Ambient Light and Human Vision Effects on High-Dynamic-Range Displays

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Abstract

Ambient light and human vision effects on high-dynamic-range mini-LED backlit LCDs (mLCDs) and OLED displays are investigated. Subjective visual experiment is also conducted to validate our analyses. As the ambient light brightness increases, the required local dimming zones for mLCDs to achieve comparable visual quality with OLED displays decreases dramatically.

Keywords

Mini-LED; high dynamic range; glare effect; ambient contrast ratio; halo effect; liquid crystal display.

1. Introduction

Recently, mini-LED (chip size: 100-500µm) backlit liquid crystal displays (mLCDs) with local dimming technology to achieve high dynamic range are emerging rapidly. Their widespread applications include laptop, desktop computers, gaming monitors, and high-resolution TVs, just to name a few. However, the halo artifacts still need to overcome. Halo artifacts [1, 2] usually appear at the edges of bright objects surrounded by dark background. According to [3, 4], the halo effect can be reduced by increasing LCD's native contrast ratio and number of local dimming zones. But there are still several unanswered fundamental questions, such as 1) when a display image received by the human vision system (HVS), the light scattering (glare spread function) inside human eye would spread out the light intensity from bright areas, thereby smearing the halo artifacts [5]. 2) How does the viewing environment (viewing angle and ambient light intensity) affect the halo effect?

In this work, we develop an optical model to simulate the images produced by a high-dynamic-range (HDR) mLCD, and then based on the CIE standard glare spread function [6] we obtain the retinal image received by HVS. The influence of glare effect on halo artifacts in HVS is analyzed. For practical applications, the influence from ambient environment, such as viewing angle and ambient light illuminance, is critically important. As the ambient light increases, the surface reflection from the display panel could washout the halo artifacts, and as the viewing angle increases which leads to an increased light leakage, the requirement of local dimming zone becomes stricter. The performances of two wide-view LCD technologies: multi-domain vertical alignment (MVA) and fringing-field switching (FFS), are compared against the required local dimming zones, dynamic contrast ratio, gamma shift, and color shift for practical applications.

2. Device modeling

In an mLCD system, the light emitted from mini-LED chips is modulated by some optical films, such as quantum dot enhancement film, optical diffuser, and brightness enhancement film, before reaching the LC panel. Therefore, the light intensity distribution is highly related to the optical design in the backlight unit. Here, we simulate a 15.6-inch 4K2K LCD with a mini-LED backlight unit composed of 20,736 (108×192) LED chips with a pitch of 1.8 mm. Here, we use following Gaussian function to present the light profile of a single mini-LED:

$$I(x_{LED}) \propto \exp-\left[\frac{(x_{LED}-x_{LED\_c})^2}{2\sigma^2}\right], \qquad (1)$$

where x_{LED_c} is the locus of the mini-LED and σ is an expansion characteristic parameter. In our simulation, the ratio of σ to the mini-LED pitch is 0.6, which provides the backlight with a uniformity better than 97%. Figure 1 illustrates the simulation process based on the point spread function theory [7] for generating HDR mLCD images. In this example, the LC panel has a CR= 5000:1, and 8-bit modulation depth. In the backlight unit, there are 648 local dimming zones; each zone contains 6×6 mini-LEDs. In Fig. 1(c), halo artifacts is clearly shown around the crown of the chess.

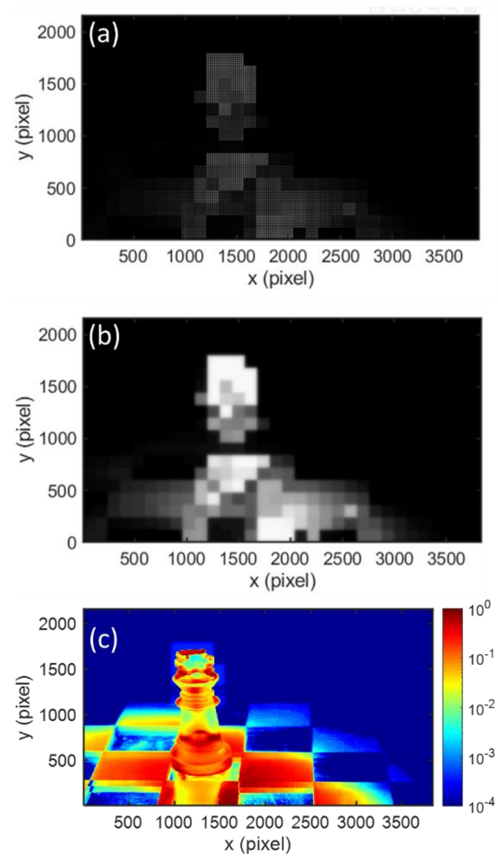

Figure 1. Displayed image of a mLCD: (a) Intensity profile of the mini-LED backlight. (b) Luminance distribution on the LC layer. (c) Normalized contrast ratio distribution of the image performed by mLCD.

So far, we have successfully simulated the image performed by HDR mLCD and clearly observed the halo effect in the simulated image. However, the observer receives all the displayed images through eyes. Therefore, considering the light scattering in human eye, known as *glare*, is very important to accurately analyze the halo artifacts perceived by the HVS. Here, we call the image on the display panel as "display image", and that received by the observer through HVS as "retinal image". To analyze the glare effect of human eye, the glare spread function from CIE standard is used to simulate the relative light intensity scattered from one pixel to

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another. According to the visual angle between each pixel, the normalized glare spread function at 550-mm viewing distance is plotted in Fig. 2(a). Employing the glare spread function to "display image", we simulate the contrast ratio distribution in "retinal image", as shown in Fig. 2(b), including the influence of light scattering from human eye. Since light scattering occurs inside human eye, the light from high brightness pixels will spread to neighboring pixels, which smears the local contrast. As a result, the halo artifacts become blurred and are difficult to distinguish.

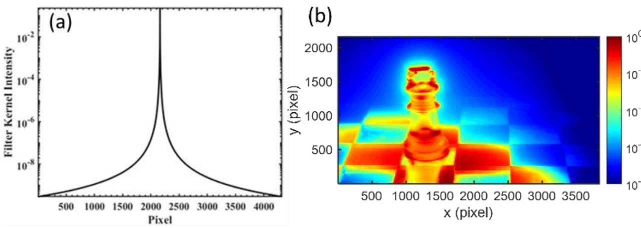

Figure 2. (a) The CIE standard glare spread function under the viewing condition in our subjective experiments. (b) Simulated retinal contrast ratio distribution.

A simple image content consisting of a white dot surrounded by a dark background is used to further analyze the influence of glare effects on halo artifacts. Figure 3(a) depicts the contrast ratio distribution of the display image generated by an HDR mLCD with CR = 5,000:1 and an OLED display with CR = 1,000,000:1. The number of local dimming zone ranges from 18 to over 20,000. As shown in Fig. 3(a), even if the number of local dimming zones exceeds 20,000, we can still easily identify the brightness difference on the area adjacent to the central white point. However, if the glare effect is taken into consideration, the light from central white point will be scattered to adjacent pixels, as Fig. 3(b) shows.

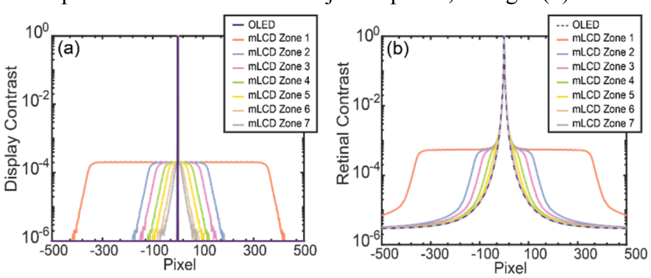

Figure 3. Comparison of image contrast between mLCD and OLED display: (a) Display image, and (b) retinal image (glare effect). The number of local dimming zones corresponding to Zone 1 to 7 is 18, 162, 288, 648, 1458, 5832, and 23328, respectively.

In above discussion, the viewing environment is completely dark, and the viewing angle is at normal direction. However, when displaying images under ambient lighting conditions, the total brightness received by the human eye consists of two parts: displayed signal and ambient light reflected from the display surface. Here, we conduct an experiment to measure the ambient light reflected from the display (OLED laptop Dell XPS15) as shown in Fig. 4(a) and 4(b). Two floor lamps and two ceiling lamps were used to generate five levels of ambient lighting conditions, namely 0 lux, 50 lux, 100 lux, 300 lux and 500 lux. The corresponding reflected ambient luminance measured by the luminance meter was 0 nit (below the measurement capability), 0.23 nit, 0.46 nit, 1.26 nit, and 2.47 nit, respectively. The corresponding surface reflectivity is about 1.5%. A simple image with a white dot in the center and surrounded by dark background was used to analyze the ambient light effect on halo artifacts. Through adding the reflected ambient luminance to the displayed image and including the glare effect of HVS, the retinal image comparison between the OLED display and the mLED (162 zones) is shown in Fig. 5(a). In addition, in Fig. 5(b), we also plot the comparison with 4% surface reflectivity, which is the typical value for commercial mobile devices. We can clearly observe that the halo artifacts in the adjacent areas of central bright spot are washed out by the reflected ambient light.

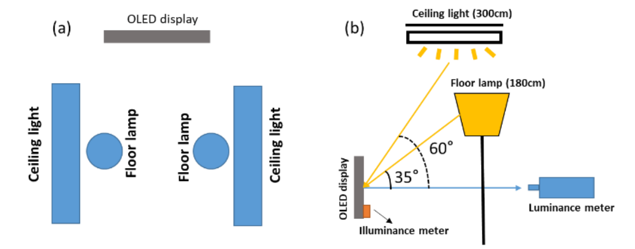

Figure 4. (a) The ambient light source arrangement (bird view) and (b) measurement condition (side view) in the ambient light experiment.

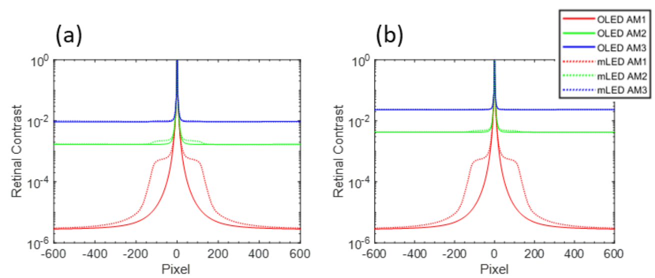

Figure 5. Contrast ratio of retinal image generated by an OLED display and a mLCD under different ambient illuminances and surface reflectivity (a) 1.5%, and (b) 4%. The ambient (AM) 1 to 3 corresponds to 0 lux, 50 lux, and 300 lux, respectively. The peak brightness of mLCD and OLED display is 400 nits.

By applying the D-value evaluation method [8] to a target image, the local area where the HVS is easier to detect the halo artifacts is found as shown in the white box in Fig. 6(a). To quantitatively analyze the halo effect in these local areas, an evaluation metric called peak signal-to-noise ratio (PSNR) is applied. Here, the PSNR in these local areas is called LocalPSNR defined as:

$$LocalPSNR = 10 \times \log_{10}\left[\frac{(I_{max})^2}{\frac{1}{M \times N}\sum_{i=1}^{M}\sum_{j=1}^{N}(\Delta I(i,j)^2)}\right], \quad (2)$$

where M and N represent the number of pixels in the local area (240×240), I_{max} is the difference between black and white, and ΔI is the brightness difference between simulated retinal image and target retinal image. Unlike the PSNR of an entire image that considers all pixels in the image, the advantage of LocalPSNR is that we can exclude pixels that are far away from areas where halo artifacts occur. To further explain the function of LocalPSNR, we plot the normalized contrast ratio distribution of mLCD system with 162 and 648 local dimming zones in Fig. 6(a) and 6(b) for comparison. First, we can clearly observe that as the number of local dimming zones increases, the halo artifacts inside the local area decreases. This image quality improvement is also reflected by the higher LocalPSNR in Fig. 6(c). As a result, for discussing the image quality degradation results from the halo artifacts, we think analyzing the image quality inside these local areas is convincing and more efficient. The LocalPSNR of all simulated images are calculated and shown in Fig. 6(c). In line with our expectation, a higher contrast ratio and more local dimming zones help eliminate halo artifacts, thereby improving the image quality of the mLCD.

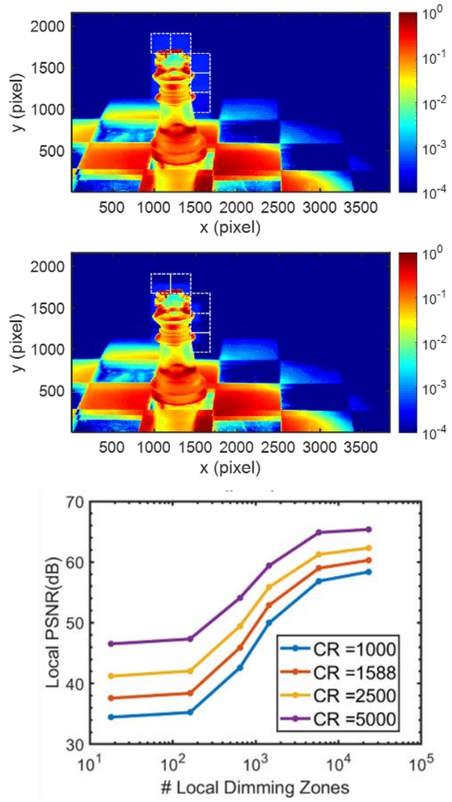

Figure 6. Normalized contrast ratio distribution of the image performed by mLCD with (a) 162, and (b) 648 local dimming zones. (c) Simulated LocalPSNR of target images.

3. Subjective Experiment

In this section, a subjective experiment is designed to find the perceptual limit of each image. The local dimming zone number required to display images with indistinguishable halo effects under different image contents and different ambient light conditions is obtained.

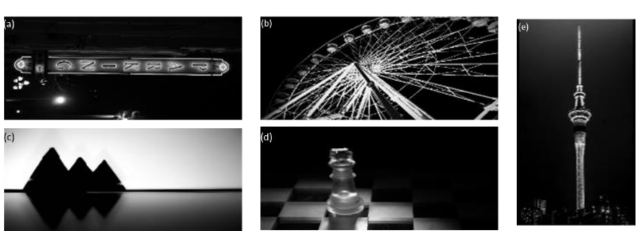

Figure 7. HDR target images for the subjective experiments: (a) Parking sign, (b) Ferris wheel, (c) Mountains, (d) Chess, and (e) Tower.

As shown in Fig. 7, five images are used in our subjective experiment. To choose a proper test image, several factors should be considered, depending on the objectives. Here, our purpose is to analyze the halo artifacts in an HDR mLCD. Therefore, all the selected test images exhibit a high contrast ratio, including high peak brightness and good dark state. Four different ambient light illuminances are used to study the impact of ambient lighting. Two OLED panels (Dell XPS 15 laptop, panel size 15.6-inch, resolution 4K2K) are employed as the image sources and placed at 55-cm away from the observer. One of the OLED panels displays a simulated mLCD images with different local dimming zone numbers and contrast ratios. The other OLED panel displays the control image. Observers are asked to determine whether they can find the difference (halo artifacts) between a pair of images. Four ambient conditions (0 lux, 100 lux, 300 lux, and 500 lux,) are used in our subjective experiment, and the required zone number of mLCD to eliminate the halo artifacts is shown in Fig. 8. In most images, as the ambient light increases, the halo artifacts are washed out and thereby fewer zone number can achieve same image quality. However, for the Tower image, there are many sparkles at the bottom, resulting in more serve halo artifacts. Therefore, even though increasing LC contrast or under strong ambient illuminance (500 lux), the required local dimming zones is still high. On the other hand, for the Mountains, the halo effect is hard to distinguish by HVS. The observers cannot see the halo artifacts even though the zone number is only 18. Thus, the benefit of making more local dimming zones is limited. In these two extreme cases, local dimming cannot provide much improvement in image quality.

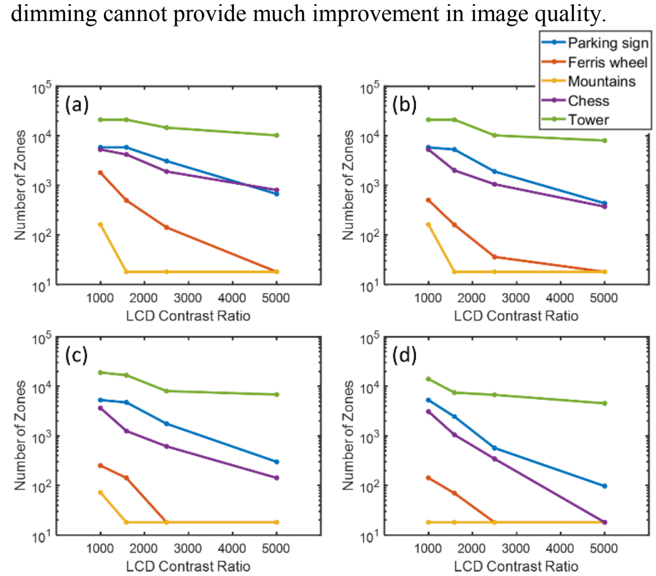

Figure 8. Required local dimming zone number to suppress the halo effect under different ambient lighting: (a) 0 lux, (b) 100 lux, (c) 300lux, and (d) 500 lux, respectively.

In the following discussion, as we define a suitable local dimming zone number for different ambient light conditions, we focus on the images whose quality can be improved by the local dimming method. The average zone number from these images under different ambient conditions is shown in Fig. 9. According to our subjective experiment, as the ambient light gets brighter, the halo effect is alleviated. Thus, an mLCD can obtain comparable image quality to OLED with a fewer local dimming zone number. In addition, the LCD panel with a higher native contrast ratio leads to weaker halo artifacts, which is easier to be washed out by the ambient light. For example, for an mLCD with CR=1000, the required zone number is reduced from 4500 to 2800 as the ambient light increases from 0 to 500 lux. However, in the same ambient light range, if the LCD's CR increases to 5000, the required zone number decreases from 500 to 40.

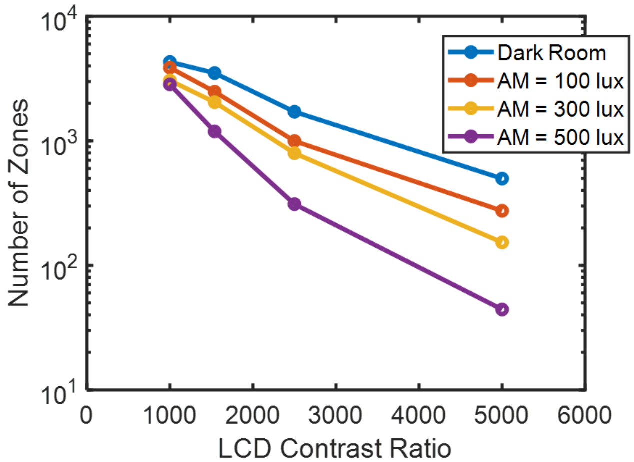

Figure 9. Required local dimming zone number to achieve indistinguishable halo effect under different ambient lighting conditions. Here, we only consider those image contents that can be improved through local dimming.

4. Discussion

As discussed above, the viewing angle in our visual experiments and simulations is at normal. However, as the panel size increases, the viewing angle for those pixels near the bezel increases. To cover entire display panel, the horizontal viewing angle is about ±40°. Therefore, the halo effect of the mLCD under different viewing angles is also very important. Two popular LCD operating modes (MVA and FFS) are analyzed below. The higher on-axis contrast ratio (CR~5000:1) is the advantage of MVA LCD, while FFS mode provides a wider viewing angle and smaller gamma shift. As the viewing angle increases from 0 to 40°, the contrast ratio of MVA LCD decreases from ~5000:1 to ~2000:1, and the contrast ratio of FFS LCD decreases from ~2200:1 to ~1500:1 [9]. Figure 10(a) and 10(b) shows the number of required local dimming zones as a function of viewing angle for MVA and FFS LCDs, respectively. We can clearly see that as the viewing angle increases, the number of local dimming zones required for MVA LCD increases dramatically. However, such an increase for FFS LCD is very mild. Therefore, to suppress the halo effect to an indistinguishable level within ±40° of horizontal viewing angle, the number of local dimming zones required for FFS and MVA LCDs is similar (~3000 in dark zoom).

In the following, we explain why FFS LCD is a better choice for the mLCD system. 1) Dynamic contrast ratio. In the mLCD system, the dark state is not only determined by the LCD's native contrast ratio but also by the local dimming of the mini-LED backlight. With the support of local dimming methods, FFS LCD can also achieve a very high contrast ratio (CR $\geq 10^5$:1). The major advantage of MVA LCD with a high on-axis contrast becomes less important. 2) Required zone number. As mentioned above, to maintain an indistinguishable level within ±40° viewing angle, the required local dimming zones in FFS and MVA LCDs is similar. 3) Gamma shift and color shift. Due to homogeneous alignment and lateral electric fields, FFS exhibits a much weaker gamma shift and color shift than MVA LCD. Therefore, FFS LCD can maintain better image quality at a larger viewing angle. Moreover, FFS is more robust than MVA for touch panels. Based on these advantages, FFS LCD is a strong contender for the mLCD systems.

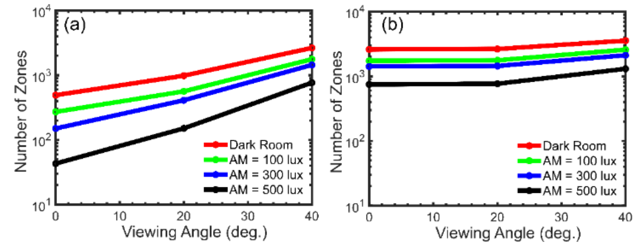

Figure 10. Required number of local dimming zones for achieving indistinguishable halo effect under different viewing angle: (a) MVA LCD, and (b) FFS LCD.

5. Impact

We have developed an optical simulation model to evaluate the influence of glare and ambient light effects on the halo effect of HDR displays, including mLCDs and OLED displays. By calculating the PSNR in these local areas, a performance metric LocalPSNR is proposed to evaluate the image quality degraded by the halo effect. In addition, we evaluate the required local dimming zones under different viewing angle and ambient light illuminance. Through analyzing the dynamic contrast ratio, gamma shift and local dimming zone requirement for practical applications (300-lux ambient light and ±40° viewing angle, we find that FFS LCD is a strong contender for the mLCD system.

6. Acknowledgments

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7. References

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