The importance of native panel contrast and local dimming density on perceived image quality of high dynamic range displays

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Abstract — We evaluated the perceived image quality of High Dynamic Range (HDR) content rendered using different types of local dimming and organic light-emitting diode (OLED) displays. Using an OLED display that is capable of achieving high contrast at a pixel level, we emulated local dimming displays to evaluate their image quality. In a set of subjective experiments, observers compared HDR images and videos rendered with different local dimming densities and native panel contrast. There was a strong effect of panel contrast on perceived quality and also a strong trend toward preference for a larger number of dimming zones. We also evaluated the panel contrast and number of local dimming zones necessary to achieve image quality comparable with OLED. The findings of these experiments demonstrated that the use of a high-contrast panel remains of critical importance. Also, the preference for panel rendering mode remains robust to normal levels of indoor ambient light.

Keywords — *HDR, high dynamic range, local dimming, image quality, contrast, dual modulation, halo visibility, leakage.*

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1 Introduction

High dynamic range (HDR) display systems are capable of producing high brightness details, such as highlights, while simultaneously producing details in dark shadows.[1] This ability to produce diverse lighting effects in a scene can lead to a more immersive and pleasing viewing experience.[2–4] High dynamic range imagery can be a strong differentiator from standard dynamic range imaging, which looks muted in comparison with attenuated highlights and washed-out dark regions.[5]

1.1 Local dimming solutions

Transitioning display technology from standard dynamic range to HDR is a technical challenge. With liquid crystal display (LCD) technology, the peak brightness and the minimum black level are directly proportional to the brightness of the backlight.[6,7] Improving the rendering of the highlights degrades the quality of the dark regions. One method to expand the contrast of display systems is to use dual-modulation in which the backlight is non-uniform; it typically has low resolution and is brightest in the bright regions of the scene and dimmest in the dark regions.[8] A liquid crystal (LC) panel with high resolution then creates the detailed image components and color while compensating for the low-resolution gradients of the backlight. This permits the display to have excellent global contrast, in which different parts of the image can have very different local average brightness and a local contrast level that enables texture visibility within that region.[9–12]

The main underpinning of the local dimming solution is that the high contrast image features are spatially separated in an image; a low-resolution backlight is adequate to represent these large global variations, and a high-resolution LC panel can produce all local details.[7] However, in scenes where there is a sharp boundary between a bright area and a dark area, light will leak through the LC near the boundary; this leakage is known as *haloing*[6,11,12] or *leakage*,[13] and is illustrated in Fig. 1. The magnitude of this halo is determined by the LC panel contrast. LC panels make use of different types of liquid crystal alignment and patterning, which heavily influences factors such as off-angle viewing characteristics, response time, and contrast.[10,14–16] For high-brightness images, native panel contrast can have a strong impact on the perceived image quality.[7] With a display peak brightness of 750–1000 nits, and a native panel contrast of 1000:1, it is possible to have elevated black levels as high as 1 nit. In a dark viewing environment, such elevated black levels are highly noticeable, and depending on the content may create non-uniformity, or halos.[17] On the other hand, by using a high-contrast LC panel, the magnitude of these raised black levels can be reduced by more than a factor of four.[17]

1.2 Specifying contrast

One of the performance metrics of a display for premium HDR performance is contrast ratio as measured with the corner-box test. In this test, white squares are turned on at either the center or the corners of the screen while a

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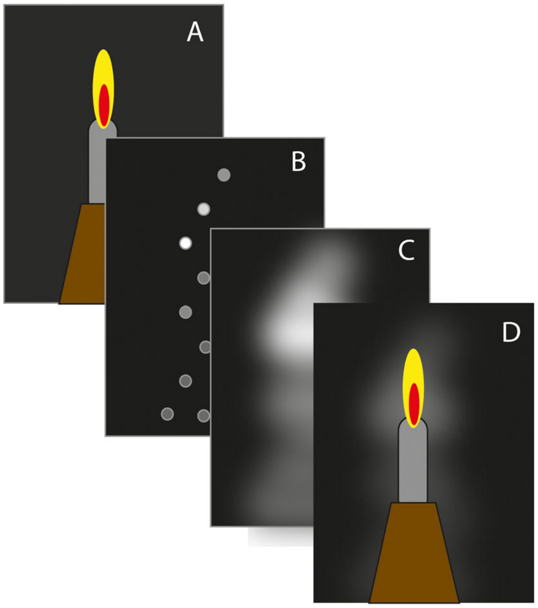

FIGURE 1 — Illustration of a dual-modulation display. A. HDR image. B. Local dimming backlight emitters. C. Optical filtering/diffusion of backlight illumination. D. Emitted image from the display, showing halo.

luminance reading is made from the center of the screen. With a uniform backlight, the contrast is equal to the native panel contrast ratio.

With a local dimming backlight, it is possible for the contrast measured with this corner-box test to be much higher, exceeding 50,000:1 with a 1000:1 LC panel.

1.3 Perceived image quality

The corner-box measure of contrast may not be closely correlated with perceived image quality. Other image attributes such as the intensity and size of haloing artifacts cannot be fully characterized with a single test. Also, the perceptual implications of these artifacts are difficult to predict. It is an empirical question to determine what local dimming zone density and panel contrast can produce the best image quality.

Consider the simple case that the display is to represent a bright feature on a black background, such as the candle shown in Fig. 1A. In order to show the image, the backlight must be bright behind the flame, dim over the candle, and off elsewhere (Fig. 1B). A diffuser layer hides the backlight emitter structure (Fig. 1C). The LC compensates for the backlight intensity to render the main parts of the image with high fidelity.[14] Given that the local backlight zone extends into the dark area and the native panel contrast is finite, the local dimming zone will be visible, thereby producing a halo (Fig. 1D).

The size of the halo is correlated to the spacing of local dimming zones and the diffusion layers.[12] With fewer local dimming zones, the diffusion must be greater to achieve uniform coverage, and the halo's size will be larger. The shape of each diffuse local zone can be complicated by the use of engineered diffusers, (light-emitting diode (LED) lens design, quantum dot phosphors, and the spatial layout of the LEDs (in some cases multiple LEDs may be used to illuminate the same block).

The visibility of these halos can be mitigated by keeping their size as small as possible (requiring more local dimming zones) such that they have the best alignment with the bright image features. The halo should also have minimum brightness, which requires a native panel contrast that is as high as possible. Understanding the perceptual severity of local dimming artifacts is an inherently perceptual question that requires subjective evaluation for which Experiment 1 is designed to answer.

Experiment 2 considers an extended aspect of visual quality, incorporating dynamic imagery, which can exacerbate local dimming artifacts. With many display technologies, an elevated black level can be tolerated; however, a rapid change in this black level can be a strong irritant. In the case of a sparse local dimming system, the zones may visibly turn on and off as the image content changes, leading to noticeable flicker in the dark areas adjacent to moving edges.

Experiment 3 assesses the number of local dimming zones that are needed for images at different LC panel contrast levels to achieve visual quality that is comparable with organic light-emitting diodes (OLED) displays.

Experiment 4 investigates whether different ambient lighting conditions impacts the image quality preferences for displays with different backlight and contrast configurations. Ambient lighting could affect the extent to which haloing artifacts are visible, thereby influencing viewing preference at different local dimming densities and native panel contrasts.

2 General methods

2.1 Display hardware

For the following experiments, we required a display platform capable of emulating the brightness, contrast, and different haloing artifacts we would expect from different dual-modulation systems. For this purpose, an OLED display is ideal because each pixel can be driven across a wide dynamic range independently from off to full brightness. We used a prototype 55-inch Samsung Display red, green, and blue (RGB) OLED panel for these experiments. The display was set for a peak brightness of 1000 nits, and was driven with an 8-bit signal with 2.2 gamma.

2.2 Local dimming

We created an emulation of the images that can be formed with a local dimming display system using the OLED display, and our workflow is illustrated in Fig. 2. This emulation allowed us to manipulate the images seen for various LC panel native contrasts and the number of the local dimming zones of the backlight independently to evaluate the perceived image quality. We simulate a Gaussian diffuser with a sigma of $\sqrt{2}/8$ of the zone center-to-center spacing.

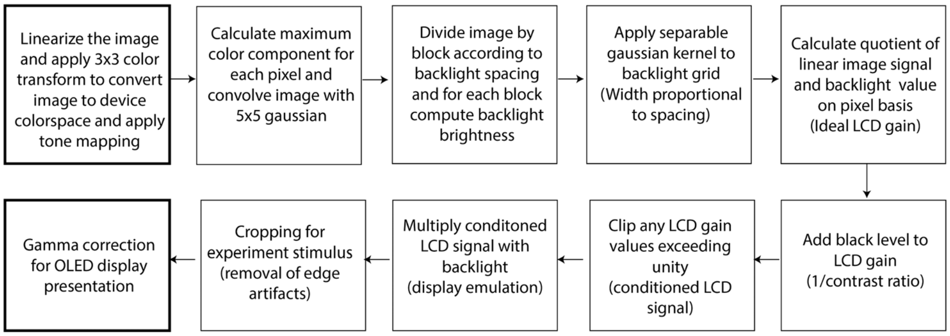

FIGURE 2 — Processing workflow used to emulate various local dimming solutions on the OLED display. A low-resolution backlight stage is calculated, followed by the ideal LC compensation to produce the original image. We then impose real-world limitations on the LC panel including baseline contrast and peak transmission. The final emulated image is the product of the constrained LC signal and the low-resolution backlight.

In the conditions with a single dimming zone, we set the backlight output to the lowest setting at which it could render the brightest pixel in the image at the coded brightness.

As part of the image generation, we performed several operations on the image to adjust the image content to fall within the display's color-reproduction volume. These operations included multiplication by a 3 × 3 matrix to convert the image from its distribution color space to the display's native color space. It also included tone mapping to attenuate highlights that were in some of the image content mastered at up to 4000 nits. In such images, we used a nonlinear attenuation of the luminance channel while preserving the chromaticity coordinates.

2.3 Viewing conditions

All imagery was viewed on the display from a distance of 215 cm corresponding to three screen heights, which is the recommended distance for viewing full high definition (FHD) imagery with a Nyquist frequency of 30 cycles per degree (The prototype panel had 4K resolution but was driven using 2 × 2 pixel resolution conversion.). This distance was held constant using a chin and forehead rest. In all experiments, testing was performed in a dark room with no lights (except for the floor lamps used as part of Experiment 4). All testing was self-paced but was divided up into short blocks of approximately 10 min followed by a short break (self-timed). Total viewing sessions were no longer than 60 min in a day.

3 Experiment 1: HDR preference in still images

The purpose of this experiment was to evaluate the viewing preference of native panel contrast and local dimming resolution using static images shown on a dual-modulation display system.

We surveyed a number of scenes from HDR movie content to identify images that could show an impact of contrast or local dimming artifacts. Most scenes had moderate image contrast that left adequate foot-room to fully compensate for the haloing of local dimming. In these scenes, the differences in native-panel contrast were not strongly noticeable. This was not the case for scenes in which there were dark or black regions of the image, as well as locations in which there were textures with dim but vivid colors (such as dark blue). In these images, halos were visible or colors could appear washed out.

3.1 Scene selection

We selected 10 scenes that had high local contrast from 3 HDR movies. Contents were drawn from Blender Foundation's "Tears of Steel" short film and two mainstream movies by a major Hollywood studio that were remastered for a 1000-nit display (Because of copyright and trademark restrictions, we refer to these movies as "*Sci-fi*" and "*Western*".).

3.2 Rendering conditions

We evaluated two simulated native-panel-contrast ratios: 1000:1 and 4500:1. For each contrast level, we tested four local dimming backlights with 1, 24, 60, and 150 zones. A total of eight renderings were created for each scene: one rendering for each combination of a panel contrast and local dimming density.

3.3 Experimental task

Experiment 1 used a forced-choice task between two renderings of the same scene. On each trial, a pair of renderings from a scene was compared side by side. All permutations of renderings were compared so that the subjective preference toward a collection of images could be estimated.[3,18,19] Observers were asked to select their preferred rendering on each comparison even if they could not detect a difference (illustrated in Fig. 3). After each session, the preference rating was estimated by calculating the number of times each rendering was chosen over all the other renderings of the same scene.

Trial 105/280

Select the preferred video clip

FIGURE 3 — Screenshot from Experiment 1.

Two renderings, each generated with the workflow shown in Fig. 2, were shown on the OLED display with randomized left-right positioning. Each full image was rendered with a specified number of local dimming zones. Then the image was cropped to be shown on the display for side-by-side subjective evaluation.

3.4 Subjects

Twelve observers participated. Four of them were familiar with the experimental hypotheses and methods, while the remaining observers were naïve to the experimental design. Observer ages ranged from 23 to 52. Male and female individuals were represented.

The task was verbally explained to the observers, but there was no description of what artifacts would be present. The observers were instructed to choose the most preferred rendering by making their selection with a gamepad.

3.5 Results

Each of the eight renderings was compared with the other seven renderings of the same scene (a total of 28 comparisons per scene). Each observer viewed all 10 scenes and completed the full set of comparisons twice, for a total of 560 evaluations. Thus, for each scene, a rendering was presented 14 times per person. We calculated what fraction of those 14 presentations the observer preferred that rendering. This fraction is plotted in Fig. 4. The top row shows a thumbnail or description of the scene (as permitted by copyright law). The second row shows the RGB histogram data acquired from the scene. Note that all of the scenes are considered high contrast with a significant component of the image falling below a brightness level of 1 nit, and containing at least one region of high peak brightness.

The third row of Fig. 4 shows the average subjective ranking (as calculated by the number of times preferred in the 14 presentations per observer) of each of the combinations of

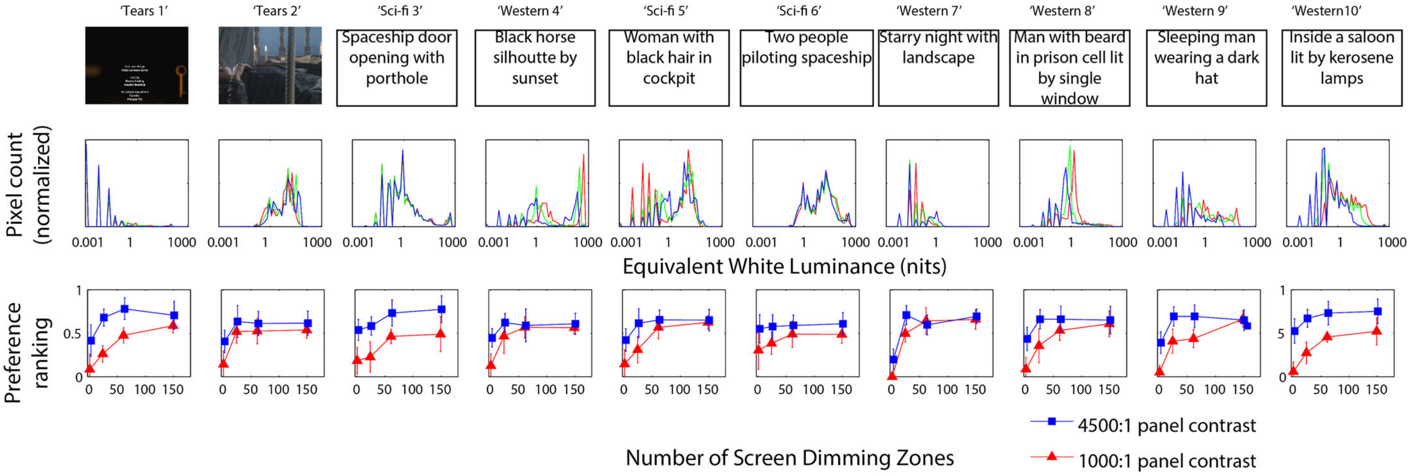

FIGURE 4 — Experiment 1 still images, image statistics, and results. The top row shows thumbnails or descriptions of the scenes that were tested (copyright permitting). The second row shows the RGB histogram of pixel brightness for each image. The bottom row shows the subjective preference ranking results for the eight conditions tested. The symbols represent the average ranking of the 12 observers, and the error bars represent the standard deviation. The data show 4500:1 and 1000:1 contrast levels in blue squares and red triangles, respectively. Each chart plots the average fraction of trials in which the designated rendering was selected over all alternatives. The abscissa represents the number of local dimming zones for the emulated display.

panel contrast and local dimming density. This ranking is shown on the ordinate while the number of local dimming zones is shown on the abscissa. The red triangle symbols represent the conditions in which the native panel contrast was 1000:1, and the blue squares represent conditions in which the panel contrast was 4500:1. The error bars indicate the standard deviation of the 12 observers' rankings. Overall, there was greater preference for the higher panel contrast, even when the number of local dimming zones was less than that of the lower contrast panel.

There was also a consistent preference for having a larger number of local dimming zones. This effect, however, appeared to saturate in a number of scenes – especially with the higher contrast panel.

The differences based on scene content were quite noticeable. In some scenes, such as the "*Western 7*" image, there was minimal impact of the panel contrast. This may be due to adequate foot-room in the night sky to minimize impact of the panel contrast. In other scenes, such as "*Sci-fi 3*", there was a strong impact of panel contrast. In other scenes with a dark area, including "*Tears 1*" showing the movie credits, the black background made the haloing quite prominent. The higher-contrast panel and larger number of dimming zones greatly mitigated the halo visibility.

To summarize the data from Experiment 1, we collapsed the data across scenes and present the average histogram statistics and average preference ranking in Fig. 5. The histogram indicates that these images have a strong dark component with tens of thousands of pixels that are less than 1 nit. The average of the preference rankings further clarifies two main trends:

1. There is a strong benefit of using a panel with high native contrast.

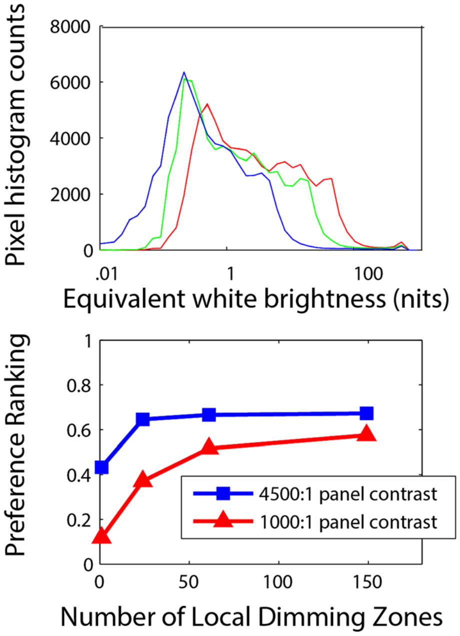

FIGURE 5 — Summary results from Experiment 1 averaged across all scenes.

2. There is a benefit of increasing the number of local dimming zones, up to a saturation point.

It is also interesting to note that the higher contrast panel needs less local dimming zones to reach the saturation level of viewing preference.

4 Experiment 2: High Dynamic Range preference in dynamic images

In the second experiment, we considered a subset of the content from Experiment 1 but introduced the motion from the original scene into the testing. The purpose was to determine whether dynamic halos from video imagery could change the conclusions from Experiment 1. With still imagery, all halos were static on the screen. In cases of low spatial frequency luminance patterns, Troxler fading can cause these types of gradients to be less visible than if there is significant motion in the image.[20–23] With motion imagery, different dimming zones constantly turn on and off, which leads to changes in the appearance and locations of the halos. These halos also do not move continuously with the moving content, but rather their location remains over their respective backlight zones.

4.1 Scene selection

For this experiment, we selected a subset of 4 scenes from Experiment 1. These scenes included "*Tears 1*", "*Tears 2*", "*Sci-fi 3*", and "*Western 4*". These scenes were selected based on having a predictable scene motion over a short duration (3 s), strong contrast, and histogram statistics that could be summarized with a single frame. Each of the 3-second clips played repeatedly until the observer made a selection.

4.2 Rendering conditions

We evaluated the same contrast and local dimming conditions used in Experiment 1.

4.3 Experimental task

The experimental task was the same as in Experiment 1.

4.4 Subjects

Eight of the 12 observers who participated in Experiment 1 also participated in Experiment 2. Three were familiar with the experimental hypothesis and methods while the remaining observers were naïve to the experimental design.

The instructions to the observers were the same as those in Experiment 1.

4.5 Results

The subjective ranking data (computed in the same fashion as in Experiment 1) are plotted in Fig. 6 with the solid lines and filled symbols and are superimposed on the corresponding data from Experiment 1 shown with dashed lines and unfilled symbols. Only the Experiment 1 data from the observers who participated in Experiment 2 have been plotted. The preference trends for higher contrast and greater local dimming zones are clear in the second experiment, and the results of Experiment 2 are in close agreement with the results of Experiment 1.

5 Experiment 3: achieving the visual quality of the organic light-emitting diode

The purpose of the third experiment was to determine the number of local dimming zones required to perceive a scene's image quality as comparable with the native OLED at different LC panel contrast levels.

5.1 Scene selection

The same clips utilized in Experiment 1 were used in this experiment.

5.2 Rendering conditions

We evaluated seven simulated native panel contrast levels: 500:1, 1000:1, 1500:1, 2000:1, 3000:1, 4000:1, and 5000:1 and 22 different emulated local dimming backlights, ranging from 1 to approximately 40,000 zones. Each of the seven native panel contrast levels was compared with the native OLED.

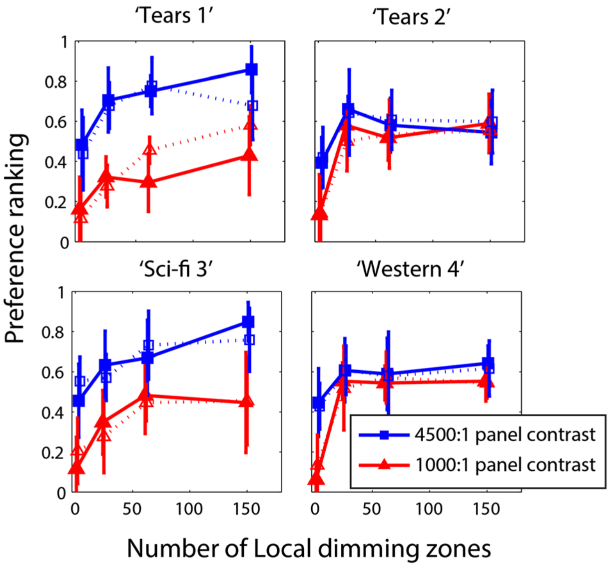

FIGURE 6 — Experiment 2 results. The number of local dimming zones is shown on the abscissa, and the preference ranking is shown on the ordinate. The 4500:1 and 1000:1 panel contrast conditions are represented by blue squares and red triangles, respectively. The solid filled symbols represent the moving imagery from Experiment 2, while the dashed lines with unfilled symbols represent the static imagery from Experiment 1. Error bars represent the standard deviation of the rankings across observers.

5.3 Experimental task

Experiment 3 used the method of adjustment.[24] On each trial, a pair of images was presented side by side. An image rendered with native OLED attributes was always presented on the left and served as the "reference". The same image rendered with one of seven different LC native-panel-contrast levels was shown on the right and was the "test". Observers were instructed to adjust the image quality (increase the number of local dimming zones) of the "test" (LC version) until it was comparable with the "reference" (OLED version). They were asked to select the lowest level at which quality was comparable.

The observers used buttons on a video game controller to adjust the number of local dimming zones in the "test", and they were able to track their adjustment setting by referencing a green tick mark placed on a ruler at the bottom of the screen (illustrated in Fig. 7). A position on the left of the scale signified a smaller number of local dimming zones, and a position on the right of the scale represented a larger number of local dimming zones. Each experimental trial began with the green tick mark placed to the left extreme of the ruler (i.e., at one local dimming zone). When observers perceived the quality of the "test" as comparable with the "reference" OLED, they proceeded to the next trial.

5.4 Subjects

Thirteen observers participated. Three of them were familiar with the experimental hypotheses and methods, while the remaining observers were naïve to the experimental design. Observers were male and female with ages ranging from 23 to 32. The results for one of the observers were excluded from the analyses because of a misunderstanding of the instructions.

5.5 Results

The experiment was divided into two sessions consisting of 70 settings (10 scenes and 7 contrast settings). Each observer viewed each condition twice, and thus made a total of 140 evaluations.

The left plot of Fig. 8 shows the variation between the different scenes. Each point is the average setting across the 12 observers. The average number of local dimming zones at which the image quality of the "test" scene was perceptually comparable with the native OLED is shown on the ordinate, and the native panel contrast of the "test" scene is shown on the abscissa. The different colored lines represent the different scenes that were examined.

Trial 7 of 70   Use the left and right buttons to adjust the quality of the right image until it appears comparable to the left image

FIGURE 7 — Screenshot captured during Experiment 3.

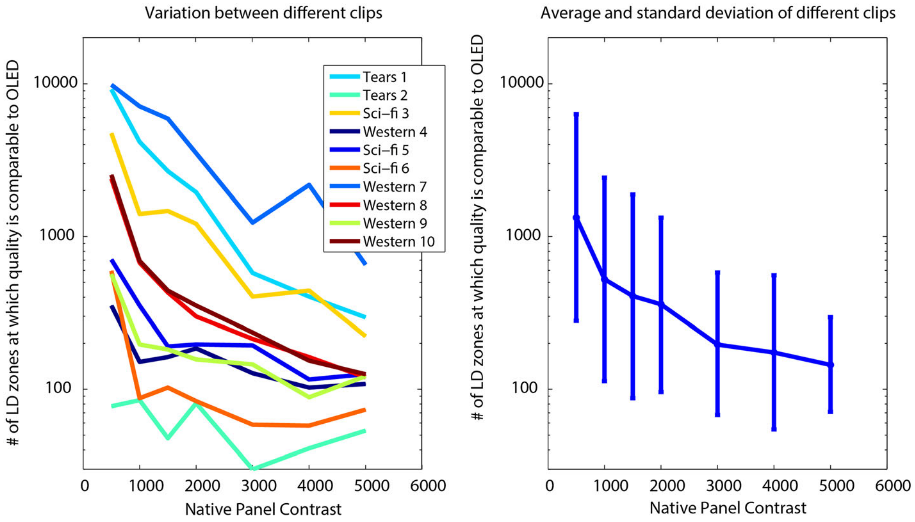

FIGURE 8 — The local dimming setting for comparable quality to OLED. The native panel contrast is shown on the abscissa, and the number of local dimming zones for the visual quality to be comparable with the OLED is shown on the ordinate (left). The number of local dimming zones required for each of the different clips. The colored lines represent the different clips tested (right). The average and standard deviation of the local dimming setting are chosen for all clips. The standard deviation was calculated based off of the local dimming setting as opposed to the number of dimming zones.

Despite the clear variation between different clips, the results trend in a similar direction in that fewer local dimming zones are required at higher LC panel contrast levels. This trend is illustrated in the right panel of Fig. 8, which shows the average number of local dimming zones for all clips at which the image quality of the "test" appears comparable with the "reference". The error bars indicate the standard deviation of the adjustment settings across clips. We use the adjustment setting (i.e., 1–22) rather than the actual numbers of local dimming zones. Again, the results clearly show that more local dimming zones are needed at lower compared with higher native-panel contrast levels.

We also observed a significant variation in settings between observers. The data from two representative clips are shown in Fig. 9, where the colored lines represent

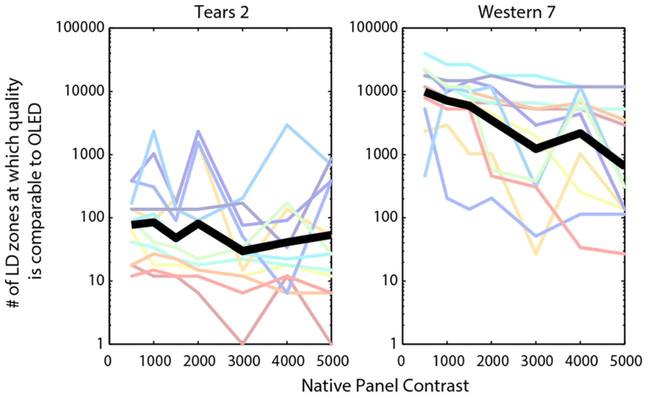

FIGURE 9 — Variation of the number of local dimming zones between different observers. The colored lines represent the different observers, and the thick black lines show the average local dimming settings across observers.

the different observers. The thick black line shows the average local dimming setting across all observers. The local dimming settings were averaged for each clip. The variation between different observers and the volatility of the individual settings are evident; nevertheless, there exists an overall decreasing trend across observers for most scenes, signifying a need for fewer local dimming zones to match the native OLED as native panel contrast increases. "*Tears 2*" is not particularly demanding, and 100 local dimming zones are adequate. The "*Western 7*" scene contains a starry night sky, and a high number of dimming zones are needed to mitigate the visibility of the halos around the bright stars. With a high contrast display, more than 1000 local dimming zones are still required to achieve comparable visual quality with the OLED, and 10 times more local dimming units are needed to show the same quality on a low contrast LC panel.

One possible reason for the large variation observed is that the task was designed to measure a subjective aspect of quality, "comparable". Each observer brings his or her own criteria for comparable quality with the evaluation, and this leads to differences in the responses measured. The criterion effect and hysteresis effects are reasons why the adjustment methods are less preferred to the forced choice methods used in the other experiments.

6 Experiment 4: High Dynamic Range preference in ambient lighting

Experiments 1–3 were all conducted in a dark room with no light sources other than the screen. The goal of Experiment 4 was to investigate if ambient lighting would influence observers' preference for different HDR displays.

Studies have found that dim or moderate ambient lighting does have an impact on the preferred image brightness level, but its effect is mixed.[4,25–27] In some displays with high diffuse reflection, ambient lighting can significantly reduce information visibility.[26] Elevated ambient light level, however, can also decrease the visibility of the artifacts and improve the relative visual quality of a display.[25] Raising the observer's, adaptation level may also lead to greater viewing comfort and thus increase detail visibility with a particular image.[28]

6.1 Scene selection

A total of eight different still images were used in this experiment. Four of the images were used in Experiments 1 and 3 ("*Tears 1*", "*Sci-fi 3*", "*Sci-fi 5*", *and* "*Western 10*"), and the other four were new images ("*Fire 11*" "*Lava 12*", "*Space 13*", *and* "*Space 14*"). "*Fire 11*" shows a man blowing fire into the air at night; in "*Lava 12*," a craft is navigating around an environment with lava; "*Space 13*" has a craft with small bright lights in space; "*Space 14*" shows a control panel of a space craft.

6.2 Rendering conditions

We evaluated three different simulated native panel contrasts: 1000:1, 4500:1, and native OLED (in which the black level is fully off). The 1000:1 and 4500:1 contrast conditions had three local dimming configurations each. Specifically, we tested 4500:1 contrast with 1, 60, and 180 zones, and 1000:1 contrast with 180, 540, and 1600 zones.

6.3 Experimental task

Experiment 4 had the same method as Experiments 1 and 2. That is, it used a forced-choice task between two different renderings of the same scene, and observers were instructed to report which image they preferred. The two renderings were shown side by side on the OLED display, with randomized left–right positioning.

For this experiment, two lamps were placed on either side of the HDR display as shown in Fig. 10. The lamps were placed to the side of the display such that their spectral reflection was not visible on the display; the lamps were a direct glare source for the eye and illuminated the front of the display similar to the HDR viewing setup of Rempel *et al.*[4] Each lamp shade was cylindrical and subtended an angular size from the eye of approximately 5° in the vertical and horizontal directions. The screen was situated approximately 1 m in front of the white-painted wall.

During half the experiment for each subject, the lamps were turned on, and during the other half, the lamps were turned off. Each lamp contained an LED bulb (2700 K, 1600 Lumens), and the luminance of the lamp shades averaged 500 nits.

When the lights were turned on, the illuminance at the display screen was 48 lux, and the background illuminance was approximately 60 lux. The measured luminance of the display screen when black was between 0.08 and 0.25 nits depending on the region of the screen measured and whether the observer was wearing dark or bright clothing. The illuminance at the observer position was 50 lux.

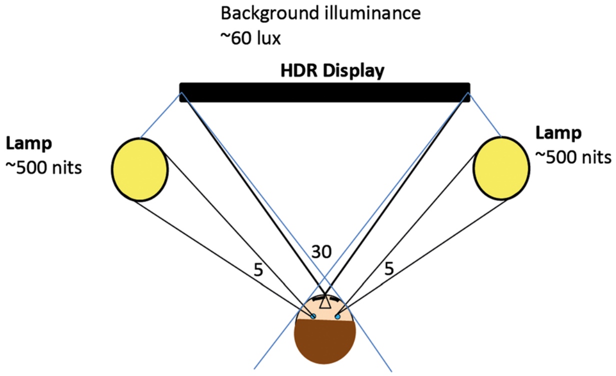

FIGURE 10 — Light position in Experiment 4.

6.4 Subjects

Eleven observers participated. Two of them were familiar with the experimental hypotheses and methods, while the remaining observers were naïve to the experimental design. Observer ages ranged from 23 to 52.

6.5 Results

Each of the seven renderings was compared with every other rendering of the same scene (a total of 21 comparisons per scene) with 8 scenes, for a total of 168 comparisons per session. Each observer completed a total of 4 sessions; two runs with the lights on, and two runs with the lights off. The ordering of the sessions was counterbalanced to control for potential order-effect bias.

For each scene, we computed the average preference ranking by calculating the fraction of times each rendering was favored over the six alternatives. The preference rankings averaged across observers are shown in Fig. 11. The lights-off conditions are shown as the solid lines and the dotted lines represent the lights-on conditions. The blue lines represent the 4500:1 contrast and the red lines represent the 1000:1 contrast. The "X" and "O" symbols represent the OLED display with lights-off and lights-on, respectively. Each panel shows the data for a different scene.

The results show a stronger preference for the higher contrast panel (4500:1) compared with the lower contrast panel (1000:1). This manifests itself as a strong difference in the 180 local dimming zones, which were tested at both contrast levels. Furthermore, the 60 local dimming zones for the 4500:1 contrast display was preferred in many cases to the 180 and 540 zone 1000:1 displays. As expected, native OLED was always ranked highest. It was not always selected with full reliability in the forced choice task.

The ambient lighting had minimal impact on viewing preference ranking. These trends are summarized in Fig. 12, which plots the data of Fig. 11 averaged across all scenes. If ambient light level had a stronger impact on image quality, we would have expected a compression of the ranking, with all conditions falling closer to 0.5 (a chance response level). The data reveal that this was not the case, and that there is close agreement in preference ranking with the lights on and off.

7 Discussion

These experiments sought to investigate the relative importance of native panel contrast and the number of local dimming zones on visual quality of HDR images. This research is particularly valuable now because the conventional measures for display contrast are increasingly becoming irrelevant. Displays with very different behaviors can achieve the same global contrast measurements but will have large differences in visual quality.

In particular, our results illustrate the importance of the native panel contrast. In many scenes, a 4500:1 panel with as few as 24 dimming zones can be perceptually superior to a 1000:1 panel with 150 local dimming zones. Additionally, LCDs using local dimming technology can attain image quality comparable with an OLED if there are enough local dimming zones such as 10,000 zones for a 1000:1 display or 1000 zones for a 4500:1 display.

Experiment 4 used a very different experimental method than Experiment 3 to examine how local dimming LC displays compare with OLED. Based on the result summary in Fig. 12,

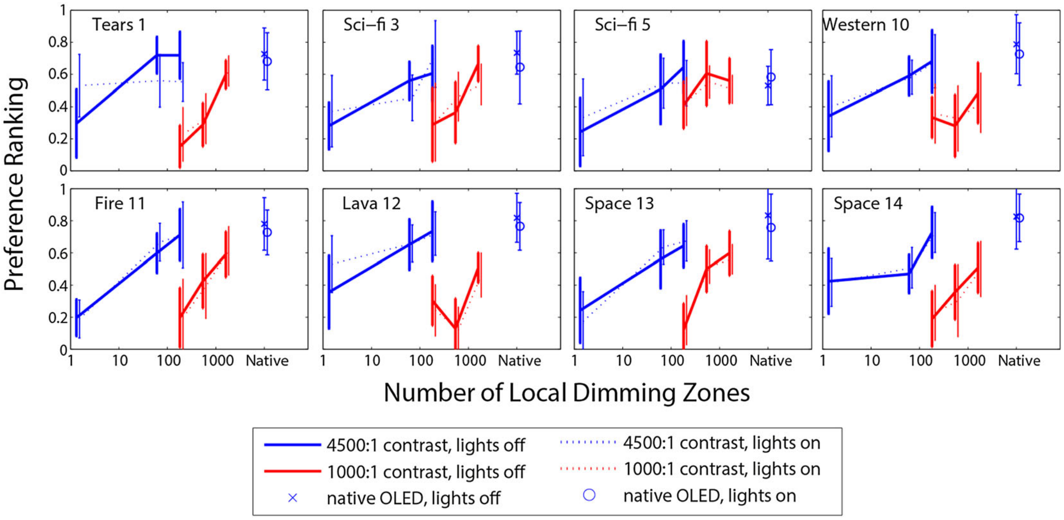

FIGURE 11 — Experiment 4 results. The preference ranking for 4500:1 contrast (blue lines) and 1000:1 contrast (red lines) with the lights off (solid lines) and lights on (dotted lines). The preference ranking for the native OLED is represented by the blue "X" for the lights off condition and the blue "O" for the lights on condition. Error bars represent the standard deviation of the observer rankings for each condition. The lights on and lights off data points have been horizontally offset for clarity.

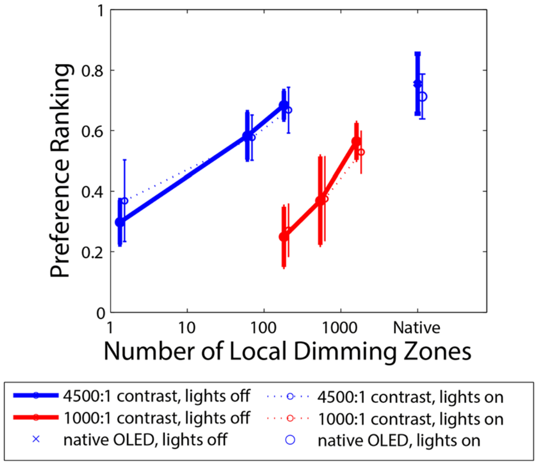

FIGURE 12 — Experiment 4 result summary. The data of Fig. 11 is shown averaged across scenes. The error bars represent the standard deviation of the four images tested. The lights on and off conditions are horizontally offset for clarity.

the OLED condition in the lights-off case has a preference ranking of ~0.75. This implies that there were a number of pair comparisons in which the LC emulation was selected as preferred over the OLED. In these situations, it is likely that the observer could not discriminate the OLED from a high zone count LC display. However, if we look at the error bars from individual images in Fig. 11, in five of the eight images (*Western 10*, *Fire 11*, *Lava 12*, *Space 13*, *and Space 14*), there were at least some observers who ranked the OLED at 1, indicating a consistent preference for the OLED condition. This level of difference is consistent with Experiment 3 that used a method of adjustment to ask observers how many local dimming zones are needed to reach equivalence with the OLED. Figure 9 illustrates that there can be large differences between the settings made by observers. Some observers are sensitive to small halos. There are also large differences depending on the content. Although Experiments 3 and 4 used different methods, content, and observers, the key results show good qualitative agreement. Based on Fig. 12, we would expect a high-contrast display to need about 100 zones, and a low contrast display to need more than 1600 zones to be comparable with OLED. The right panel of Fig. 8 indicates that a low contrast display needs nearly 1000 zones, and a high-contrast display needs over 100 zones to be comparable with OLED.

7.1 The role of local dimming algorithms and hardware

In this study, we used a heavily simplified model of a dual-modulation display based on rectangular blocks with Gaussian diffusion. We also used an LCD compensation algorithm that knows the exact light level behind each simulated pixel. In actual dual-modulation displays, each light source may consist of one or more LED emitters. There are diffusive layers above the emitters and reflective layers behind them. There may also be quantum dot films that introduce additional color dependent diffusion. Careful design of the diffusion properties can mitigate the halo visibility but may do so at the expense of being able to reproduce high spatial frequency contrast.

It is also important to not underestimate the importance of high quality local dimming algorithms. A commercial local dimming algorithm may condition the original image to control each dimming zone not by the maximum pixel level, but by a more representative pixel value. There has been excellent work by Korhonen and colleagues to identify the optimal tradeoff between high-quality blacks and clipping of highlights.[29,30] Some algorithms can also create the foot room needed to further hide halo artifacts by using additional emitters and strong diffusion layers. Some of these halo attenuation strategies lead to spatial nonlinearities; for example, as a small object increases in size, the object may also inadvertently increase in brightness as more zones are recruited. As a medium object grows to fill more of the screen, the brightness may inadvertently fall as the total system load grows. Also, as an object transitions from one zone to another, there are opportunities for flicker if there is a lack of coordination between the backlight and LC panel.

Knowing the optical properties of the backlight and having effective algorithms to compensate the LC panel can greatly reduce many of these artifacts. However, these algorithms can only improve the image quality when the desired brightness is within the localized working dynamic range of the display. When the image calls for a black level that is outside of this regionalized dynamic range, there is no way to compensate with algorithms. Only a higher-native-panel contrast can reduce the problems with this type of content.

7.2 Viewing distance and local dimming zones

In these experiments, we used a fixed viewing distance. What might we expect if the observer moved closer to the screen as has been proposed for ultra high definition (UHD)? Approaching the screen decreases the spatial frequencies of the local dimming halos. Thus, we would expect that many of the halo artifacts associated with the high density local dimming displays could be more prominent from a closer viewing distance.

7.3 Ambient lighting conditions and viewing preference

The results of Experiment 4 are somewhat counterintuitive. Turning on the lights reduces contrast in three ways.

1 There are specular reflections from the display surface.
2 There is general scatter and haze from scatter within the eye.
3 There is scatter from the display.

We sought to reduce the first source of reflections by keeping the lights far enough to the sides so that no specular lamp reflections reach the eye. There were some unavoidable reflections of the observer himself off the display. This type of reflection can have a highly position-dependent impact on local-image contrast. The second source of contrast attenuation is from the light the lamps shine directly into the eye. Although the position of the retinal image of the lamps does not coincide with the image from the display, scatter from the cornea and lens, as well as retinal scattering, will cause some stray light to decrease the retinal contrast of the HDR image. The third source of contrast reduction is that some of the light from the lamps that falls on the display surface will scatter and reduce the image contrast at the display. This impact is fairly minimal because the OLED display makes use of a contrast enhancement film that greatly attenuates non-spectral reflections.

We had expected that the reduction in retinal contrast from all three of these sources, but especially the second, would mitigate the visibility of the halo artifacts visible in dark regions. The experiment assessed artifact visibility only indirectly by asking observers to choose their preferred rendering, and the ambient lighting did not impact these choices. One reason for this finding is that the artifacts were generally above threshold, and observers were asked to choose which was less objectionable. The lighting environment we set up, which was designed to be consistent with evening TV viewing in the living room,[31] was not bright enough to push these artifacts below threshold, and the task remained a preference of impaired images.

Another hypothesis for these results is that although the contrast of the artifacts is reduced in the ambient lighting, the adaptation state of the observer is more appropriate for the image-light level. An elevated adaptation level from ambient lighting has been shown to be helpful in certain discrimination tasks on LCD displays.[28]

The results of this experiment show that the preference for high-contrast images and local dimming is fairly robust to the ambient light level. In a competitive evaluation environment between sets, we can expect that image-quality differences due to panel contrast and local dimming will remain visible.

7.4 Limitations of organic light-emitting diode emulation

In this research study, we have used an OLED display to emulate the visual image characteristics of a LCD display and backlight. This emulation has several important limitations.

7.4.1 Temporal differences of organic light-emitting diode and liquid crystal display

Liquid crystal panels can have slow switch times and can require tens of milliseconds to switch between gray levels, and may employ overdrive methods to accelerate these transition times. These liquid crystal switching times can manifest themselves as leading and trailing blur in the images. The ways in which these temporal switch attributes interact with backlight to create new image quality artifacts are beyond the scope of this research and are not considered in the emulation.

7.4.2 Organic light-emitting diode current limiting

Organic light-emitting diode displays will often limit the total current to the display and cannot support peak brightness over 100% of the screen area at once. The display used for these emulations had such a limitation, but this did not impact the experiments for several reasons. The panel loading for the content selected was low and did not trigger aggressive current limiting. Any current limiting that did occur was applied globally and would thus equally affect both of the images presented during a test.

7.4.3 Differences in organic light-emitting diode and liquid crystal display reflectance properties

The OLED display utilizes a circular polarizing contrast enhancement film to minimize surface reflection, and the pixel drive level has negligible impact on reflected light. For an LCD, linear polarizers form an integral component of the system and, as light valves, the pixel drive states can change reflected light properties. In our emulations, we did not attempt to reproduce the differences in reflected light that can occur with different pixel architectures and contrast enhancement films.[32]

7.5 Variety of content

In these experiments, we chose a collection of images that were weighted toward having dark regions. The goal in this selection was not to represent typical scene content, but rather to examine a common subset of real-world imagery that will greatly stress the capabilities of a display. With content that emphasized high average brightness, we would expect that there would be adequate foot room to avoid many of the local dimming artifacts that we observed, and there could be minimal effect of dimming zone spacing or the native panel contrast.

7.6 Measures of contrast

Part of the motivation for this testing was to expand the understanding for what measures of contrast are most important for visual quality. We have chosen for these measures the native panel contrast, which we can take as a proxy for local contrast, and the number of local dimming zones that correlates with the maximum spatial frequency of the global contrast. Additionally, there is contrast in the image content, and the retinal contrast that is influenced by the total light output of the display and ambient lighting.

The visual experience will be determined by a subset of these different contrasts that may even vary from scene to scene. Some of the existing metrics for display contrast such as ANSI 5×5 contrast or the corner-box measurement technique[33] may not correlate with the contrast measures most closely associated with visual quality. Indeed, many of the displays we emulated in the testing revealed a strong visual preference, but would have had similar corner-box contrast and even ANSI contrast.

We hope that future work follows on reconsidering which measures of location specific contrast, especially in real scenes, are effective in predicting the visual quality of display systems.

8 Conclusions

In these experiments, we evaluated the respective contribution of local dimming and native panel contrast on visual quality. Specifically, in Experiments 1, 2, and 4, we have shown that native panel contrast remains the strongest predictor of image quality, even in a system with local dimming. Indeed, the benefits of high contrast and local dimming are robust to ambient lighting. Thus, HDR displays that make use of high-contrast panels will have less objectionable haloing than ones making use of lower contrast panels, thereby providing a strong point of differentiation in the marketplace.

Additionally, our results illustrate that it is possible, although impractical, to achieve OLED-like image quality if there are enough local dimming zones. In particular, the findings from Experiment 3 reveal that high-native-panel contrast levels require fewer local dimming zones for image quality to be considered perceptually comparable with a native OLED. Overall, the results from these experiments have implications for what combination of display panel and backlight module will produce the best possible visual experience for HDR imagery.

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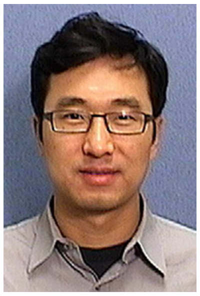

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