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Effect of Pixel Aperture Ratio on Subjective Spatial Resolution

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ABSTRACT

We conducted a psychophysical experiment to evaluate the subjective spatial resolution of random dot stimuli with different pixel aperture ratios. It was confirmed that even at an angular resolution of 30 cycles per degree, which corresponds to the standard viewing condition, the pixel aperture ratio affects the subjective spatial resolution.

1 Introduction

There is an increasing demand for high-quality display images to convey fine details in digital images. Spatial resolution is the most important factor for displaying fine images [1, 2]. Studies have also reported that as the angular resolution (resolution per unit viewing angle) increases, the perceived realism of images also increases [3].

Recently, mini/micro-LED displays have attracted attention as the next-generation displays [4]. Mini/micro-LED comprises minute LED pixels and are characterized by a significantly high ratio of black color on the surface. Current mainstream LCDs require a high pixel aperture ratio to maintain brightness; however, LED displays can achieve a low pixel aperture ratio owing to their high brightness [5]. Each of these new displays has a wide variety of pixel structures, and it has been reported that these differences in pixel structures may result in different subjective spatial resolutions, even for displays with the same pixel resolution [6, 7]. However, our prior studies [6, 7] have focused only on the case where the pixel aperture ratio is 100%, which is not the case for most actual displays.

The purpose of this study is to clarify if the pixel aperture ratio affects subjective spatial resolution through a subjective evaluation experiment.

2 Experiment

In the experiment, random dot images with two different pixel aperture ratios were compared. Two pixel aperture ratios of 100% and 9% were simulated by considering 10 × 10 real pixels of an actual display as a single virtual pixel. Figure 1 shows conceptual images of random dot stimuli created in this manner. The luminance of each real pixel in a virtual pixel is inversely proportional to the virtual pixel aperture ratio such that the luminance of the entire virtual pixel is constant regardless of the aperture ratio. Using this simulation method, for each pixel aperture ratio, stimulus images were created within a region of 100 × 100 virtual pixels in 1000 × 1000 real pixels on the display, with 25 white virtual pixels randomly placed, and the other pixels being black. An example of dot pattern pair is shown in Fig. 2. The dot pattern was randomly changed each time while the relative coordinates of the virtual pixels of the dots on the left side were always identical to those on the right side in each pair.

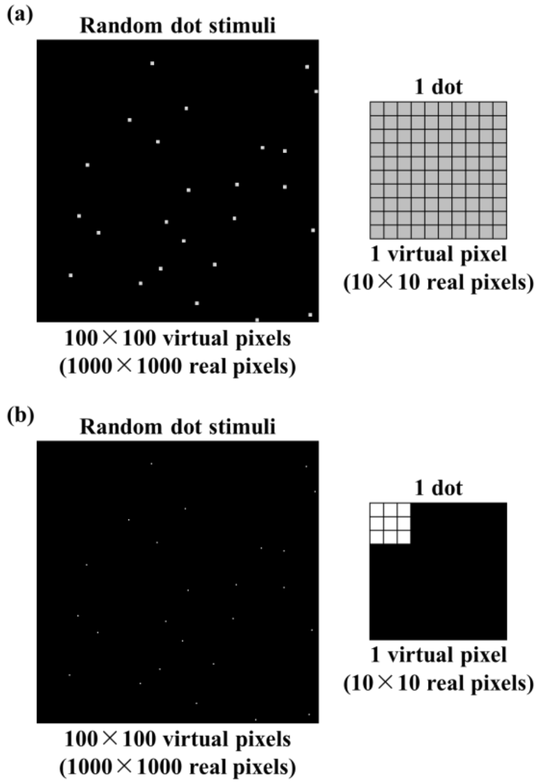

Fig. 1 Random dot stimuli. (a) 100%-pixel aperture ratio. (b) 9%-pixel aperture ratio.

The experimental stimuli were displayed on a 30-inch 4K OLED master monitor (BVM-X300, SONY Corp., Japan). A spectroradiometer (CS-2000, Konica Minolta, Japan) was used to measure a virtual pixel with 9%-pixel aperture ratio, with the pixel value set to 255, resulting in a white luminance value of 37 cd/m^2. Therefore, to equalize the luminance values of the virtual pixels at each pixel aperture ratio, the white luminance value was set to the same luminance of 37 cd/m^2 by adjusting the pixel value with 100%-pixel aperture ratio.

The experiment was conducted in a dark room with three observers with binocular vision of 20/20 or better. At the beginning of the experiment, each observer stared at the black background of the monitor for 3 min to become accustomed to the darkness of the room.

The viewing distances between the monitor and each observer's eye were set at 3.71 m (20 cpd) and 5.57 m (30 cpd). The latter angular resolution is used in the standard viewing condition recommended by ITU-R [8]. Here, the angular resolutions were calculated based on the virtual pixel.

For each angular resolution of 20 cpd and 30 cpd, four dot pattern pairs were used: two pairs with different pixel aperture ratios (9%-100%, 100%-9%) and two pairs with the same pixel aperture ratio (9%-9%, 100%-100%) to check that there is no bias in the left and right responses. The four dot pattern pairs were randomly presented 16 times for each pair. Therefore, in total, 64 pairs were presented for each viewing distance.

The experiment comprised a pair of random dot patterns displayed on the left and right sides of the monitor as the evaluation target, and they were asked to verbally respond to the stimuli they perceived sharper using the two-alternative forced-choice (2AFC) task method. After one evaluation response, a black background was presented for 1 s to eliminate the influence of the previously presented stimuli, and then the next stimulus was presented.

3 Results

The average response rates for each dot pattern pair calculated by the three observers are shown in Fig. 3. A response rate exceeding 75 % for each experiment was defined as a significant difference. In Fig. 3, dot pattern pairs that showed the significant difference were circled with a number indicating the angular resolution. Fig. 3 shows the average response rates for each pixel aperture ratio in each pair. In Fig. 3(a), the value on the left side of each bar graph represents the average response rate for 100%-pixel aperture ratio, and the right side shows the average response rate for 9%-pixel aperture ratio. The 9%-pixel aperture ratios exhibited higher values for both 20 cpd and 30 cpd angular resolution. Similar results were obtained when random dots with a pixel aperture ratio of 9% were presented on either the left or right side of the screen. These results indicate that the subjective spatial resolution differs with the pixel aperture ratio, even at the ITU-R recommended angular resolution of 30 cpd. Furthermore, the results suggest that a lower pixel aperture ratio may result in a higher subjective spatial resolution. In Figs. 3(b) and 3(c), the average response rates are shown when random dots with the same pixel aperture ratio are compared. These results show the average of observers' response was not significantly biased when the same stimulus was displayed on the left and right sides in this experiment.

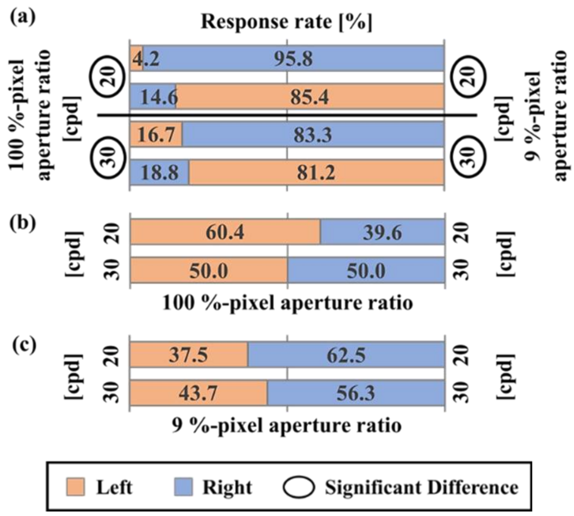

Fig. 3 Average response rates between (a) 100%-pixel aperture ratio and 9%-pixel aperture ratio, (b) the same 100%-pixel aperture ratios, and (c) the same 9%-pixel aperture ratios.

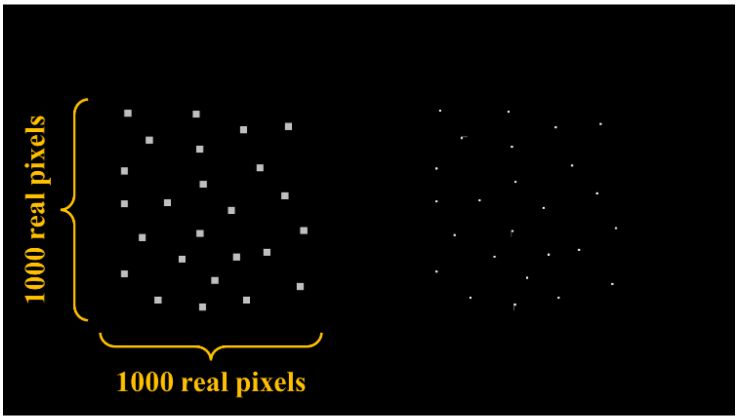

Fig. 2 An example of dot pattern pair presented on the display (left: 100%-pixel aperture ratio, right: 100%-pixel aperture ratio).

4 Discussion

Spatial resolution is among factors that determine the performance of a display. Modulation transfer function (MTF) is an objective and quantitative measure of the spatial frequency characteristics of a display. In this study, we calculated display MTFs based on a line-based method [9] and considered the relationship between the MTFs and subjective spatial resolutions.

The line spread function $\mathrm{LSF}(x)$ of the vertical luminance profile for each pixel aperture ratio was calculated as follows.

100%-pixel aperture ratio:

$$\mathrm{LSF}(x) = \mathrm{rect}(x); \quad (1)$$

9%-pixel aperture ratio:

$$\mathrm{LSF}(x) = \mathrm{rect}\left(\frac{x+7/20}{3/10}\right), \quad (2)$$

where rect denotes a rectangular function. Note that the luminance profile of the RGB stripe of a real pixel was not considered for simplicity.

The $\mathrm{MTF}(\xi)$ for each pixel aperture ratio is obtained by performing a Fourier transform on the obtained $\mathrm{LSF}(x)$, and then normalizing it such that it becomes one at $\xi = 0$ as follows:

100%-pixel aperture ratio:

$$\mathrm{MTF}(\xi) = |\mathrm{sinc}(\xi)|; \quad (3)$$

9%-pixel aperture ratio:

$$\mathrm{MTF}(\xi) = \left|\mathrm{sinc}\left(\frac{3}{10}\xi\right) e^{j\frac{7}{10}\pi\xi}\right|, \quad (4)$$

where ξ is the spatial frequency in cycles per pixel. Fig. 4(a) shows the MTF curves for each pixel aperture ratio. Here we compare the experimental results simply considering the modulations at the Nyquist frequency, since the MTFs are typically a monotonically decreasing functions. According to Fig. 4(a), the MTF for the 9%-pixel aperture ratio has a higher modulation than that for the 100%-pixel aperture ratio, and the difference is larger than 30%. As shown in Fig. 4(b), we found a significant difference of subjective spatial resolution in our previous studies [6, 7] using black and white grille patterns as experimental stimuli with the modulation difference of approximately 20%. From these results, it is necessary to further examine in detail how small the difference in modulation should be to make the difference in pixel aperture ratio indistinguishable, considering other visual artifacts, such as screen door effects.

5 Conclusions

In this study, we hypothesized that the pixel aperture ratio affects the subjective spatial resolution and verified this hypothesis through a subjective evaluation experiment. In our experiment, random dot stimuli corresponding to pixels with a 100%-pixel aperture ratio and pixels with a 9%-pixel aperture ratio were created, and stimuli with different pixel aperture ratios were presented on the left and right sides of the display and evaluated at 20 and 30 cpd. The results showed that the lower pixel aperture ratio was perceived to be significantly clearer even at an angular resolution of 30 cycles per degree, which corresponds to the standard viewing condition, confirming that the difference in pixel aperture ratio affects the subjective spatial resolution. The results of this experiment suggest that there is a correlation between the MTF and subjective spatial resolution. In the future, we will investigate the threshold at which the difference in pixel aperture ratio becomes indistinguishable and an analysis that also considers the effect of the black mask. We also plan to investigate the effects of the pixel aperture ratio on subjective spatial resolution for simple natural images.

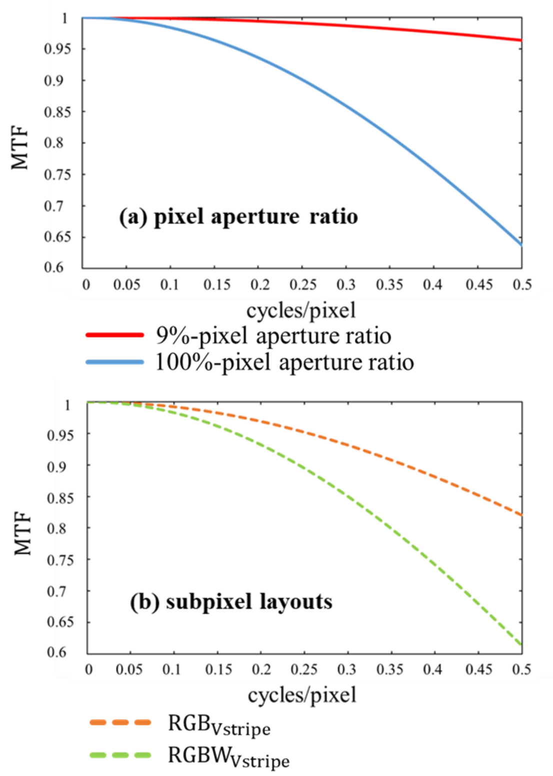

Fig. 4 MTF for (a) 9%- and 100%-pixel aperture ratios and (b) different subpixel layouts [6, 7].

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