EG UK Theory and Practice of Computer Graphics (2012)
Hamish Carr and Silvester Czanner (Editors)

Physical and perceptual limitations of a projector-based high dynamic range display

Robert Wanat, Josselin Petit and Rafal Mantiuk[1]

[1] School of Computer Science, Bangor University, United Kingdom

Abstract

High dynamic range (HDR) displays capable of reproducing scenes of high luminance (exceeding 2,000 cd/m^2) and contrast (more than 10,000:1) are a useful tool for research on visual performace, image quality or colour appearance. In this paper we describe a projector-based HDR display, giving details on its hardware components and software for driving and calibrating the display. We report the colorimetric properties of the display: the colour reproduction accuracy, colour gamut and local contrast dependent on the size of displayed checkerboard pattern. To verify whether our display can produce local contrast inducing the colour that appears perfectly black to the observer, we conducted an experiment with human observers. Our results indicate that for the test pattern, the effective local contrast of our display (2500:1) is sufficient to produce perfectly black colour, which requires a contrast between 1300:1 and 2400:1.

Categories and Subject Descriptors (according to ACM CCS): I.4.0 [Computer Graphics]: Image processing and computer vision—Image displays/Image processing software

1. Introduction

The improvements in the quality of digital photography, made possible by the introduction of more sensitive image sensors, pushed the boundaries of how real life scenes can be captured and reproduced. Nevertheless, the luminance range that a camera sensor can capture is still one of the limiting factors of currently existing technology. Multi-exposure high dynamic range imaging techniques, as described in [DM97], aim at providing a solution to this problem. This method combines several images of different exposures to form one image with a much higher ratio between the peak luminance and the lowest luminance than any of the images it was composed of. Such ratio became known as the dynamic range.

The introduction of the methods of acquiring high dynamic range (HDR) images revealed a major limitation of the existing imaging pipeline: the display devices were unable to show the full luminance range perceivable by the human eye. Typical LCD displays on the market can produce between 2 and 3 orders of magnitude of luminance with peak luminance rarely exceeding 500 cd/m^2. Thus, in order to visualise HDR images, their dynamic range had to be compressed to match that of the display by using one of the tone mapping alogrithms. This results in a loss of quality, usually in the form of reduced contrast, colour shift or introduction of halos, depending on the tone mapping operator (TMO) used [ČWNA08].

In 2003, Seetzen et al. demonstrated in [SHS*04] a method of creating an HDR display by combining two light modulation devices of low dynamic range. This approach allowed for extending the dynamic range of the resulting display and, as a result, reproduction of HDR images with much higher fidelity than what was available on existing output devices. Their original design gained much popularity, owing much to the simplicity, and has been introduced to the mass-produced displays under the name of local dimming.

In this paper, we describe an HDR display built for research purposes that follows the principle presented by Seetzen et al. We measure the limitations of such a display from both physical and perceptual standpoint. This allows to not only determine how the display differs from commercially available displays. Finally, we describe an experiment designed to answer the question what is the minimum required local contrast for our display, so that any further increase will not be perceived by an average observer.

The main contributions in this paper are as follows:

- description of a custom-built projector-based HDR display and its components,
- description of the software driver that is responsible for rendering on the HDR display,
- physical evaluation of the capabilities of such display,
- an experimental measurement of what an ideal dynamic range should be for an HDR display.

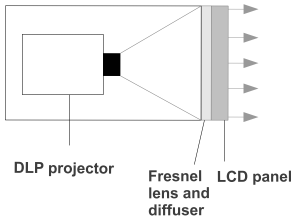
2. Related work

2.1. First HDR displays

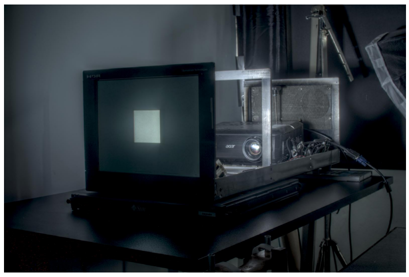
One of the first HDR displays was constructed by Seetzen et al. and described in [SHS*04]. To produce an HDR display using existing technology, the authors used the observation that LCD panels modulate light in a multiplicative manner. Thus, if such panel is connected serially to the output of an another device that produces modulated light, then the effective dynamic range of the image created is going to be a product of dynamic ranges of both modulators. Seetzen et al. demonstrated two combinations of LDR devices that can be used for creating an HDR display. The first approach employed a digital light processing (DLP) projector producing a modulated backlight that later falls on the back of an LCD panel. In the second design, a hexagonal matrix of individually controlled white light emitting diodes (LEDs) is used to produce the backlight for the LCD panel.

The technology was further developed by a university spin-off company SunnyBrook Technologies (later known as Brightside). The company built a small quantity of displays, mostly for the purpose of research and advancing the technology. Their two most well-known displays were the LED-based DR37-P and a projector-based SBT1.3. The SBT1.3 model used an Optoma DLP EzPro737 digital mirror projector aligned with and providing backlight for a 15" XGA Sharp LQ150X1DG0 LCD panel, which was connected to an EarthVision AD2 LCD controller. The light from the projector passes through a Fresnel lens, which collimates it, and through a diffuser which inhibits the formation of Moiré patterns, before finally falling on the LCD panel. This design achieves a contrast of $54,000:1$ and a peak luminance of 2,700 cd/m^2. A more in-depth description of the display can be found in [SHS*04]. A schematic representation of the display is presented in Figure 1. The DR37-P model used $1,395$ controlled LEDs to provide a backlight for a 37" LCD display with a resolution of 1920x1080, with an effective contrast of $200,000:1$. The display is no longer in production but its specifications can still be found in [Bri].

In 2007 the company was bought by Dolby Laboratories and the production of the above mentioned HDR display models was stopped. Instead, Dolby Laboratories offers a patent portfolio for companies interested in producing their own HDR displays. The technology is branded as Dolby Vision. The displays created by Brightside Technologies can still be found in various research laboratories.



(a)



(b)

Figure 1: *A schematic representation of a projector-based HDR display (a) and a tone-mapped HDR photograph of the display (b).*

In 2009 an Italian company, Sim2, released a series of displays using the Dolby Vision technology. The HDR47 series is currently the only off-the-shelf HDR display. The HDR47E S 4K model uses $2,202$ controlled LEDs to create backlight for a 47" LCD panel, providing the resulting display with a peak luminance of 4000 cd/m^2. The display has a theoretically infinite contrast, as the individual LEDs provide no light when turned off thus reducing the minimum luminance to 0 cd/m^2. To compare it with other existing displays the producers provide the contrast with the next-to-black luminance, which still falls above $1,000,000:1$. A more detailed description of an HDR47 series display can be found on the website of its producer [Sim].

2.2. Custom-built displays

Given a limited number of commercially available displays, university laboratories started building their own displays, mostly based on the projector-based design. One of such displays was created by Ferwerda and Luka at Munsell Color Science Laboratory and presented in [FL09]. Their approach uses a tiled array of DLP projectors (only 2 DLPs were used in the display created by authors but the display algorithm was designed to accomodate for a larger number of projectors) providing backlight for a 30" Apple LCD panel with a top resolution of 2560x1600 pixels. Using multiple low-resolution projectors helped reduce the cost of creating the display, as it is cheaper to buy two projectors with lower resolutions than one that matches the resolution of the LCD panel. One of the drawbacks of the presented display is its lower peak luminance when compared with previous designs, only 760 cd/m^2, which is still better than an average LCD display available on the market. The dynamic range of the display was reported to equal $41,500:1$. The advantage of this display is its large resolution achieved with low-cost components.

A different design was proposed by Bimber and Iwai in [BI08] and later improved by Zhang and Ferwerda in [ZF10]. The main goal was to create an HDR display that would require virtually no engineering abilities or specialised equipment to implement, which could be used by vision researchers to conduct experiments on the human visual system. To achieve this intent, the display is composed of a projector and a print. The original HDR image is separated into two, one of the images is printed while the other is sent to the projector. When both the images are aligned, what the observer sees is the multiplication of both the projector image and what was reflected/suppressed by the ink on the printed image, thus extending the dynamic range of the result. Zhang and Ferwerda report in [ZF10] that their display has a peak luminance of ~2000 cd/m^2 and a dynamic range of $\sim 20,000:1$. The main limitation of this design is the fact that it can only show static images, unless a controllable reflective surface display, such as E-Ink, is used instead of a print.

The final display described in this section was developed by Guarnieri et al. and described in [GAR08]. Instead of using two different devices for light modulation, the luminance produced by a backlight unit is passed through two stacked, identical LCD panels. When the panels are aligned, then the light modulated by the first panel, called the "backpanel", forms the input of the second panel, known as the "frontpanel". Due to the HDR display being designed for medical purposes, both LCD panels have no colour filters and can only produce greyscale images. The use of symmetric modulation devices simplifies the display algorithm, as only one image has to be produced and sent to both displays, rather than calculating two images that use separate display models for non-symmetric modulators. The display was described as having a peak luminance of 500 cd/m^2 and a dynamic range of $50,000:1$.

2.3. Image decomposition methods

All HDR displays operate on a similar premise, that the image created by the first modulator is then multiplied by the image on the second modulator. Assuming both modulators have a low dynamic range, to display an HDR image it needs to be decomposed into two LDR images that, when multiplied by each other, create the original image. Over the years several algorithms have been developed for that purpose.

The first approach to the problem of HDR image decomposition was described by Seetzen et al. in [SHS*04]. Their algorithm uses the simplest decomposition of the HDR image, by taking its square root. To simplify the decomposition, the projector is assumed to produce a greyscale image and the colour is added by the LCD. After the square root image is derived from the original image, it is passed through the inverse display model of the DLP projector at which point the projector image is ready. Because the projector image passes through a diffuser, the image that is sent to the LCD needs to compensate for that. This is achieved by simulating in the software the image produced by the DLP and dividing the original image by the result. The resulting image is then passed through the inverse display model of the LCD panel, at which point the image decomposition is finished. The schematic diagram of the algorithm can be seen in Figure 2. A similar algorithm was also proposed for an LED

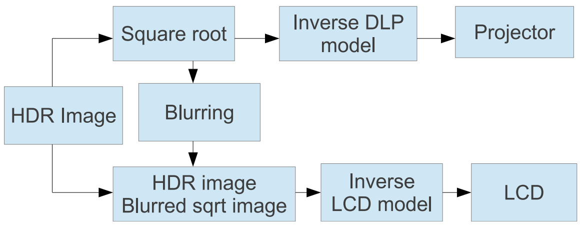


Figure 2: *A schematic representation of the decomposition algorithm presented by Seetzen et al. in [SHS*04].*

based display, which follows the same principal idea, but takes into account the difference in the backlight structure.

One of the problems with the approach by Seetzen et al. is the fact that using the projector only to provide greyscale image can severely limit the colour gamut of the display. This problem was addressed by Luka and Ferwerda in [LF09]. Their idea was to find a plane in the normalised CIE XYZ colorspace containing the desired colour, a maximum white and a minimum black. The luminance of the backlight for a specified pixel is then calculated using a new model, which retains the functionality of the square root model near the neutral axis of the plane, while becoming progressively linear close to the limits of the gamut.

2.4. Brightness perception in HDR displays

The perception of brightness in HDR displays was analysed in-depth in a study by Allred et al. described in [ARGB12]. The authors measured how the perceived brightness of a greyscale patch changes depending on its surround. The stimulus was positioned in the middle of a checkerboard pattern with randomly assigned luminance per each tile. It was observed that the perception of brightness shifted with the changes of overall checkerboard luminance; the lower the surround luminance the brighter the patch appeared to the observers and the opposite was also true. This is consistent with the previous findings in the research on perception, where the effect became known as simultaneous contrast.

In [MDK10] the deepest black perceivable on an HDR display was measured. Each observer was presented with two dark patches placed next to each other in random order on a uniform bright background. One patch was the reference representing the lowest luminance achievable on the display and the other was the currently tested threshold value. Both patches were covered by a neutral density (ND) filter with 2.0 index reducing their luminance 100 times, which allowed to display luminances much lower than what could normally be achieved on a BrightSide DR37 HDR display used in the study. The goal of the observers was to choose the brighter patch until they were unable to do so, in which case they were asked to choose randomly. The results showed that with high surround luminance a contrast of 900:1 is enough to produce a black level deep enough for an average observer not to be able to see a difference between it and any darker value. Their results were further expanded upon in [KR10] where Kunkel and Reinhard measured the top distinguishable contrast of the human visual system to be in the range of 3.7 log-10 units.

3. Bangor HDR display

3.1. Hardware setup

The HDR display at Bangor University is a retrofitted version of a display similar to SBT1.3 model introduced by Seetzen et al. in [SHS*04] and described in section 2.1. It uses the same Sharp 15" colour LCD model LQ150X1DG0, but we replaced the originally mounted DLP projector with Acer model P5290. The main advantage of the new projector is a much higher peak brightness, 4000 ANSI lumens, as compared to 1100 ANSI lumens produced by EzPro735 used in the original design. This, in turn, allowed us to retain the colour wheel of the DLP, which is used to change the colour of the light it projects, but lowers its peak brightness. The importance of keeping the colour wheel in the projector will be further explained in section 4.1. Apart from a higher brightness, the new projector has also a much higher contrast (3700:1, as opposed to 500:1 offered by the Optoma DLP) and a greater focal range adjustment, allowing to focus the image on the back of the LCD panel and thus reduce the amount of blur.

3.2. Display controller

The software created to control Bangor HDR display can be separated into two parts: the calibration software and the display driver.

Calibration software The calibration of the display is composed of two major blocks, geometric calibration and colorimetric calibration. Both stages are almost fully automatic and require little input from the user. In the geometric calibration part, a Canon Rebel XS digital SLR camera is used to calculate the transformation that aligns the backlight with the LCD screen, while also measuring the PSF of the DLP as well as the DLP non-uniformity image. Such image is then used to compensate for the projector luminance non-uniformity during rendering. The effect of vignetting on the photographs was measured beforehand to remove its influence on the result.

Initially, image alignment between the LCD and DLP projector was achieved by finding a projective transformation of DLP image corners. This proved to be insufficient, as the DLP projector introduced a non-linear deformation that could not be compensated by the projective transformation. This is why in the final algorithm the image is rendered on a freely deformable grid mesh, with the position of each vertex transformed using the projective transformation and then translated individually to overlap with the LCD. The translations of the vertices are calculated during the calibration procedure.

The colourimetric calibration was done using a spectrometer (JETI Specbos 1211). Because the DLP produces greyscale image, its calibration consists in measuring a 1D look-up table describing the function mapping pixel values to luminance. For the LCD, a more complex model needs to be fitted, as it is responsible for adding colour to the resulting image. The gain-offset-gamma (GOG) model [DTB04] was used to characterise the LCD panel.

Display driver The image passed to the driver is assumed to be represented in the RGB colour space with the sRGB primaries. Any value below or above the range supported by the display is clamped. The software driver uses Matlab with Psychophysics Toolbox [KBP07] for rendering. To increase the performance of the driver, all image processing is conducted in OpenGL with shaders programmed in GLSL.

An important problem with HDR displays is the existence of the parallax effect, as explained by Guarnieri in [GAR08]. If the DLP projector is properly focused on the LCD panel, then the image looks sharp when viewed directly from the front. As the angle at which an observer looks at the screen becomes wider, the image rapidly becomes increasingly blurry. This can be countered by defocusing the DLP projector, but the blur introduced by the projector optics is asymmetric and difficult to simulate efficiently. This is why we introduced a possibility to increase the backlight blurring factor in the software, which is then compensated for by the LCD, similarly to the approach presented by Guarnieri in [GAR08]. The trade-off for this approach is the increased computational complexity, which is, however, still lower than what would be necessary to properly model the blur available from defocusing the DLP.

4. Measured limitations of the display

4.1. Colour gamut

We measure the colour gamut of our display to determine how it compares with other displays. The measured gamut can be seen in Figure 3. It should be noted that when the achromatic (ie. providing greyscale image only, with colour added only by the LCD panel) backlight is used, the gamut of the display is much smaller than the sRGB gamut, which is supposed to represent the colour gamut of a typical display available on the market. This is caused by the fact that our backlight was not selected specifically for the LCD panel we use. We decided to determine if it would be beneficial to use a chromatic backlight instead of achromatic. We measured the gamut, but for each primary colour on the LCD, the DLP was set to the corresponding colour. The result, which is also presented in Figure 3, shows that the colour gamut can be extended to be similar to the sRGB gamut if the chromatic backlight is used. This requires a more complicated decomposition algorithm than the one we use, because each colour can be represented as multiple combinations of LCD and DLP values and some of them can not be produced by either of the devices. This is also the reason why we decided to retain the colour wheel of our DLP, as it might help us extend the colour gamut of the display in the future.

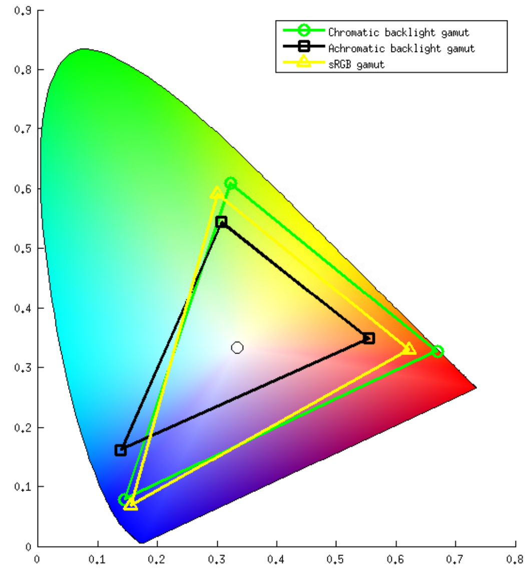


Figure 3: *Comparison of our current colour gamut with the sRGB gamut and a theoretically achievable gamut if a chromatic backlight is used. The underlying colour gamut represents the full range of colours visible to humans as defined by the CIE 1931 standard.*

4.2. Colour reproduction

We determine the quality of the colour reproduction of our display model. This is achieved by comparing the colour measured with the photospectrometer with the target colour sent to the display driver. A set of random colours is first chosen in the sRGB colour space and then converted to the CIE XYZ colour space to be used as the reference. The colours outside of the display colour gamut are removed. The remaining sRGB colours are passed through our display driver and shown on the LCD panel with a constant, measured backlight. The results of the comparison can be seen in Figures 4 and 5. It can be seen that the luminance is rendered almost perfectly at higher values, whereas at lower luminances this rendition is less accurate. The chromatic error is spread randomly across the gamut indicating there is no systematic error in our model.

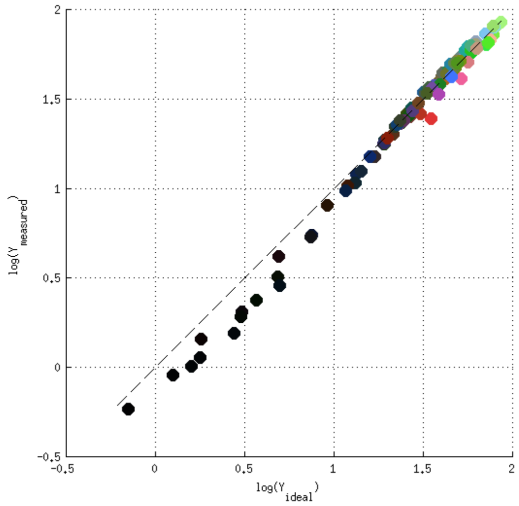


Figure 4: *The expected and measured luminance of our display in $log_{10}(cd/m^2)$.*

To determine the perceptual quality of the colour reproduction of our display we compared the ideal and measured colours using the CIEDE2000 metric. With over a 100 random colours tested, we achieved a mean value of CIEDE2000 equal to 4.3.

4.3. Display contrast

Next, we measure the contrast of our display. There are two popular methods of measuring contrast: the full on/full off measurement and the ANSI measurement. In the first method, the luminance is measured when the whole screen is set to the brightest white, then to the darkest black and

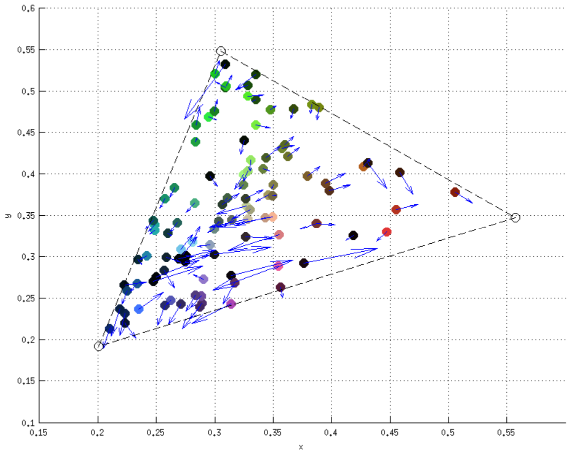


Figure 5: *The chromatic error of our display model in the CIE xyY space. The dashed line indicates the measured colour gamut of the display, the coloured points indicate the expected sRGB colour and the arrows point to the chromaticity of the colour measured.*

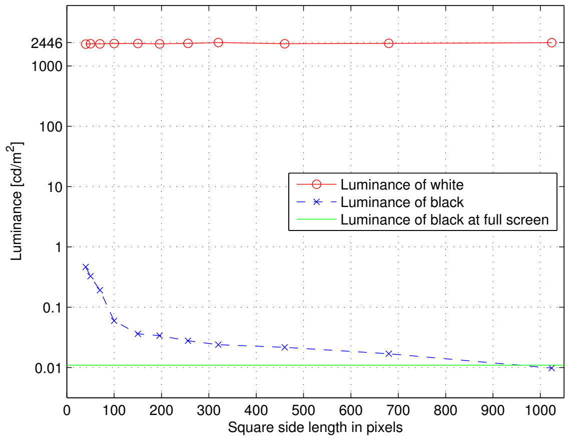


Figure 6: *The luminance of white and black tiles of the checkerboard depending on the tile size in pixels.*

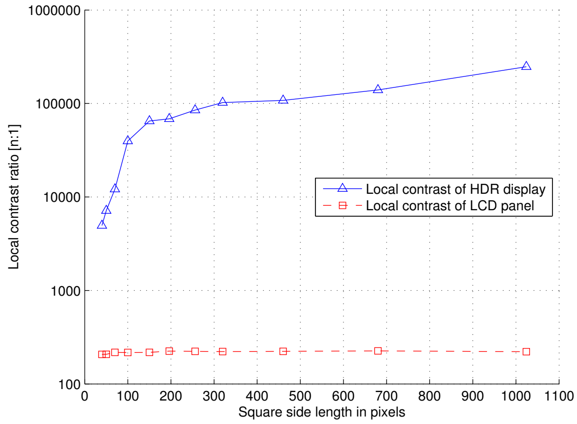


Figure 7: *The local contrast of our HDR display versus the size of the checkerboard pattern displayed. The dashed line represents the same contrast measured for the LCD panel of our display.*

the results are divided by each other. The second approach takes into account that when actual images are displayed, some light from the bright areas may increase the brightness of dark areas. Thus, to measure the ANSI contrast, a rectangular checkerboard with 4x4 tiles is displayed on the screen and the luminance is measured in the middle of any white and in the middle of any black tile. This results in a measurement that is much more applicable to real life situations. The ANSI contrast tends to be lower than the full on/off contrast.

In this paper, we took an approach that provides more information about the true contrast than the ANSI measurement. ANSI contrast was created to measure the contrast of displays with uniform backlight, whose properties do not change much depending on the size of the pattern displayed. Because our backlight is provided by a projector and is passed through a diffuser before falling on the back of the screen, the problem of the light bleeding from light to dark areas is much more pronounced and varied depending on the size of pattern displayed. For this reason, our measurements included a wider range of checkerboard tile sizes, from the size that covers the full screen with a single tile to the smallest area our spectometer could cover, which amounts to 40 pixels. The results of our measurements can be seen in Figures 6 and 7. As expected, the luminance at white squares is almost independent of the tile size in pixels. The luminance of black, however, changes substantially depending on the pattern displayed. This limits the available dynamic range from 5.4 orders of magnitude (17.9 f-stops, $251,190:1$) in the full on/full off mode to 3.7 orders of magnitude (12.3 f-stops, $5,012:1$) when a very fine pattern is being shown. We also compare these results with the local contrast offered by the LCD panel used in our HDR display. This is achieved by conducting identical measurements when the DLP provides a constant, uniform backlight. The results are presented for comparison in Figure 7.

To measure the perceptual contrast limitations of our display, we transform the physical contrast to the number of Just Noticeable Differences (JNDs). JNDs indicate the smallest luminance increments that an average observer can detect. The same method was used to evaluate the limitations of the original display by Seetzen et al. [SHS*04]. We calculate the number of JNDs offered by our display using the DICOM standard function, which is based on Barten's CSF model [Bar93]. In [SHS*04], Seetzen et al. reported their display to be able to reproduce 962 JND steps in full on/full off mode. For our display, the amount of JNDs ranged from 893 for the smallest pattern size to 945 in the full on/full off mode.

It should be noted that the measured luminance was achieved with the backlight from the projector at its peak resolution. It was mentioned in section 3.2 that this introduces the unwanted parallax effect. It can be counteracted by blurring the backlight, but by doing so we also decrease the local contrast of our display. Thus, we can increase the viewing angle at which the image looks sharp on the display at the cost of reducing the local contrast. This trade-off leads to an important question: what dynamic range should our HDR display offer until a further increase can no longer be perceived by the observer.

5. Deepest black experiment

We conducted an experiment to find the smallest local contrast that can produce the black indistinguishable from the deepest black. The results will determine whether the physical contrast of the HDR display can match the highest contrast the eye can see.

5.1. Stimuli

The stimulus consisted of two black disks of the 64 mm diameter shown on the brightest surround achievable on our HDR display. The schematics of the stimulus is shown in Figure 8 . The measured luminance of the surround was 2340 cd/m^2 and the luminance of the reference disk was 0.024 cd/m^2. This gave the physical contrast of 4.99 log-10 units or 16.6 f-stops. To achieve such high contrast, the disks were covered by Kodak Wratten 2.0 neutral density filters (75 × 75 mm), which reduced the luminance of the areas underneath 100 times. The transmission of both filters was measured before the experiment to verify the correctness of their ND value. The filters were encased in frames and attached to the display. The distance between the disks was 76mm.

5.2. Participants

Five volunteers aged between 24 and 42 participated in the experiment. All of them had normal or corrected to normal vision. Apart from one participant (the author), all observers were naïve about the purpose of the experiment.

5.3. Experimental procedure

Every participant made a single measurement at each of the three viewing distances used in this study: 1m, 1.5m and 2m, which translates to the angular size of the disk of roughly 1.83°, 1.22° and 0.91°, respectively. A chin rest was used to ensure an accurate viewing distance. At each distance, the participants were presented with two disks: a reference disk of the lowest luminance our display setup could produce; and a test disk of adjustable luminance. The task was to choose the brighter of the two patches. If a participant could not see any difference, she was encouraged to make the best guess. After each selection, the luminance of the test disk was adjusted using the QUEST algorithm [WP83]. After 35 trials, the threshold value was established as the value at which the participant could answer correctly 75% of the time. The 75% correct rate was chosen as the middle ground between a random guess of 50% and the full positive rate of 100%. To ensure the correctness of the result, the luminance of the test disk was verified with a spectrometer after the experiment was finished with the ND filters removed.

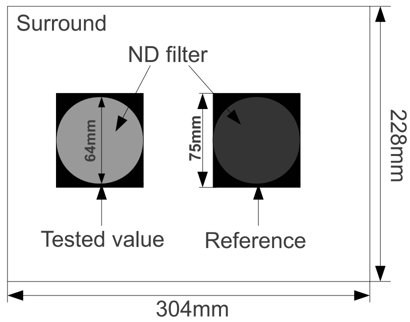


Figure 8: *Schematics of the stimuli used for the deepest black experiment.*

5.4. Results

The results of the experiment, shown in Figure 9, indicate that the luminance indistinguishable from the deepest dark ranges from 1.81 cd/m^2 for the patch of 0.91°, to 0.98 cd/m^2 for the patch of 1.83°. Given the background luminance of 2340 cd/m^2, the highest perceivable contrast is equal to 3.11 log-10 units (≈1300:1) and 3.38 log-10 units (≈2400:1) respectively, which is much lower than the contrast of the reference patch: 4.99 log-10 units (≈100,000:1). These results are in the range of values reported for the luminance of black in [MDK10]. However, it is difficult to compare both studies as the highest luminance used in their measurements was 1000 cd/m^2.

Figure 9 shows the highest luminance the observers perceive as perfectly black found in our experiment. Such luminance is higher than the black level of the display for the same image as used in the experiment. This indicates that for the given size of the disk, our display is capable of reproducing luminance low enough to appear as perfectly black to observers. The display black level is likely to rise for smaller disk sizes (refer to Figure 6), but this will be accompanied by

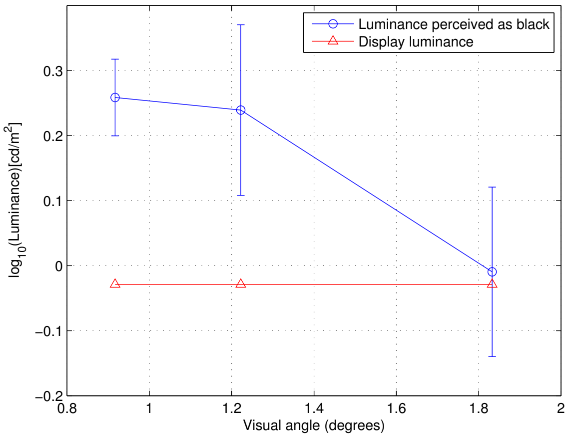


Figure 9: *The results of the experiment, shown as blue lines with error bars, indicate the highest luminance the participants could not distinguish from the lowest luminance we could achieve in our laboratory conditions (0.024 cd/m^2). The red markers indicate the measured black level of our display for the same pattern as used in the experiment but with the ND filter removed.*

the raise of luminance perceived as perfectly black because of smaller angular size of the disk. However, more experiments are needed to determine how the threshold changes with further changes of angular size as well as the luminance of surround.

6. Conclusions

In this paper we described a retrofitted HDR display along with the typical problems that can be encountered when building a projector-based HDR display. We also described the limitations of such display, both from the physical and perceptual standpoints, including an in-depth contrast measurement that is more suitable to describe the properties of an HDR display than currently existing methods. Finally, we conducted a new experiment to determine what the ideal dynamic range of our display should be, given the capability to distinguish between two very dark luminance levels of an average observer. The result of the experiment show that our display is capable of displaying luminance necessary to produce a patch perceived as perfectly black for the tested conditions.

References

[ARGB12] ALLRED S. R., RADONJIĂĞ A., GILCHRIST A. L., BRAINARD D. H.: Lightness perception in high dynamic range images: Local and remote luminance effects. *Journal of Vision 12*, 2 (2012). 3

[Bar93] BARTEN P. G. J.: Spatiotemporal model for the contrast sensitivity of the human eye and its temporal aspects. Allebach J. P., Rogowitz B. E., (Eds.), vol. 1913, SPIE, pp. 2–14. 7

[BI08] BIMBER O., IWAI D.: Superimposing dynamic range. In *ACM SIGGRAPH Asia 2008 papers* (2008), SIGGRAPH Asia '08, ACM, pp. 150:1–150:8. 3

[Bri] BRIGHTSIDE TECHNOLOGIES: DR37-P preliminary specifications. Downloaded from `web.archive.org/web/20070116130447/http://www.brightsidetech.com/products/info/dr37p_specs.pdf` on 01.05.2012. 2

[ČWNA08] ČADÍK M., WIMMER M., NEUMANN L., ARTUSI A.: Evaluation of HDR tone mapping methods using essential perceptual attributes. *"Computers & Graphics" 32* (2008), 330–349. 1

[DM97] DEBEVEC P. E., MALIK J.: Recovering high dynamic range radiance maps from photographs. In *Proceedings of the 24th annual conference on Computer graphics and interactive techniques* (1997), SIGGRAPH '97, ACM Press/Addison-Wesley Publishing Co., pp. 369–378. 1

[DTB04] DAY E. A., TAPLIN L., BERNS R. S.: Colorimetric characterization of a computer-controlled liquid crystal display. *Color Research & Application 29*, 5 (2004), 365–373. 4

[FL09] FERWERDA J., LUKA S.: A high resolution, high dynamic range display for vision research. *Journal of Vision 9*, 8 (2009), 346. 2

[GAR08] GUARNIERI G., ALBANI L., RAMPONI G.: Image-splitting techniques for a dual-layer high dynamic range lcd display. *Journal of Electronic Imaging 17*, 4 (2008). 3, 4

[KBP07] KLEINER M., BRAINARD D., PELLI D.: What's new in Psychtoolbox-3? vol. 36, Pion Ltd. 4

[KR10] KUNKEL T., REINHARD E.: A reassessment of the simultaneous dynamic range of the human visual system. In *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization* (July 2010), ACM New York, NY, USA, pp. 17–24. 4

[LF09] LUKA S., FERWERDA J. A.: P-55: Colorimetric image splitting for high-dynamic-range displays. *SID Symposium Digest of Technical Papers 40*, 1 (2009), 1298–1301. 3

[MDK10] MANTIUK R., DALY S., KEROFSKY L.: The luminance of pure black: exploring the effect of surround in the context of electronic displays. Rogowitz B. E., Pappas T. N., (Eds.), vol. 7527, SPIE, p. 75270W. 4, 7

[SHS*04] SEETZEN H., HEIDRICH W., STUERZLINGER W., WARD G., WHITEHEAD L., TRENTACOSTE M., GHOSH A., VOROZCOVS A.: High dynamic range display systems. In *ACM SIGGRAPH 2004 Papers* (2004), SIGGRAPH '04, ACM, pp. 760–768. 1, 2, 3, 4, 6, 7

[Sim] SIM2: HDR47E S 4K technical specifications. Found on `http://www.sim2.com/HDR/hdrdisplay/hdr47e_s_4k` on 01.05.2012. 2

[WP83] WATSON A., PELLI D.: Quest: A Bayesian adaptive psychometric method. *Attention, Perception, & Psychophysics 33* (1983), 113–120. 7

[ZF10] ZHANG D., FERWERDA J.: A low-cost, color-calibrated reflective high dynamic range display. *Journal of Vision 10*, 7 (2010), 397. 3