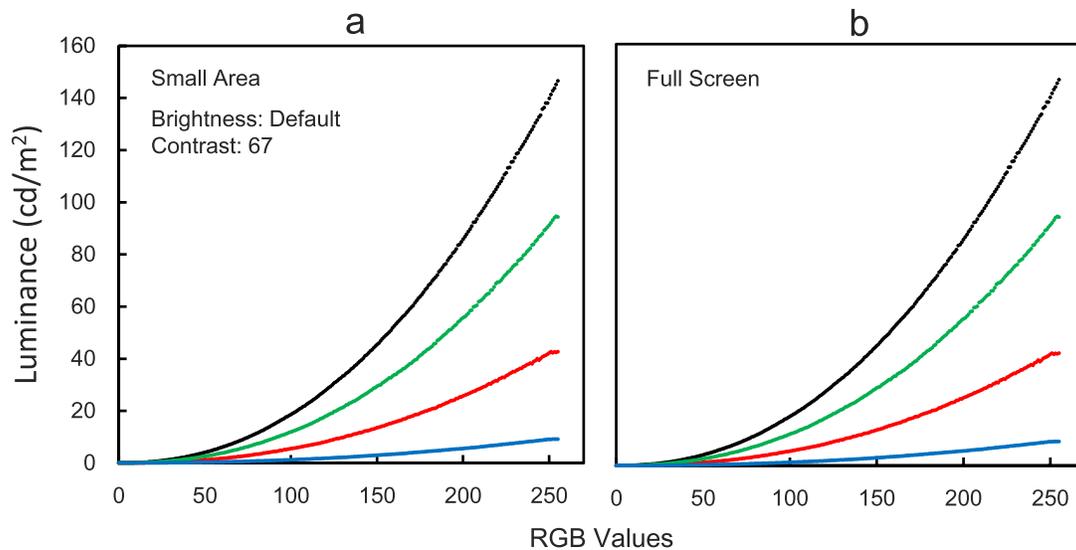


Figure 6. Gamma curves for white, green, red, and blue colors with a contrast of 67 measured with a CS2000 spectral radiometer. (a) and (b) show the luminance values measured under the small-area and full-screen condition, respectively.

We think that this OLED display may be especially suited to experiments using a dark stimulus, e.g., scotopic or mesopic vision experiments, which may be difficult using an LCD without optical filters. We used a contrast of 20, where the maximum luminance is

suppressed to around 10  $\text{cd/m}^2$  (CS2000). Figure 7 shows the luminance gradation in the very dark region on the display. It is clear that luminance gradation is found even under  $0.01 \text{ cd/m}^2$ . This is an obvious advantage of the OLED display over LCDs and even

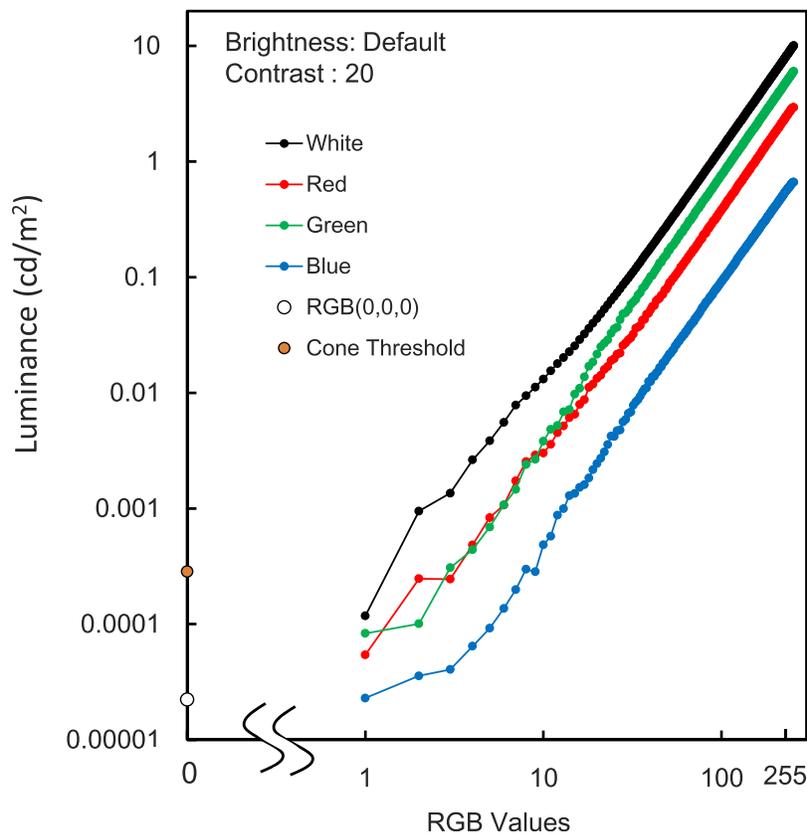


Figure 7. Luminance gradation in a very dark region when the contrast was set at 20. The luminance was measured with a CS2000 spectral radiometer. The cone threshold was calculated according to Haig (1941) assuming a pupil diameter of 7 mm.

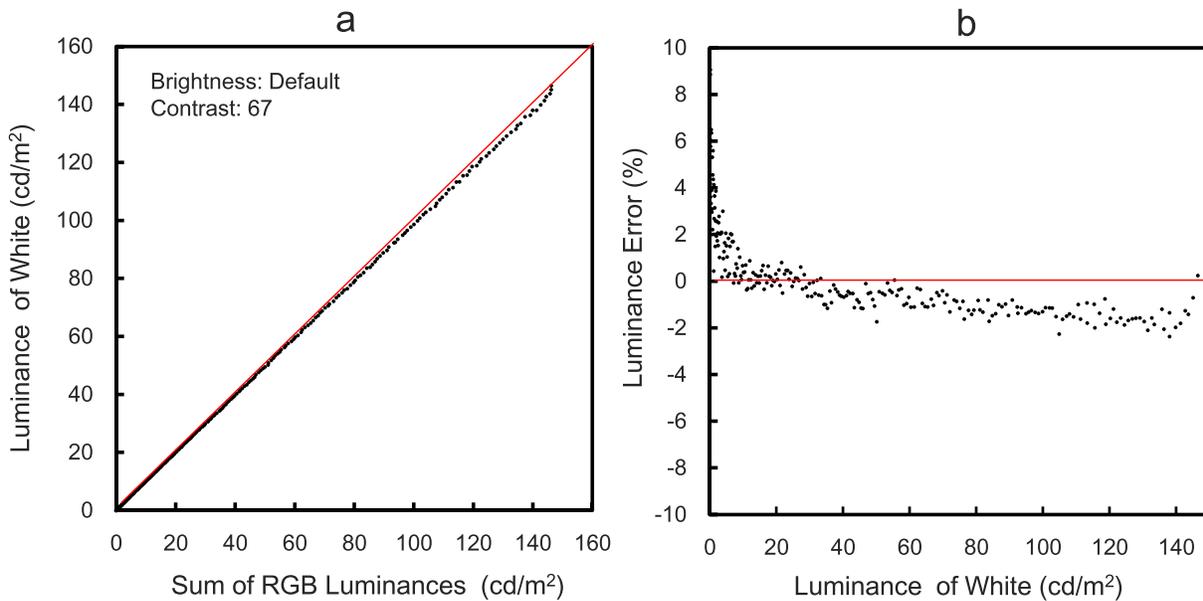


Figure 8. Additivity of luminance values of the RGB primaries. Luminance was measured with a CS2000 spectral radiometer. In (a), the horizontal axis indicates the sum of the luminance values of the red, green, and blue primaries when each primary was luminous. The vertical axis indicates the luminance of the achromatic colors when the RGB primaries were luminous simultaneously. The red line with a slope of 1 indicates that the additivity of luminance values of the RGB primaries was retained. In (b), the vertical axis indicates the luminance error calculated as  $([\text{luminance of white} - \text{sum of RGB luminances}] / \text{luminance of white}) \times 100$ .

CRT displays. The PVM-2541 exhibited excellent luminance gradation in a low luminance region, thus an experiment with a dark stimulus should be correctly executable.

With default settings in brightness and contrast, one should be careful of unexpected changes in luminance in the high luminance region. When the display area is less than 40% of the whole screen, when the RGB values are under (220, 220, 220), or when the contrast value is below 67, the luminance artifact may be avoidable. In addition, we observed that the first frame of full-screen white after a dark scene passed the luminance limitation. In other words, the luminance limitation became effective from the next frame following the trigger frame. When it is possible to sacrifice the maximum luminance, we recommend that the contrast be set below 67.

## Additivity of RGB luminance values

One of the most important characteristics of displays used for vision research is the additivity of RGB luminance values. Any color can be displayed by a combination of RGB values. Because it is not practical to measure all displayable colors, we generally calculate the chromaticity and luminance of any RGB values from the gamma curves and the chromaticity values of the RGB primaries. The additivity of the luminance values and the stability of the chromaticity values of the

RGB primaries are required for this calculation. In this section, we investigated the additivity of RGB luminance values of the OLED display.

To examine the additivity of RGB luminance values, we compared the gamma curve produced from the sum of the RGB luminance values with that of the achromatic color displayed when the RGB values were the same. We used the gamma curves observed when the display area was  $2^\circ \times 2^\circ$ .

The gamma curves are compared in Figure 8a. The points should form a line with a slope of 1, which indicates the additivity of RGB luminance values. All of the measured points are plotted around the slope of this line.

As shown in Figure 8b, the deviations from the line were within a range from  $-2.37\%$  to  $+2.57\%$  when the white luminance value was above  $2.0 \text{ cd/m}^2$ . These errors are very low and comparable to those of CRT displays currently used in vision research. We can therefore conclude that the PVM-2541 shows additivity of RGB luminance values, and that there is little interference among the RGB primaries in this display.

## Color space and spectral distribution

The tested OLED has four different color space settings: off, EBU, ITU-709, and SMPTE-C. The off

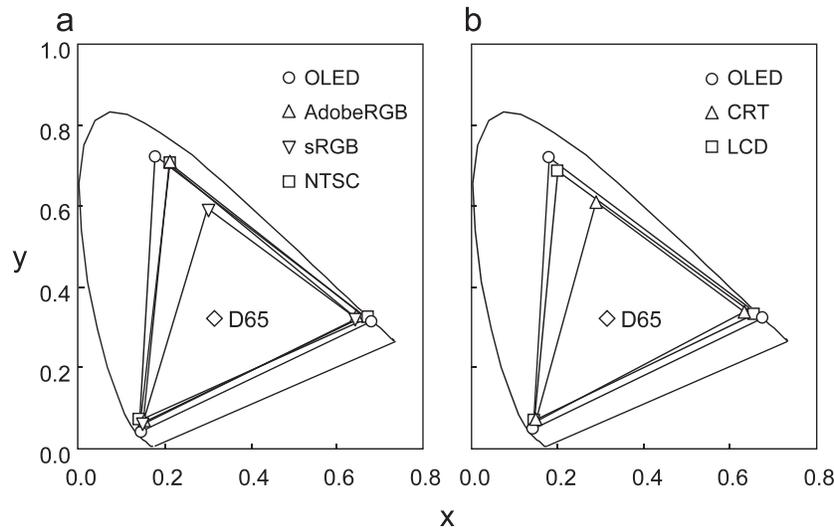


Figure 9. (a) CIE 1931  $xy$  chromaticity coordinates of the RGB primaries of the OLED display measured with a CS2000 spectral radiometer and the standard primary colors defined in the AdobeRGB, sRGB, and NTSC color systems. (b) Comparison of CIE 1931  $xy$  chromaticity coordinates of the RGB primaries of the OLED display, a CRT display (Mitsubishi, RDF193H), and an LCD (Eizo, ColorEdgeCG241W).

setting indicates the native color space of this display. We measured the spectral distributions and CIE 1931  $xy$  chromaticity values of the RGB primaries when the RGB values were set at (255, 0, 0), (0, 255, 0), and (0, 0, 255) in the off setting. A color square ( $4^\circ \times 4^\circ$ ) with an area less than 40% of the whole screen was positioned at the center of the screen on a black background. In these measurements, we used another computer (a Dell Inspiron 410) to present the color square on the display and a spectral radiometer (CS2000) to measure the spectral distributions of the RGB primaries.

Figure 9 shows the chromaticity coordinates of the RGB primaries of this display on the CIE 1931  $xy$  diagram. The primary colors in the Adobe RGB, sRGB, and NTSC systems are also shown in Figure 9a for comparison. The color gamut of this display almost entirely covers the other three color gamuts. In addition, we compared the chromaticity coordinates of the RGB primaries of the OLED display (PVM-2541) with those of a CRT display (Mitsubishi, RDF193H) and an LCD (Eizo, ColorEdgeCG241W, with a cold cathode fluorescent lamp [CCFL] backlight; Figure 9b). The purity of the green primary of this display was particularly high. The possibility to display stimuli that show saturated green or high chromatic contrast is an advantage of the OLED display, because it cannot be achieved using a conventional CRT.

The CIE 1931  $xy$  chromaticity values of the RGB primaries for the other three types of color space settings, EBU, ITU-709, and SMPTE-C, for this display were close to those of a conventional display, such as a CRT (data not shown). In the case where an image of a natural scene taken by a conventional digital camera is presented as a stimulus, the display should be

set at one of these three types of color space because digital cameras are typically designed to provide good color reproduction on conventional displays.

Figure 10 shows the spectral distributions of the RGB primaries of the OLED display, a CRT display, and an LCD. The spectral distribution of the PVM-2541 seems to be quite artificially determined. The peak wavelengths and half-band widths of the RGB primaries for each of these displays are listed in Table 1. The half-band widths of the green and blue primaries of the OLED display were narrower than those of the CRT and nearly equal to those of the LCD. However, the half-band width of the red primary of the OLED was broader than those of both the CRT display and LCD, in which the red primary is composed of a set of narrow bands. A primary with a narrow bandwidth yields a difference in color appearance based on the individual differences of the color matching functions (Ramanath, 2009). Therefore, an individual difference in color appearance for bluish or greenish colors will become larger in the PVM-2541 than in a CRT, but the difference for reddish colors will be smaller in the PVM-2541 than in a CRT or LCD. In general, vision researchers would be likely to prefer the OLED display because it does not have a primary consisting of extremely narrow bands like the red primary in the CRT and LCD.

As noted above, each of the color primaries exhibited a monotonic increase in luminance as the RGB values increased from 0 to 255. We also tested the stability of colors through the whole luminance range using a CS2000 spectral radiometer. The results show that the  $xy$ -values of white and the RGB primaries remain constant, including in the very dark luminance

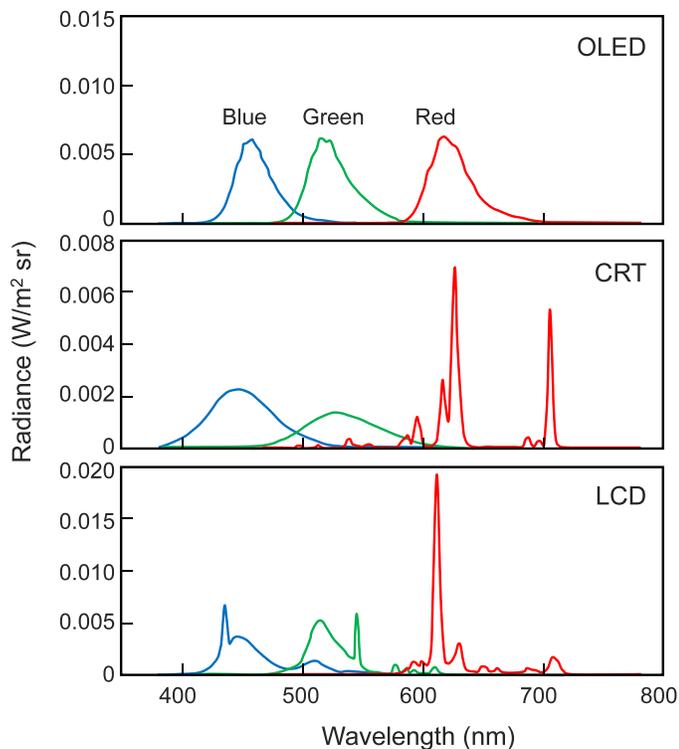


Figure 10. Spectral distributions of the RGB primaries of the OLED display (Sony PVM-2541), a CRT display (Mitsubishi RDF193H), and an LCD (Eizo ColorEdge CG241W) measured with a CS2000 spectral radiometer.

region (Figure 11). For white, when the luminance exceeded  $0.2 \text{ cd/m}^2$ ,  $x$  was  $0.310\text{--}0.320$  and  $y$  was  $0.325\text{--}0.327$ . When the luminance was over  $0.005 \text{ cd/m}^2$ ,  $xy$ -values remained virtually constant for red ( $x$ :  $0.674\text{--}0.676$ ,  $y$ :  $0.324\text{--}0.325$ ). Similarly, when the luminance was over  $0.11 \text{ cd/m}^2$ ,  $xy$ -values for green ( $x$ :  $0.185\text{--}0.190$ ,  $y$ :  $0.720\text{--}0.725$ ), and blue ( $x$ :  $0.141\text{--}0.142$ ,  $y$ :  $0.049\text{--}0.052$ ) remained nearly constant. The  $xy$ -values for green and blue were not as stable as those for red in the lowest luminance region. However, the gradation and color purity shown by this display under low luminance are great advantages compared to most LCDs and even to CRTs. CRT displays and LCDs do not produce complete black. This means that all colors, including the primaries, lose saturation in a dark region. If the luminance of the floating black is  $0.5 \text{ cd/m}^2$  on a CRT or LCD, the  $xy$ -values of the primaries gradually converge to those of the bright black when the luminance decreases and approaches  $0.5 \text{ cd/m}^2$ . This is not the case for the PVM-2541.

A PVM-2541 can handle 10-bit colors (so called “deep color”). Because of a technical problem, we did not test 10-bit colors controlled through an HDMI (note that this display does not have an analog RGB input). The expanded color depth will contribute to increasing steps in luminance changes and controlling colors in more detail than for conventional 8-bit colors.

	OLED	CRT	LCD	
Blue				
Peak	458	447	—	448
Half-bandwidth	31	61	—	36
Green				
Peak	515	528.5	—	515
Half-bandwidth	36	74	—	29
Red				
Peak	617	626	706 <sup>†</sup>	611
Half-bandwidth	36	6	5.5	5.5

Table 1. Peak wavelengths and half-band widths of the spectral distributions of the RGB primaries of an OLED display (Sony PVM-2541), a CRT display (Mitsubishi RDF193H), and an LCD (Eizo ColorEdge CG241W). Notes: <sup>†</sup>Second peak; <sup>‡</sup>Narrow peak in the broad main distribution.

Measurements using 10-bit colors should be conducted in the future.

## Luminance/color uniformity

The luminance of a CRT display is usually high in the center but lower on the periphery of the screen (Bohnsack, Diller, Yeh, Jenness, & Troy 1997; Metha, Vingrys & Badcock, 1993; Wang & Nikolic, 2011). LCDs do not always show this property, but will sometimes exhibit a gradual change in luminance depending on the position measured on the screen. If the backlight is an edge-type light, the edges of the screen tend to be brighter than its center. When an LCD screen is large and/or the viewing distance is short, the viewing direction, i.e., the angle between the visual axis and plane of the screen, can change greatly depending on the location of a stimulus on the screen, which sometimes results in a luminance and/or color shift.

OLED displays are self-illuminating, so we may expect constant luminance/color of a target area irrespective of the viewing direction and uniformity in luminance/color across the entire screen. We first measured the variation in luminance caused by changes in viewing direction when the center of the screen was the target area. We define here the viewing angle deviation as the difference between the measuring direction and the right angle to the screen, as shown in Figure 12a. Figure 13a shows the results, which indicate that as the viewing angle deviation moves from zero (i.e., at right angles to the screen), the luminance of a white, red, green, or blue target decreased monotonically. The rate of decrease of blue luminance was higher than that of other colors. When viewing the screen from  $80^\circ$  in the right or left direction (almost parallel to the screen), white on the screen was seen as

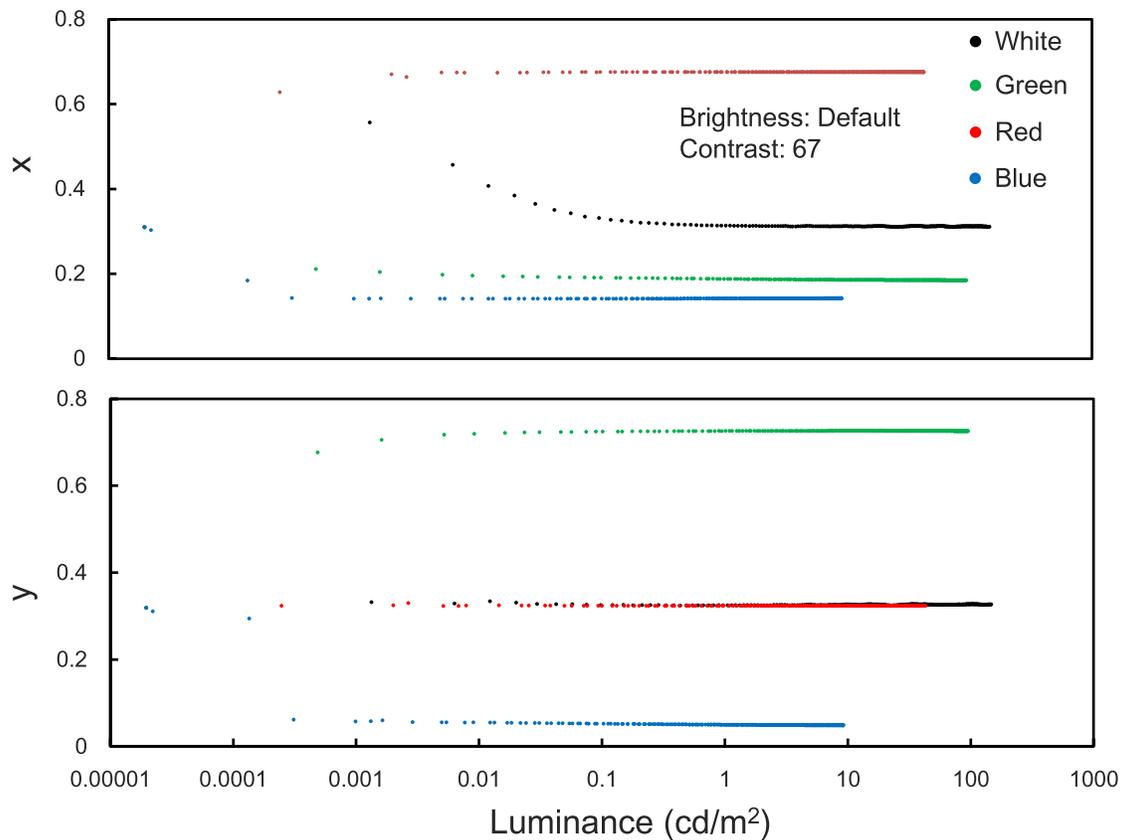


Figure 11. Distributions of  $xy$ -values as functions of luminance. Values were measured with a CS2000 spectral radiometer under default brightness and a contrast of 67.

bright cyan. We performed the same experiment using another PVM-2541 and found that the color shift is inherent in this model. Sony has announced that the successive model (PVM-2541A) will halve this color shift. However, when a very large field-of-view is required, projection onto a curved screen is likely to be a better solution than short viewing distances to a flat screen.

We next tested the uniformity of colors by measuring the luminance at various screen locations while presenting white, red, green or blue signals under the full screen condition. The screen was divided into a  $9 (v) \times 16 (h)$  matrix of squares. The luminance in the center of each of the 144 local square areas was measured. Figure 12b and c shows schematic illustrations of the two measurement methods used in this

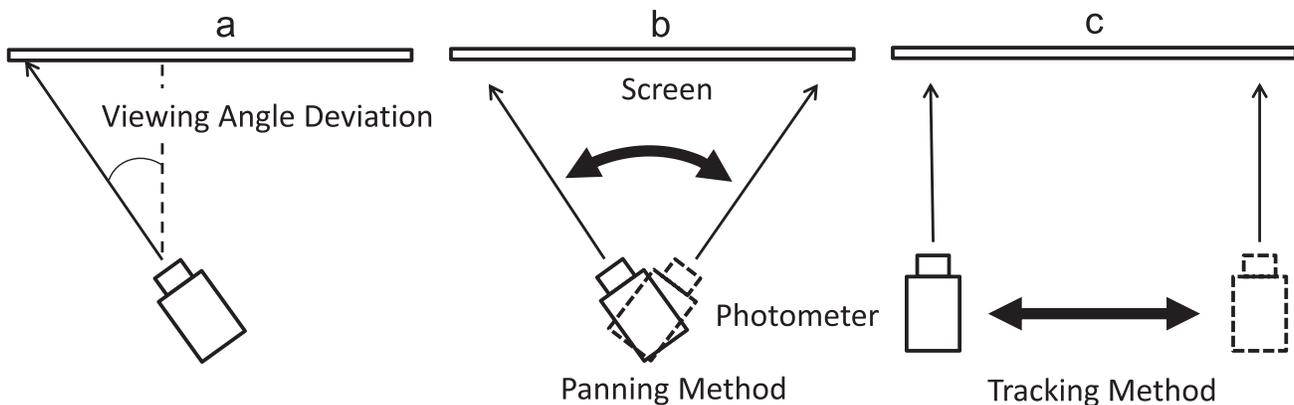


Figure 12. Measurement strategies. (a) shows the definition of the viewing angle deviation. (b) shows the panning method. The viewing angle deviation changes depending on the two-dimensional locations on the screen with the panning method. (c) shows the tracking method, which maintains a viewing angle deviation of  $0^\circ$ .

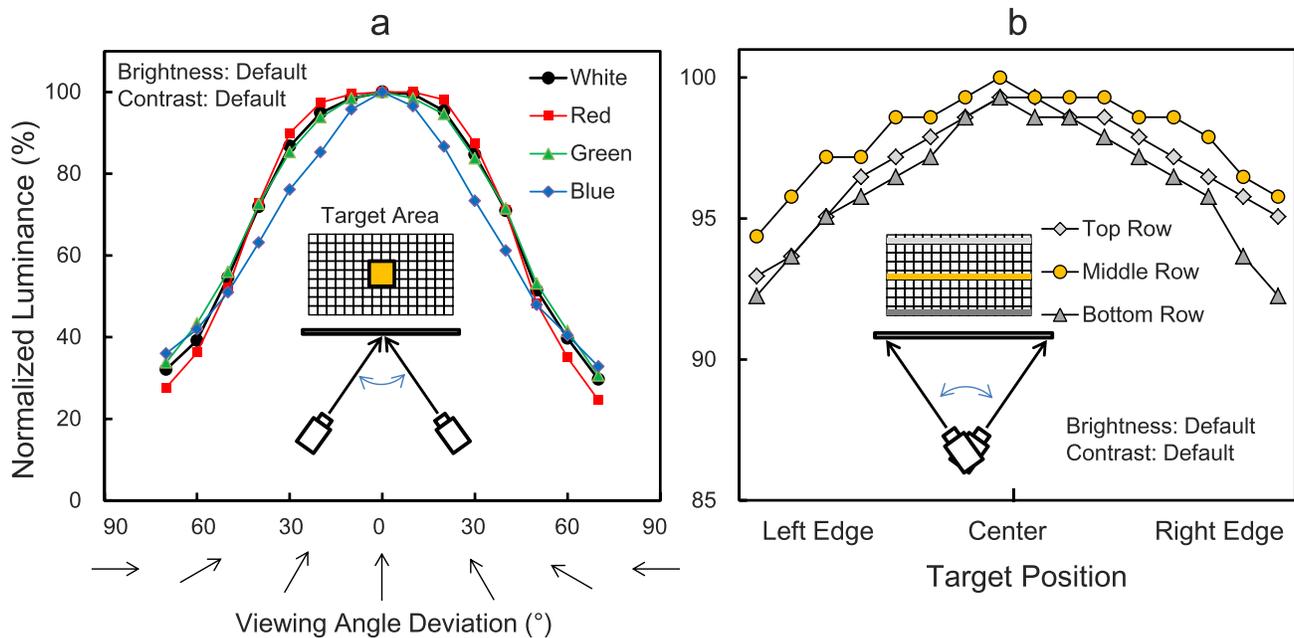


Figure 13. Luminance distribution measured by a CS100A colorimeter. (a) shows the normalized luminance of a square in the center of the screen changing with viewing angle deviation. 100% corresponds to the luminance measured at a viewing angle deviation of 0. The curves in (b) show the white luminance as a function of horizontal screen position measured with the panning method. The three curves represent the luminance values measured along the top, middle and bottom horizontal rows of the matrix. 100% corresponds to the luminance measured at the center of the middle row.

experiment. We first used the panning method (Figure 12b), where the colorimeter was fixed in front of the center of the screen. The luminance/color of each area was measured by rotating the colorimeter on a tripod without changing its position. This simulates the situation where the head of a subject is fixed by a chinrest in a psychophysical experiment. The viewing angle deviation depended on the measured screen locations and was equivalent to the eccentricity in a subject's visual field when they are fixating on the center of the screen. When a measured target was at the center of the screen, the viewing angle deviation was 0°, meaning that the angle between the visual axis and plane of the screen was 90°. The RGB values set on the computer were (255, 255, 255) for white, (255, 0, 0) for red, (0, 255, 0) for green, and (0, 0, 255) for blue.

Figure 13b shows the luminance values in white measured at the top, middle, and bottom rows of the matrix noted above. This clearly shows that with the panning method, the luminance is highest at the center of the screen and gradually decreases as the distance from the center increases. Luminance values at the edge of the screen were, at most, 8% darker than the luminance at its center. The percentages of the luminances at the 144 screen locations noted above relative to that at the screen center as a function of viewing angle deviation, i.e., the eccentricity for an eye, are plotted in the top-left panel in Figure 14. We treated the viewing angle deviation as an absolute

value. The luminance gradually decreased when the viewing angle deviation exceeded 10°. This means that when a subject is fixated on the center of a screen, the luminance of visual objects may decrease accordingly as the eccentricity increases beyond 10°. Similar trends were observed for red, green, and blue. However, the rate at which luminance decreases is highest for blue, as shown in the top-right panel in Figure 14. Blue luminance at the edge of the screen decreased at most to 80% of that of the center of the screen.

We also tested the color uniformity, measuring the color shifts of white, red, green, and blue at each of the 144 screen locations with the panning method. The CIE 1931  $xy$  chromaticity values of white and the RGB primaries were not uniform across the screen. For white, as shown in the left panels of Figure 14, the color shift depends on the measuring angle, as was found in the luminance measurements. At larger viewing angle deviation,  $x$ -values decrease and  $y$ -values increase. This means that white shifts toward cyan when the viewing angle deviation is large, as observed above. We found that the shift was very small within a visual field of 15° eccentricity when fixating on the center of the screen, and a slight color shift exists for eccentricity over 15°. If the viewing distance is sufficient or if mainly the central area of the screen is used, the color shift may be negligible. However, it should be noted that  $xy$ -values in green shift linearly with increasing viewing angle deviation. When planning a fine color experiment in

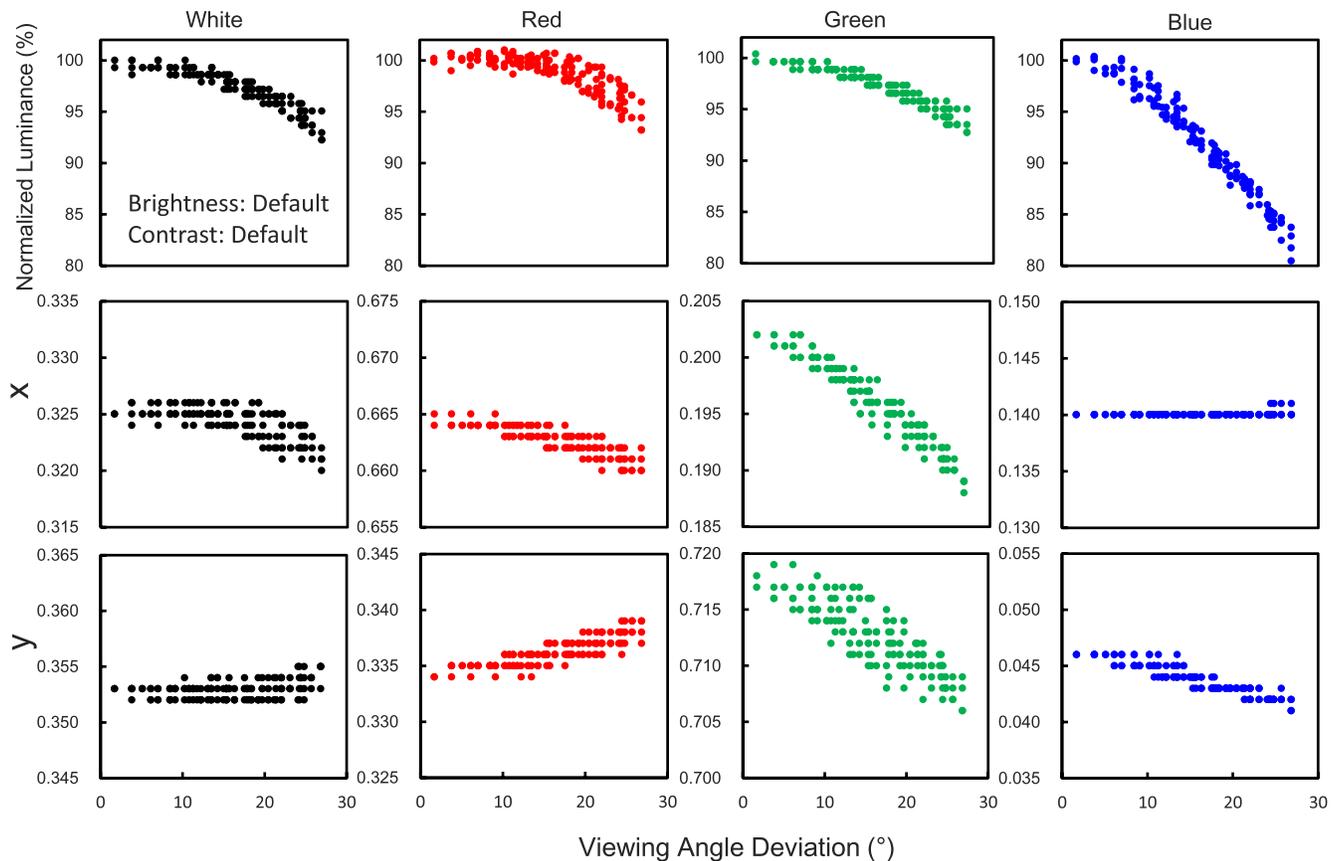


Figure 14. Luminance and color distributions as functions of viewing angle deviation determined with a CS100A colorimeter. The top panels indicate the luminance values measured at 144 screen locations and normalized relative to the luminance at the center of the matrix. The luminance at each measured location is indicated by a dot. The corresponding x- and y-values are shown in the middle and bottom rows of the panels.

peripheral vision with this model of OLED display, close attention should be paid to the green color shift.

Next, we compared the properties of the luminance distributions of the three displays determined by both panning and tracking methods, in which the colorimeter was moved while keeping the viewing angle deviation at  $0^\circ$  (Figure 12c). The top-left panel in Figure 15 shows that with the panning method, the horizontal screen position affected the measured luminance, while the vertical screen position had smaller effect (also shown in Figure 13b). However, the bottom-left panel in Figure 15 clearly demonstrates that luminance from the PVM-2541 was almost perfectly uniform when the viewing angle deviation was kept at  $0^\circ$  (tracking method). The luminance of the OLED display depended on the viewing angle deviation, but not on the location on the screen.

It is well known that the luminance on a CRT screen decreases with increasing distance from the center of the screen (Bohnsack et al., 1997; Metha et al., 1993). We measured the luminance of a 19-in. CRT display (Mitsubishi, RDF193H) from a distance of 57 cm. As shown in the center column in Figure 15, we found that

the luminance at one corner was 13% lower than that measured at the center, while at the same time, the luminance at another corner was 3% higher using the panning method. The small differences between the data from the panning and tracking methods show that the variation in luminance from the CRT screen depended on the location on the screen but was independent of viewing angle deviation. This tendency is the opposite to that found for the PVM-2541 OLED display.

The LCD monitor (Eizo ColorEdge CG241W) also shows gradation in luminance (right panels of Figure 15). The luminance of the LCD was influenced by both viewing angle deviation and the measured location on the screen. When the luminance from a corner of the screen was measured with the panning method, the decrease in luminance from that from the center of the screen was as high as 32%. It should be noted that this property largely depends on the individual LCD model, and that the performance of some LCDs may be excellent in this respect.

The low luminance loss at the periphery of the screen for the PVM-2541 display might not be indicative of

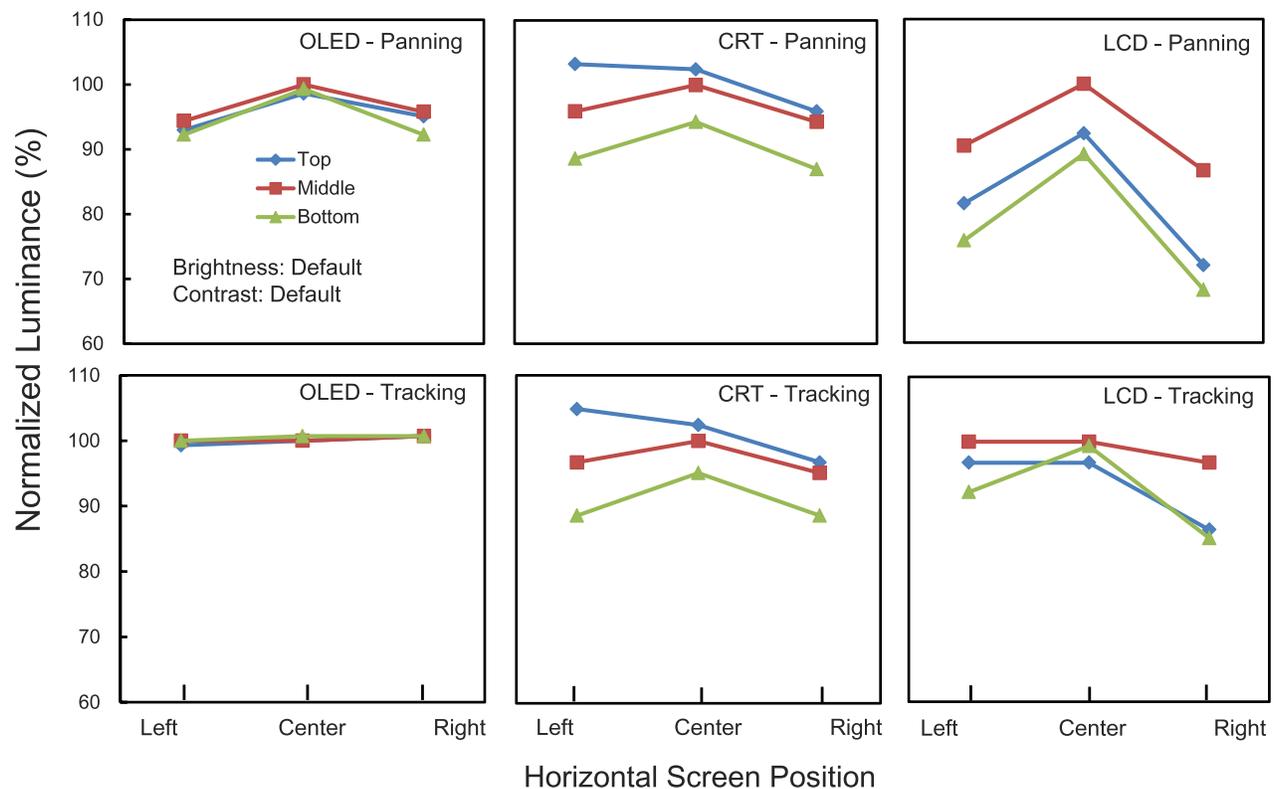


Figure 15. Comparison of luminance distributions determined with the two measuring methods. Luminances were measured with a CS100A colorimeter at nine screen locations; i.e., in combinations of three horizontal positions (left edge, center, and right edge) and three vertical positions (top edge, middle, and bottom edge). 100% indicates the luminance measured at the center of the display.

the typical performance of OLED displays. The change in luminance may depend on the model, although few other OLED models are currently available on the market to confirm this. However, the luminance loss in the PVM-2541 display of 8% loss at a corner of the 24.5-in. screen from a measuring distance of 57 cm using the panning method is much better than those measured for the CRT and LCD models tested here. However, the CRT and LCD models used for comparison also did not perform poorly in this respect. The measured properties of these models are equal to or better than those measured for CRT and LCD models in the literature (e.g., Wang & Nikolic, 2011). When taking screen size (24.5 in.) into consideration, the luminance loss in the PVM-2541 display may not be considered important for many studies. Use of a limited central area (within an eccentricity of  $10^\circ$ ) or a greater viewing distance are ways to ensure luminance uniformity, because the viewing direction relative to the screen plane (or eccentricity) determines both luminance and color, as shown in Figures 13 and 14. The excellent luminance uniformity measured with the tracking method will benefit constructing a stereoscopic display system with mirrors to present a stereo image on the screen.

## Differences between individual displays

We measured the properties of three OLED displays of the same type—one that we mainly tested (termed “main display”), another from the same lot, and a display from a newer lot. Changes in the luminance/color of the main display were tested again four months after obtaining initial measurements. We measured the luminance at nine screen positions with a CS100A colorimeter. Figure 16 (large panel) shows the results for white under the full screen condition. The luminance of the main display changed little after four months of use. The display from the same lot showed similar results. However, the display from a newer lot showed luminances that were  $10 \text{ cd/m}^2$  higher than those of the main display. As shown in the small panels in Figure 16, the luminance distributions for each color changed little in the display from a newer lot compared with those of the main display. Thus, the change in luminance observed for white may be caused by changes made by the manufacturer to setting parameters to relax the luminance limitation that appeared under high-luminance full-screen conditions noted above. Figure 17 shows the measurement results for the

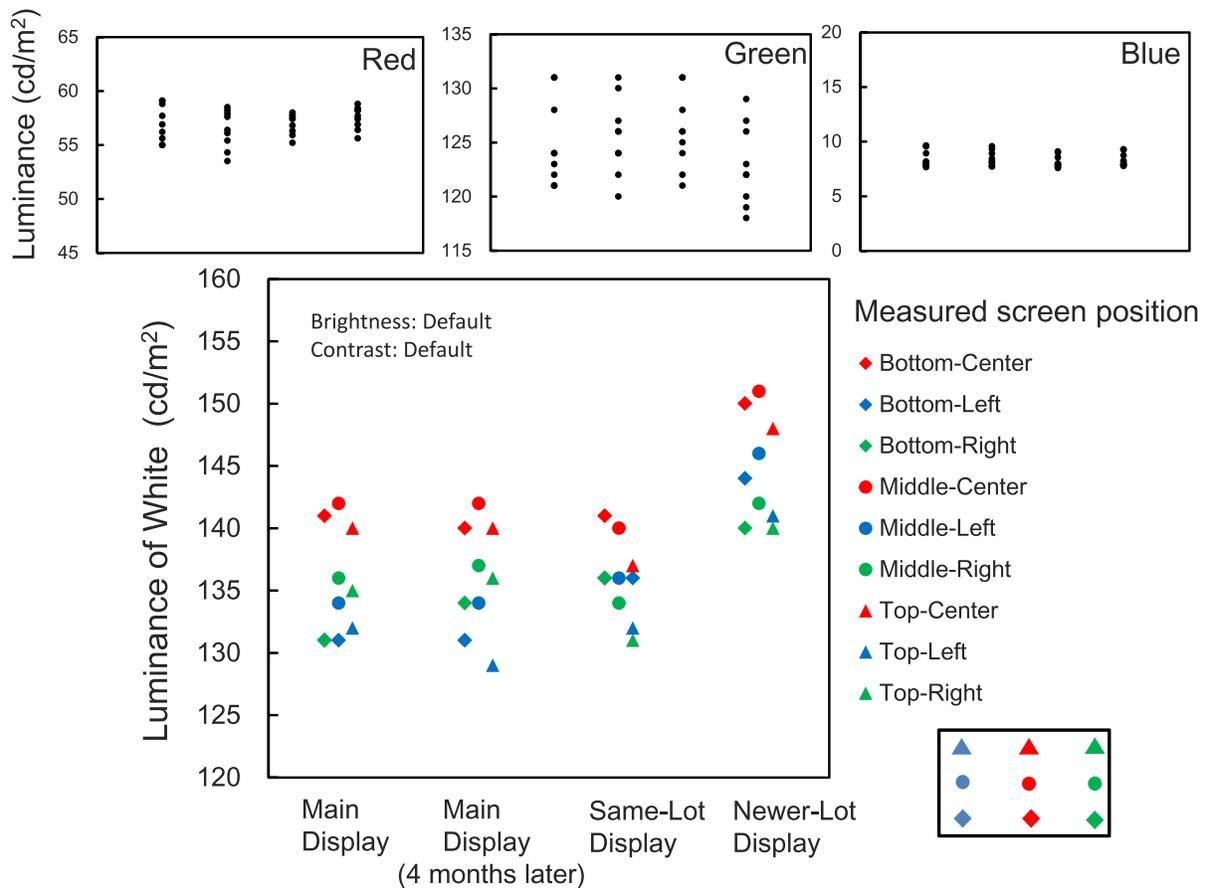


Figure 16. Luminance measured at nine screen positions by a CS100A colorimeter using the panning method under the full screen condition. The larger panel shows the luminance of white. The positions of plotted symbols are shifted horizontally to avoid occlusion. The three small panels indicate the luminance of each color. Horizontal axes are the same as in the larger panel.

colors of the three displays. Small variations in  $xy$ -values were observed among the three displays for green and white. No systematic changes were found over time, or by changing the lot or display. However, the lifetime of the OLED display is not clear at present. To determine this, changes in luminance and color should be monitored for a long period of time.

### Difference in luminance between vertical and horizontal gratings

As noted in the Introduction, CRTs generally show a difference in luminance between vertical and horizontal lines because of horizontal beam scanning, which is not seen in LCDs. One would not expect an OLED display to show a difference in luminance between vertical and horizontal lines. To confirm this, we measured the luminance of half tones: a vertical line pattern, a horizontal line pattern, and a checkered pattern, as shown in Figure 18. The line patterns were composed of alternating black and white lines of the same width.

The black and white areas were always the same. Therefore, ideally, the luminance measured in a certain area may equal half the white luminance. The line or check (square) width was varied from one to four pixels. Unexpectedly, in the default setting, the alternating black and white vertical lines with a width of one pixel were not resolved, i.e., homogeneous gray was seen on the whole screen. According to the manufacturer, this is caused by a low-pass spatial filter. The effect of this filter is controlled by the “aperture” parameter in the pop-up menu. The aperture ranges from 0 (default, strong) to 6 (weak). We measured the three half tones varying the aperture and width of the line (or square).

Figure 18 shows the results from this experiment. When the aperture was 0, the luminance of the vertical line pattern was much less than half that of solid white (Figure 18a). This is similar to a result for a CRT reported by Mulligan and Stone (1989), who tested the effect of halftoning on measured luminance by changing dot density. They found that the luminance in the 50% white dot condition was lower than half of the white luminance. They explain this phenomenon by the

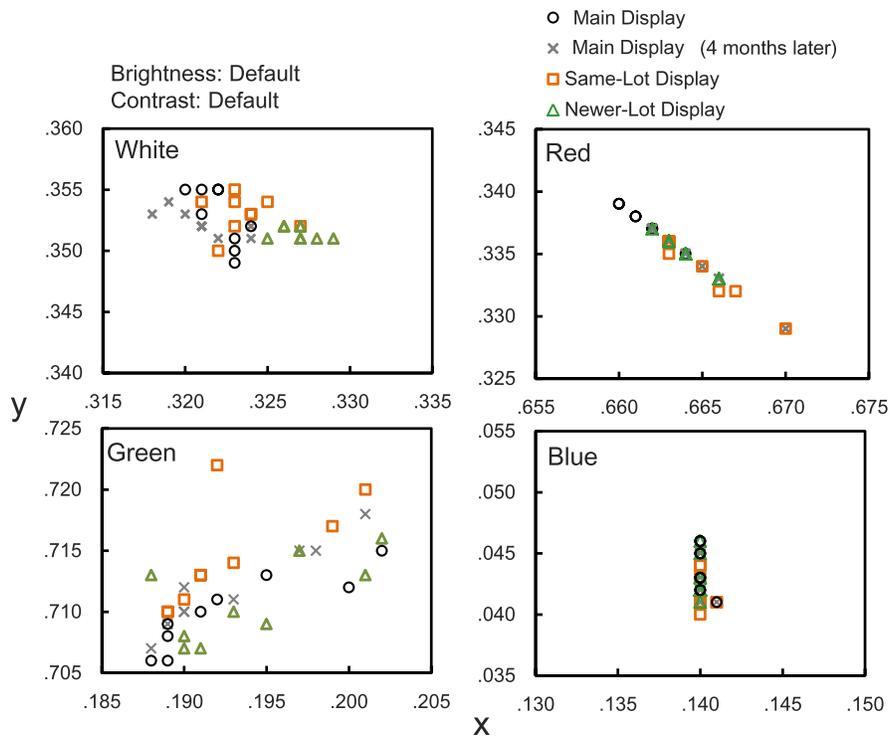


Figure 17. Variation of xy-values measured at nine screen positions by a CS100A colorimeter using the panning method under the full screen condition.

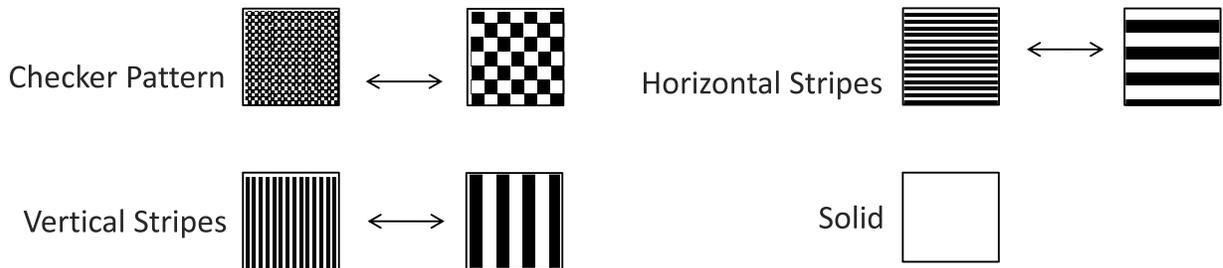
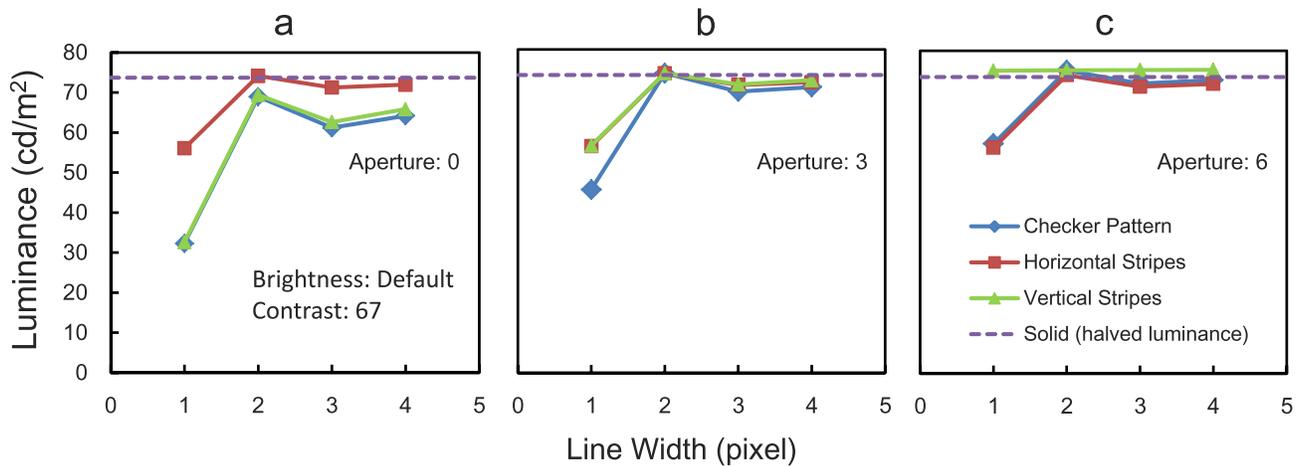


Figure 18. Changes in luminance of half-tone patterns at three aperture levels. (a), (b), or (c) shows the results with an aperture parameter of 0, 3, or 6, respectively. The luminance was measured with a CS2000 spectral radiometer.

combination of low-pass filtering of the input signal by the monitor electronics and the average-point shift by the power function of the CRT gamma. The result for the present OLED model fits this explanation because the default value of the aperture, 0, makes the effect of the low-pass spatial filter the strongest. The filtering may be purely digitally executed in this display, unlike in a CRT. Together with the gamma property of the OLED display, the low-pass filter decreased the luminance of the vertical line pattern. When the aperture level was set to 3 and the vertical line width was two pixels or more, the luminance nearly equaled half that of the white luminance (Figure 18b). When the aperture was set to 6, the luminance for the vertical line pattern almost equaled half the luminance of solid white irrespective of the line width, so no low-pass spatial filtering was found for the horizontal dimension under these conditions (Figure 18c). In contrast, for the horizontal line pattern, changes in the aperture had no effect on the measured luminance. When the line width was one pixel, the luminance of the horizontal line pattern was 75% of half of the solid white luminance irrespective of the aperture level. However, when the line width was two or more pixels, the luminance was almost half of the solid white luminance. The mild low-pass spatial filtering in the vertical dimension seems to work constantly and not to be cancelled out by manipulating the aperture. For the checkered pattern, the luminance depended on the width of the checks. When the aperture was 0, the luminance of the checkered pattern equaled that of the vertical line pattern (Figure 18a). Conversely, when the aperture was 6, the luminance equaled that of the horizontal line pattern (Figure 18c).

In short, because spatial filtering may be troublesome for fine vision experiments, we recommend setting the aperture at 6. Unfortunately, the mild filtering in the vertical dimension cannot be cancelled out. Care should be taken when lines or dots with a width of one pixel are used.

## Temporal characteristics

Elze (2010a, 2010b) and Lagroix et al. (2012) have compared the temporal characteristics of CRT displays and LCDs. In general, a pixel on a CRT monitor flashes intensely over microseconds and the light emission vanishes after a few milliseconds, whereas the light emission from an LCD monitor pixel slowly rises, is sustained, and then loosely falls. Thus, the concept of presenting the duration calculated from the sum of the frames was questioned (Elze, 2010b). However, the temporal characteristics of actual LCD monitors depend on the display model. Even rise and fall times

can be improved in some models by using a recently developed technique called “overdrive” (Lagroix et al., 2012). Also, the backlights of some LCDs may not emit constant levels of light but show their own luminance modulation patterns (Elze, 2010a).

For the OLED display tested here, the rise and fall in luminance intensity was rapid and light emission can be sustained. Figure 19 shows the time course of the light emission intensity for the PVM-2541 display. Changes in light intensity were measured using a photodiode aimed at a point on a white horizontal line with a black background. Because this monitor displays images that are refreshed at a frequency of 60 Hz, the duration of each frame is 16.7 ms. It is clear that, during a frame, both light-emitting and inserted black periods are present. Thus, sustained white signals from a computer result in a repeated 16.7-ms sequence of white followed by black (see Figure 19a). A two-frame presentation of white corresponds to a sequence of white–black–white–black. The duration of the black period seems to be constant irrespective of the white luminance level. Because of the rapid rise/fall in luminance and the black period, the luminance in one frame may not affect that in the next, which is a great advantage for OLED displays. The time course of the light intensity on the PVM-2541 display differs considerably from those of both CRT displays and modern LCDs (see Elze, 2010a).

Figure 19b shows a detailed wave form of the changing luminance intensity in the PVM-2541 display. The light emission rises quickly from the black level and reaches 50% of peak luminance intensity after 240  $\mu$ s and 88% of peak luminance intensity after 1 ms of rising (assuming that the output voltage of the photodiode is proportional to the luminance intensity). It takes the luminance approximately 2 ms to reach the 100% level (RGB level of [255, 255, 255]). When the luminance intensity decreases, it reaches 16% of the maximum level after 500  $\mu$ s, and 6% after 1 ms. Sony states that the response time of this OLED device is tens of microseconds. However, the rise of light emission of the actual OLED display is apparently slower than that of a CRT, as shown in Figure 19c, which was recorded with the same measurement system as in Figure 19b. It takes only 150  $\mu$ s for the CRT to reach its maximum light emission intensity. After 2 ms of rising, the light emission almost disappeared (cf. Elze, 2010a). These results indicate that the rise time of the present OLED display is faster than that of most LCDs but slower than that of CRTs.

The time course of an actual image displayed on the screen is illustrated in Figure 20. To assess the detailed time course of the light emission, we used the test chart shown in Figure 20. The numbers in the test chart indicate raster line numbers from 0 to 1079. The upper panel shows the time course of the test chart that

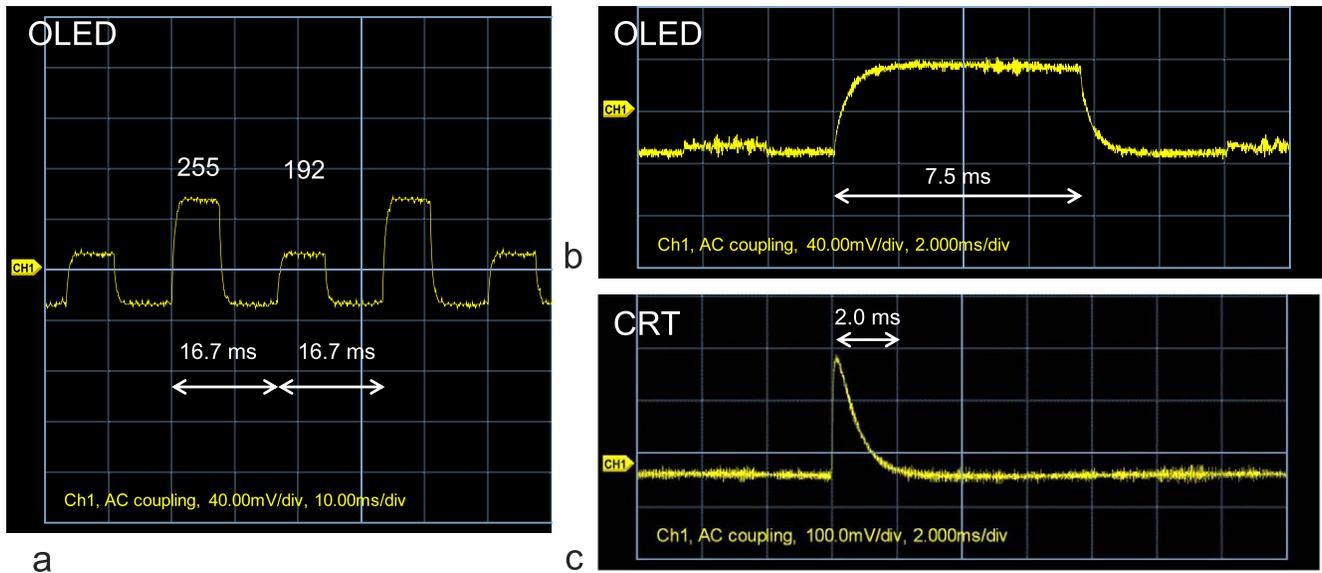


Figure 19. Time course of light emission. Waveforms were captured by an oscilloscope (Tektronix MSO 2024B). (a) shows the time course of the light emission intensity observed at a fixed point on the screen when two colors with RGB values of (192, 192, 192) and (255, 255, 255) were alternated at each frame refresh. The horizontal axis indicates time course in a scale of 10 ms/div. Black is present for slightly more than half of one refresh cycle. One rectangular wave cycle corresponds to one monitor refresh cycle of 16.7 ms. (b) shows the detailed waveform of the luminance change when white in RGB values of (255, 255, 255) was presented. The horizontal axis indicates the time course in a scale of 2 ms/div. (c) shows the waveform of the luminance change on a CRT screen (Sony, Multiscan 15SFII) in the same time scale as in (b).

actually appeared on the screen. In this figure 0 ms is an arbitrary point in time. The screen images were sampled at intervals of 2 ms with a shutter speed of 100  $\mu$ s using a high-speed digital camera system (Detect, HAS-L1). The scanning of the screen image progresses from the top to the bottom, just like that on a CRT. One critical difference between the two types of display is that the image remains for a while on the OLED display, as shown in Figure 20. Thus, displayed image and black areas translate vertically in the form of a band. The proportion of each indicates the relative times of light emission and black. As shown in Figure 20a and b, the ratio of the displayed area to the black is approximately 0.45:0.55. This suggests that within a frame of 16.7 ms the duration of light emission is 7.5 ms, and that of the black period is 9.2 ms. These values correspond well with the time course of light intensity shown in Figure 19.

To precisely exhibit a visual stimulus, presentation of the visual stimulus should be synchronized with the refresh cycle of the display. We produced a movie using DirectX technology to synchronize our program with the refresh cycle and observed the results on the display. A Sony VAIO computer with an nVIDIA GeForce 9300M GS graphic card was used to create the movie. We observed a vertical line moving horizontally on the PVM-2541 and could not find any tearing of the line. In addition, we observed a movie including a one-frame presentation of a stimulus, which required

synchronization of the program with the refresh cycle and sufficient temporal resolution of the display. The OLED display was placed beside an LCD (Mitsubishi, RDT233WX-3D). The displays presented the same frame sequence of a blank frame followed by a frame with vertical stripes, one with horizontal stripes and finally a blank frame. Both displays received the same HDMI signal from a computer through an HDMI distributor. The results of this experiment are presented in Figure 21. For the OLED display, frames exhibiting vertical or horizontal stripes were clearly defined and independent from each other. In contrast, the LCD could not resolve the vertical and horizontal stripes and showed a 2–3 frame delay in presentation relative to the OLED display.

## General discussion

The characteristics of the tested OLED display, the Sony PVM-2541, are summarized as follows: excellent luminance and color uniformity, excellent low luminance gradation, stable white and three primaries throughout the wide luminance range, wide color space (especially for saturated green), and rapid luminance rise/fall times. Few LCD or CRT displays can produce this level of image quality. The excellent low luminance gradation performance and quick luminance rise/fall

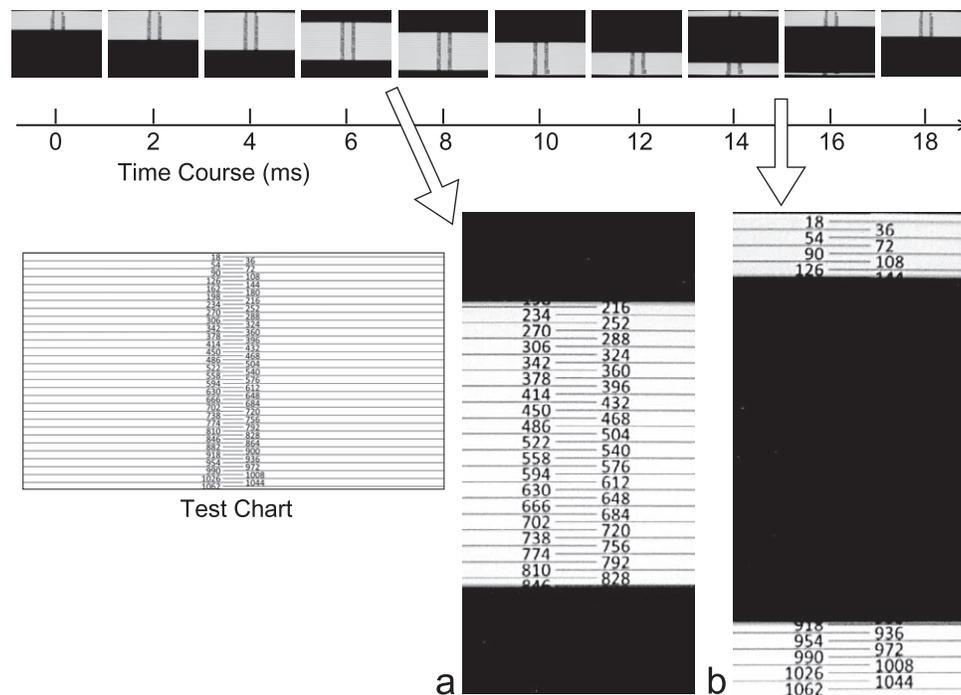


Figure 20. Time course of an image displayed on the OLED screen. The static test chart in the figure was displayed on the screen. The displayed area moves vertically. (a) and (b) show the areas of the displayed image and black field on the screen when each area appears fully. It should be noted that the sum of the two areas exceeds the screen size. Estimating from these pictures, it is assumed that about 1,410 horizontal lines (1,080 plus additional blank lines) are vertically scanned with a visible window of approximately 630 horizontal lines. Thus, the relative proportion of the two fields on the screen depends on the moment sampled (compare the images observed at 4 and 16 ms displayed above).

observed here may be characteristic of a general OLED display. However, the stability and uniformity of the luminance and color may be, at least partly, a result of good quality control by the manufacturers or from strict product design. Therefore, cheaper OLED displays that will appear in the future may not show this level of stability. The quick rise/fall in luminance of OLED displays may be advantageous in low-level vision experiments (e.g., experiments involving detection of light, motion and color).

It should be noted that the concept of one frame in the PVM-2541 is different from those in an LCD or CRT display. One advantage of the PVM-2541 is that each frame is clearly defined, i.e., its luminance is independent from that of the previous frame, unlike that in an LCD. However, it is unclear whether these differences will affect human perception of briefly presented stimuli. This should be investigated to ensure that the concepts of frames or duration calculations based on the number of frames could be translated from a CRT to an OLED display.

A disadvantage of this OLED display is that the frequency of the frame presentation is fixed at 60 Hz, which is because it is a video monitor designed for a broadcasting studio. For precise psychophysical or physiological measurements, e.g., in motion detection

experiments, a refresh rate of more than 100 Hz may be required. Recent LCD monitors receive video signals with a frequency of 120 Hz; however, at the same time, LCDs may hold an image during each frame, which produces perceived motion blur. For the OLED display, the sustained duration of each dot is approximately 7.5 ms, rather than the full 16.7 ms of each frame. The resulting black period is considered to contribute to producing the perception of smooth moving images with reduced motion blur, similar to black periods inserted by backlight scanning in some LCDs. Wang & Nikolic (2011) proposed using a 120 Hz LCD display to mimic a CRT scanning at 60 Hz by inserting alternate black frames. The produced luminance change on the screen was similar to that on the OLED display scanning at 60 Hz. Thus, some modern LCDs can be used to present visual stimuli under precise temporal control like the present OLED. In contrast, in CRTs, the light-emitting period in each pixel is less than a few milliseconds, as shown in Figure 19c, which is considerably shorter than that of the OLED display (or an LCD). We still believe that the smoothest motion will be observed on a CRT with a high refresh rate because of its shorter image-holding duration. It is possible that brief or fast presentation of moving images or a flickering stimulus looks different

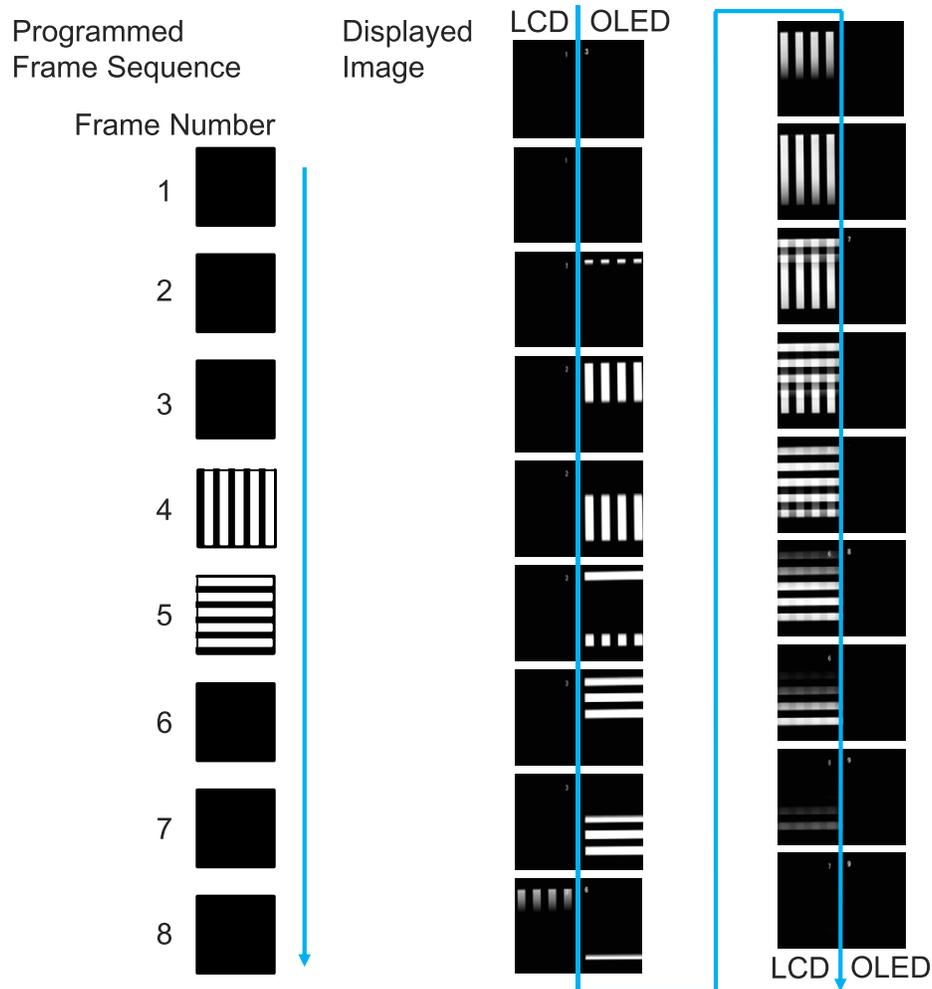


Figure 21. Movie presentation including one-frame stimuli. The left panel shows the programmed frame sequence. Each frame duration was 16.7 ms. The right panel shows the images actually displayed on an LCD (Mitsubishi, RDT233WX-3D) and the OLED display placed side-by-side. Photographs were taken every 6 ms. The shutter speed was 1 ms. The left (right) side in each picture shows the image on the LCD (OLED display). The LCD was set in Game mode with the “Overdrive mode 1” on. Each programmed frame was clearly defined on the OLED display, whereas the vertical and horizontal stripes were not separated on the LCD screen. Note that the image appearing on the LCD screen is delayed by two to three frames relative to that on the OLED display.

on the three displays. In addition, results for some low-level electrophysiological measurements may be affected by the difference in the illumination-black proportions of the different types of displays. The practical differences of using the three types of displays in vision experiments are not clear at present, and should be studied in the future.

The limiter for the screen brightness that acts when the default setting is used must also be addressed. Our measurements show that white displayed on the full screen is reduced in luminance ( $153 \text{ cd/m}^2$ ) compared with that of white displayed in a small region ( $213 \text{ cd/m}^2$ ) (measured with a CS2000 spectral radiometer). The limiter may not work when white is under the level of RGB values at (220, 220, 220), when the white area is under 40% of the screen area, or in the first frame of presenting bright white. Because the screen consists of

$1920 \times 1080$  pixels on a 24.5-in. display,  $1024 \times 768$  pixels could be used on the screen (under 40% in area) without a limiter. However, the best way of avoiding this artifact would be to set the contrast value at 67 or below. Then, although the maximum luminance may be suppressed to  $147 \text{ cd/m}^2$ , any unexpected changes in luminance will be avoided. We recommend this lower contrast setting during general use of the OLED display as a CRT replacement.

The OLED display could also be used as an illumination device. This may be beneficial for vision scientists who study color and illumination because the OLED display has a plain spectral distribution and broad gamut.

In summary, most psychological experiments that need visual displays could be carried out using this OLED display. This model is favorable for research

involving lower-level vision that requires precise control of visual stimuli in terms of luminance, color, contrast and duration. For experiments that require refresh rates of more than 60 Hz, it may be necessary to wait for a more suitable model to be developed. The problem of viewing angle dependency in color/luminance is expected to be reduced in the successive model (PVM-2541A).

*Keywords:* OLED display, visual stimulus, display device, CRT, LCD

## Acknowledgments

Xinguang Cao, Yuanyuan Bai, and Mariko Matsmoto are thanked for data collection. This study was partly supported by KAKENHI (Grant no. 23243076).

Commercial relationships: none.

Corresponding author: Hiroyuki Ito.

Email: [ito@design.kyushu-u.ac.jp](mailto:ito@design.kyushu-u.ac.jp).

Address: Faculty of Design, Research Center for Applied Perceptual Science, Kyushu University, Fukuoka, Japan.

## References

- Bach, M., & Meigen, T. (1992). Electrophysiological correlates of texture segregation in the human visual evoked potential. *Vision Research*, *32*(3), 417–424.
- Bach, M., Meigen, T., & Strasburger, H. (1997). Raster-scan cathode-ray tubes for vision research—limits of resolution in space, time and intensity, and some solutions. *Spatial Vision*, *10*(4), 403–414.
- Bohnsack, D. L., Diller, L. C., Yeh, T., Jenness, J. W., & Troy, J. B. (1997). Characteristics of the Sony Multiscan 17se Trinitron color graphics display. *Spatial Vision*, *10*, 345–351.
- Elze, T. (2010a). Achieving precise display timing in visual neuroscience experiments. *Journal of Neuroscience Methods*, *191*, 171–179.
- Elze, T. (2010b). Misspecifications of stimulus presentation durations in experimental psychology: A systematic review of the psychophysics literature. *PLoS One*, *5*(9), e12792.
- Haig, C. (1941). The course of rod dark adaptation as influenced by the intensity and duration of pre-adaptation to light. *Journal of General Physiology*, *24*, 735–751.
- Kihara, K., Kawahara, J., & Takeda, Y. (2010). Usability of liquid crystal displays for research in the temporal characteristics of perception and attention. *Behavior Research Methods*, *42*(4), 1105–1113.
- Krantz, J. H. (2000). Tell me, what did you see? The stimulus on computers. *Behavior Research Methods, Instruments, & Computers*, *32*(2), 221–229.
- Lagroix, H. E. P., Yanko, M. R., & Spalek, T. M. (2012). LCDs are better: Psychophysical and photometric estimates of the temporal characteristics of CRT and LCD monitors. *Attention, Perception, & Psychophysics*, *74*(5), 1033–1041.
- Metha, A. B., Vingrys, A. J., & Badcock, D. R. (1993). Calibration of a color monitor for visual psychophysics. *Behavior Research Methods, Instruments, & Computers*, *25*, 371–383.
- Mulligan, J. B., & Stone, L. S. (1989). Halftoning method for the generation of motion stimuli. *Journal of the Optical Society of America A*, *6*, 1217–1227.
- Pelli, D. G. (1997). Pixel independence: Measuring spatial interactions on a CRT display. *Spatial Vision*, *10*, 443–446.
- Stockman, A., & Sharpe, L. T. (2006). Into the twilight zone: The complexities of mesopic vision and luminous efficiency. *Ophthalmic & Physiological Optics*, *26*(3), 225–239.
- Ramanath, R. (2009). Minimizing observer metamerism in display systems. *Color Research & Application*, *34*(5), 391–398.
- Wang, P., & Nikolic, D. (2011). An LCD monitor with sufficiently precise timing for research in vision. *Frontiers in Human Neuroscience*, *5*, 85.