SPATIAL COMPARISONS:
THE ANTIDOTE TO VEILING GLARE LIMITATIONS IN IMAGE CAPTURE AND DISPLAY

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ABSTRACT

Many labs are studying High Dynamic Range (HDR) image capture and display. This paper describes the long history of HDR imaging from Renaissance paintings to modern digital imaging. Then it as reviews experiments that measure camera and human responses to calibrated HDR test targets. It describes tests showing that image dynamic range is limited by the camera's and the eye's veiling glare, testing its physical limits and evaluating the role of accurate reproduction of luminance in imaging. Glare is an uncontrolled spread of an image-dependent fraction of scene luminance caused by unwanted scattered light in the camera and in the eye. The paper discusses why HDR is better than conventional imaging, despite the fact the reproduction of luminance is inaccurate.

1. INTRODUCTION

High Dynamic Range (HDR) images capture wide ranges of scene luminances and render that information for human observation. Usually the high scene range is a result of non-uniform illumination, such as sun/shade or night scenes in artificial light. Renaissance artists rendered HDR scenes in the low range available in paintings. Both photographers and digital imaging algorithms followed the painters' spatial rendering techniques. Recently, multiple exposure techniques have been combined with LED/LCD displays that attempt to accurately reproduce scene luminances. However, veiling glare is a physical limit to HDR image acquisition and display. We performed camera calibration experiments using a single test target with 40 luminance patches covering a luminance range of 18,619:1. Veiling glare is a scene-dependent physical limit of the camera and the lens. [1,2] Multiple exposures cannot accurately reconstruct scene luminances beyond the veiling glare limit. Human observer experiments, using the same targets, showed that image-dependent intraocular scatter changes the identical display luminances into different retinal luminances. Vision's contrast mechanism further distorts any correlation of scene luminance and appearance.

There must be reasons, other than accurate luminance, that explains the improvement in HDR images. The multiple exposure technique significantly improves digital quantization. The improved quantization allows displays to present better spatial information to humans. When human vision looks at high-dynamic range displays, it processes scenes using spatial comparisons.

2. HISTORY OF HDR IMAGING

Pre-renaissance paintings render people and scenes in uniform illumination. Leonardo da Vinci is credited with the introduction of chiaroscuro, the painting of light and dark. [3] His portraits of Benois Madonna, (1478 AD) and Lady with an Ermine, (1483-1490) capture the illumination as well as the figures. One sees that the illumination comes from a particular direction and there are highlights and shadows. Caravaggio's paintings, such as *The Musicians*, (1595-6), portray people and illumination with equal importance. In turn Caravaggio influenced several Dutch painter, among them Gerrit van Honthorst (Figure 1).

Figure 1 shows van Honthorst's 1620 painting "The Childhood of Christ". The boy holding the candle has the lightest face. The father, further from the light, is darker. The other children, progressively further from the light are proportionally darker.

Rembrandt's, *Night Watch*, (1642) is an almost life size painting (363x437 cm) of a military company receiving orders to march. It is known for its effective use of light and shadow, and perceived motion. All these painting are just of few examples of capturing an HDR scene and rendering it in low-range reflective paint.

With the growth of photography in the mid 19th century HDR scene presented a severe problem for existing films. Multiple exposure techniques for rendering (HDR) scenes go back to the earliest days of negative–positive photography. H.P. Robinson's 1858 composite print "Fading Away" was made using five differently exposed negatives. [4] This dramatic still life was staged using actors.

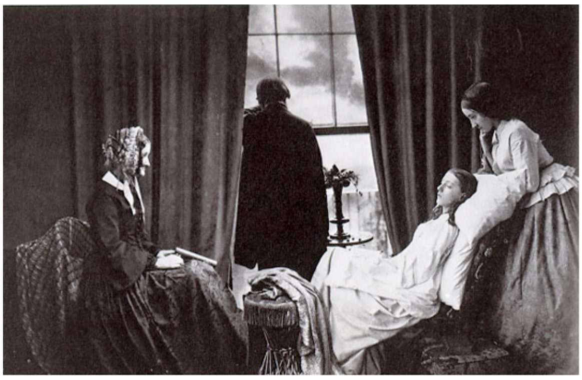

Figure 2 shows H.P. Robinson's 1858 photographic print "Fading Away" made from 5 combined negatives.

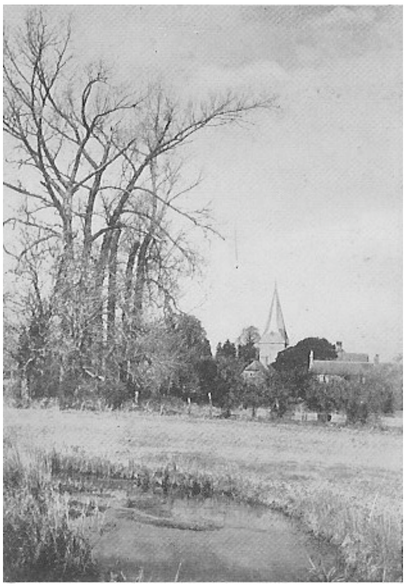

Figure 3 shows Mees's combined enlargement from two negatives.

Mees's "The Fundamentals of Photography", 1920, shows an example of a print made with multiple negatives with different exposures. [5]

Over the years the science of silver-halide imaging improved rapidly. Mees's long career (1890-1956) studying photographic sensitometry at University College London and Kodak established standards for high-dynamic range image capture on the negative, and high-slope rendering on prints. [6] Ansel Adams's zone system established three sets of procedures: first, for measuring scene radiances; second, for controlling negative exposure to capture the entire scene range, and third, spatial control of exposure to render the high-range negative into the low-range print. [7]

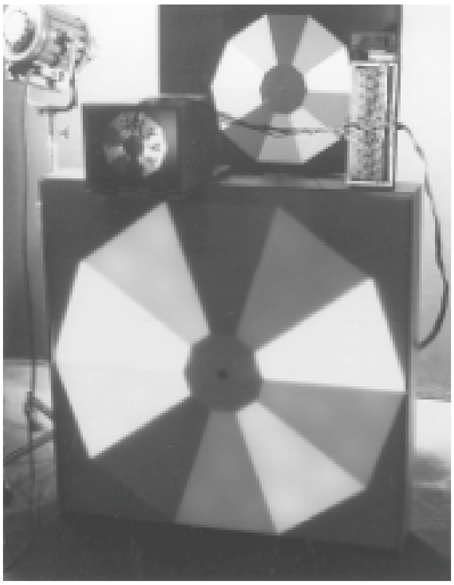

Figure 4 shows Land's Retinex analog image processing demonstration, using spatial comparisons.

In 1968, Land demonstrated the first electronic (analog) HDR rendering in his Ives Medal Address to the Optical Society of America. (Figure 4) [8] Here, the intent was to render HDR images using spatial comparisons that mimic human vision.

Figure 5 shows an example of an HDR scene processed with spatial comparisons. (1978 Frankle and McCann patented application). The illumination on the white card in the shadow is 1/30th that on the black square in the sun. Both have the same luminance. The spatial processing converted equal input digits (~luminance) into very different output digits, thus rendering the HDR scene into the small reflective print range.

Figure 5 shows an example of a very efficient digital, multi-resolution HDR algorithm, using spatial-comparisons. [9] In 1984&5 McCann described HDR image capture using low-slope film in Siggraph courses. [10]

In digital imaging, the popular multiple exposures technique attempts to extend cameras' range in recording darker scene regions. In 1997 Debevec and Malic used multiple exposures and least-square fits to solve for camera response function and the luminance of each pixel in the scene. [11] Their rendering intent is to accurately determine the scene luminance of each pixel for processing and display. This is a departure from traditional HDR imaging in that it requires higher range displays.

Comparisons of actual luminances versus camera-based estimates of luminance show that the estimates' accuracy is limited by veiling glare. [1,2] ISO9358:1994 Standard, " Veiling glare of image forming systems" [12] defines veiling glare and describes two standard techniques for measuring it. It describes how veiling glare is the sum of individual stray light contributions to a single pixel from all other light from the scene, even from light beyond the field of view of the camera. Stray light reflected from lens surfaces, sensor surfaces and camera walls cause veiling glare. The ISO standard defines the glare spread function (GSF), which is a measure of the amount of stray light as a function of angle from a small very bright light source. Veiling glare is measured by ISO9358:1994 as the fraction of a very large white surround scattered into a small opaque central spot. For commercial camera lenses veiling glare values are in the range of 1 to 10 %, depending on the lens and the aperture.

3. HDR TEST TARGETS

While ISO 9358:1994 provides a standard to compare different lenses and apertures, we wanted to measure the effects of veiling glare on HDR imaging. We used a single calibrated test target with 40 test luminance sectors (dynamic range = 18,619:1). Nearly 80% of the total target area was an adjustable surround; 20% of the area was luminance test patches. Using opaque masks to cover the surrounding portions of the scene, we photographed three sets of HDR test images with different amounts of glare. The experiment compares camera digits with measured scene luminance over a very wide range of luminances and exposure times. This experiment measured the extent that veiling glare distorts camera response in situations common with HDR practice.

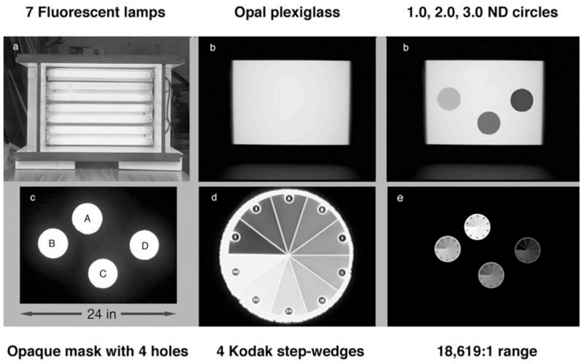

Figure 6a shows the light source made of 7 fluorescent tubes (20W). Figure 6b shows an opal-Plexiglas diffuser placed 6 inches in front of the lamps. Figure 6c shows the addition of 3 circular neutral density filters attached to the Plexiglas with densities of 1.0, 2.0, and 3.0. Figure 6d shows an opaque mask that covered the entire lightbox except for four circular holes registered with the N.D. filters. Figure 6e shows an enlarged view of a single Kodak Projection Print Scale. Figure 6f shows the assembled *4scaleBlack* target with a dynamic range of 18,619:1 [2049 to 0.11 cd/m^2]. Using opaque black masks, the luminance of each sector was measured with a spot luminance meter.

The components of our test display are shown in Fig 6. The display is made of transparent films attached to a high-luminance light-box. The are four Kodak Print Scale transparencies mounted on top of 0.0 (ScaleA), 1.0 (B), 2.0 (C), and 3.0 (D) N.D. filters. The 40 test sectors are constant for both minimal (*4scaleBlack*) and maximal (*4scaleWhite*) glare so that both targets have the same range of 18,619:1. For minimal glare, we covered all parts of the display except for the pie-shaped projection scales with an opaque black mask (*4scaleBlack*). For maximal glare, the opaque black mask was removed so that the zero-glare surround was replaced with maximal glare (*4scaleWhite*). The diagonal line in *4scaleWhite* is an opaque strip in front of the display. To control glare also in low dynamic range condition, background and scale A, B and C have been covered, leaving only the light coming from scale D (*1scaleBlack*) on a 20:1 range.

4. CAMERA VEILING GLARE LIMITS

We made separate sets of measurements with a digital camera and with a 35mm film camera using slope 1.0 duplication and conventional negative films. We used all three HDR calibrated target to measure the camera response. With the *1scaleBlack* target we measured the camera response using only the lowest luminances. With the *4scaleBlack* target we measured the camera response using a high display range of 18,619:1 with minimal glare. With the *4scaleWhite* target we measure the camera response using the same display range with maximal glare.

4.1 Digital Camera Response

We made photographs using a typical compact, high-quality digital camera (Nikon Coolpix 990) with manual, mid-range aperture (f 7.3) and exposure time controls. The experiment photographed 3 sets of images shown in Figure 7.

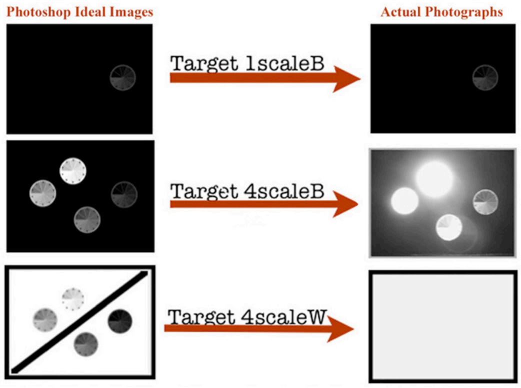

Figure 7 compares camera responses to the three displays using a single exposure time. This 16 sec time is the optimal exposure for *1scaleBlack*. The left column shows synthetic images in which digits, proportional to spot meter luminances, were pasted into each pie-shaped sector. The digital value for each sector was calculated using [256*Actual luminance/18,619]. These are the goal images with accurate 8-bit renditions of these scenes. The top row shows the goal image and an actual 16 sec exposure (best exposure for the lowest luminance scale D). The middle row shows the goal image and an actual 16 sec exposure of *4scaleBlack*. The bottom row shows the goal image and an actual 16 sec exposure of *4scaleWhite*.

Figure 7 (left) shows ideal synthetic Photoshop images of the three test targets and (right) shows the actual 16 sec exposures of the test target acquired with the digital camera. The 16-sec exposure is optimal for recording the luminances of the lowest luminance scale D. The punctual luminance values at each wedge sector remain unchanged in the scene. A 16 sec exposure of the *1scale Black* target shows a typical camera response with digits from 37 to 201. Veiling glare has a small, but significant incremental effect on camera response to *4 scales Black*. Glare from the other test sectors has increased camera digits. The darkest sector digit increased from digit 37 to 98. Veiling glare overwhelms the camera response to *4scales White*. All pixels have the saturated maximum value (242).

The intent of multiple exposures in HDR imaging is to synthesize a new image with a significantly greater dynamic range record of the scene. The idea is simply to assume that scene flux [(cd/m^2) * sec] generates a unique camera digit. Longer exposures collect more scene photons, and can move a dark portion of the scene up onto a higher region of the camera response function. This higher exposure means that the darker portions of the scene have better digital segmentation, more digits for better quantization of luminances. The HDR multiple exposure proposal [11] claimed to extend the cameras range by calibrating flux (luminance * time) vs. camera digit. This assumption is correct up until unwanted veiling glare distorts the camera responses. The results in Figure 7 show that glare can be substantial.

We measured the veiling glare's influence with 16 shots taken with exposures and the same f-7.3 aperture. The *1scaleBlack* photographs have the lowest veiling glare and provide an accurate measure of the camera sensor response function. The only sources of glare are the test patches themselves (range 20:1).

In *4scaleBlack* the camera's digit responses to four 10-step scales attempt to capture a combined dynamic range of 18,619:1. This target measures the minimum glare for a scene with this range, because it has an opaque black surround. The only source of glare is the test patches that vary from 2094 to 0.11 cd/m^2. The data shows that camera digit does not predict camera flux because the data for scale D fails to fall on a single function. The same digit is reported from different luminances. This is important because this display was intended to measure the minimal glare for an 18,619:1 image.

When we removed the black mask covering the lightbox in background we go to the situation with maximal veiling glare (*4scaleWhite*). Nearly 80% of the pixels are making highest possible contribution to veiling glare. Here the influence of glare is dramatic. Camera digits are controlled as much by glare as by luminance (Figure 8).

The data from all three sets of photographs are different. Data from *1scaleBlack* provides a single camera sensor response function. Data from *4scaleBlack* shows variable camera sensor response vs. luminance for low luminances. Data from *4scaleWhite* shows many scene-dependent responses vs. luminance.

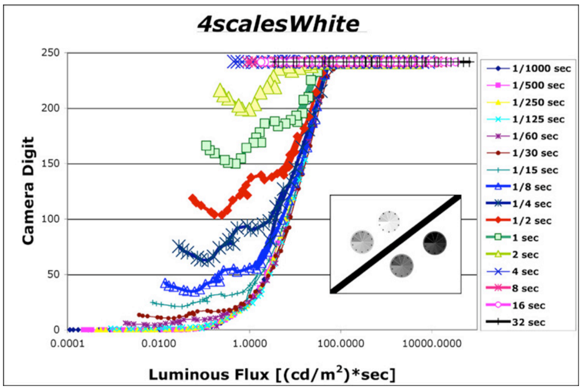

Figure 8 shows the camera digits from 16 different exposure times for the *4scaleWhite* high glare target. Departures from a single line are due to glare.

Camera digits from multiple exposures cannot provide a trustable means of measuring HDR scene flux. Camera digits cannot accurately record HDR scene flux because of glare. Veiling glare is image dependent. We also have performed tests using different cameras, and various changeable lenses, and we obtained similar results.

We used data from all Scale D *1scaleBlack* exposures to measure the camera response to flux. We compared the multiple-exposure technique flux estimates to actual flux for *4scaleBlack* and *4scaleWhite* targets. *4scaleBlack* has no glare from 77% of the image area, yet shows worst-case errors as large as 300% distortions. *4scaleWhite* (77% area with maximal glare) shows 10,000% errors. All possible backgrounds with Scales A, B, C, D will fall between these data sets. There are different, large glare distortions for the same luminance depending on exposure. [2]

4.2 Duplication Film-Camera Response

We made another set of photographs with a typical high-quality 35 mm film camera (NikonFM with a Nikkor 50mm 1:2 lens) using Kodak Slide duplication film. This follows the single exposure HDR capture technique described by McCann in tutorials at Siggraph conferences in 1984 and 1985. [9] Slide duplication film has slope 1.0 on a log exposure vs. log luminance plot. In other words, output luminance equals input luminance. Since it is a color film it can be scanned for color and does not require calibration to remove the color masks found in color negative film. Here we use multiple exposures to capture both 18,619:1 displays

(*4scaleBlack* and *4scaleWhite*). This data show that this particular camera-film-scanner system has less veiling glare than the digital camera in section 3.1. The *4scaleWhite* data showed that the white surround adds veiling glare to generate 8 different response functions.[2]

4.3 Negative Film-Camera Response

We made another set of photographs with the same NikonFM camera using Kodak Max 200 negative film. Here we use single exposures to capture both 18,619:1 displays. We used 7 different exposures to measure the camera-film-scanner process using the low glare 20:1 single scale. The 3 sets of scanned negative film digits are shown in Figure 9.

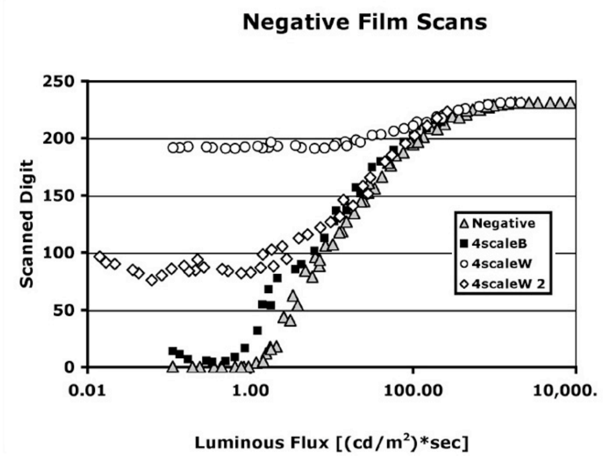

Figure 9 plots scanned single negative digits vs. $\log_{10}$ luminous flux for *4scaleBlack* (black squares) and *4scaleWhite* (white circles and diamonds) targets. The *1scaleBlack* (gray triangles) data plots data from 7 negatives with different exposures. The triangles report the response of the camera-film-scanner process with the lowest level of glare. It shows that the negative process can accurately record fluxes from 2639 to 0.24 sec*cd/m^2. The curve from *4scaleBlack* saturates at 1181 sec*cd/m^2 and inverts at 0.34 sec*cd/m^2. The inversion is caused by glare that limits usable range. There are two different exposures for *4scaleWhite* target; one is 8 times longer than the other. The data from *4scaleWhite* (white circles) saturates at 1,181 cd/m^2 and inverts at 6.17 cd/m^2. The curve from *4scaleWhite2* (white diamonds) has a maximum digit at 2094 cd/m^2 and inverts at 5.8 cd/m^2.

Figure 9 shows that the negative-camera-scanner process can accurately record fluxes from 2639 to 0.24 sec*cd/m^2 (dynamic range of 11,100:1, or 4.05 $\log_{10}$ units). The data from *4scaleBlack* show a small effect of glare from the addition of 30 higher luminance test areas. This glare reduces the dynamic range of the image to 3.5 $\log_{10}$ units. The glare from the white surround in *4scaleWhite* and *4scaleWhite2* reduces the dynamic range of the image measurements of 2.3 and 2.6 $\log_{10}$ units.

The negative-camera-scanner process in the lowest glare condition is capable of capturing slightly greater than 4.0 $\log_{10}$ units. The data also show that system response to the 18,619:1 *4scaleBlack* test target has a veiling glare limit of 3.6 $\log_{10}$ units. Two different *4scaleWhite* exposures have very different curves, but almost the same glare limited measurements (2.3 and 2.6 $\log_{10}$ units).

The fact that the light dynamic ranges for the two exposures of the *4scaleWhite* target are almost the same is important. Their response curves in figure 9 are very different. The *4scaleWhite* scanned digits have a max of 231 and a min of 191. The *4scaleWhite2* scanned digits have a max of 223 and a min of 94. The range of digits representing the scene is only of secondary importance. The range of digits describes the number of quantized levels used to represent the image. It controls discrimination, but does not control the dynamic range of the image. Too often the number of bits of quantization is confused with scene and image dynamic ranges. The number of bits can only describe quantization. As seen in the above results, both the scene and the camera image dynamic range must be calibrated separately.

Conventional negative film can capture a greater range of luminances than falls on the camera image plane from these targets. The dynamic range of a single exposure negative-film-scanner process exceeds the glare limited *4scaleBlack* image by 0.5 $\log_{10}$ units and glare limited *4scaleWhite* image by 1.6 $\log_{10}$ units. Multiple exposures with negative films serve no purpose. The glare-limited ranges of the camera and these HDR scenes are smaller that the film system

The above data suggests that in high, and in average glare, scenes the image dynamic range on the film plane is less than 3.0 $\log_{10}$ units. Only in special cases, very low-glare scenes, does the limit exceed 3.0. The data here show how well the designers of negative films did in optimizing the process. They selected the size distribution of silver halide grains to make the negative have a specific dynamic range, around 4.0 $\log_{10}$ units. Thus, single-exposure negatives capture the entire range possible in cameras, with low glare scenes. For most scenes this image capture range provides a substantial exposure latitude, or margin of exposure error. After reading the papers of C. K. Mees, L. A. Jones, and H. R. Condit, it is easy to believe that this fact is not a coincidence. [13-15]

5. VISUAL RESPONSE TO HDR DISPLAY

The second effect of veiling glare on HDR imaging is intraocular scatter that controls the dynamic range of luminances on the retina. In section 3.0 we saw that camera lenses limit the range of luminances falling on the camera sensor plane. Human intraocular scatter limits dynamic range more than glass lenses. Here we will describe the range of discrimination and the corresponding range of retinal luminances. In addition, we will measure observed appearance for both *4scales Black* and *4scales White* test targets.

5.1 Veiling Glare on the Retina

In 1983 Stiehl et. al. [16] described an algorithm that calculated the luminance of each pixel in an image on the human retina after intraocular scatter. It calculated the luminance at each pixel on the retina based on that display pixel's measured luminance and the calculated scattered light from all other scene pixels. The calculation used Vos and Walraven's measurements of the human point spread function. Stiehl measured the actual display luminance and calculated the retinal luminance for the display shown in Figure 9.

These results show that measures of discrimination are completely distinct from measurements of dynamic range. Humans continue to discriminate appearances of display blacks that are 1/1000th the white luminance, although the stimulus on the retina is limited by scatter to only 1/30th the white. Discrimination has to do with spatial comparisons. The fact that humans can discriminate luminance differences cannot be used in any analysis of dynamic range. Discrimination depends on the local stimulus on the retina. Discrimination and dynamic range are scientifically unrelated.

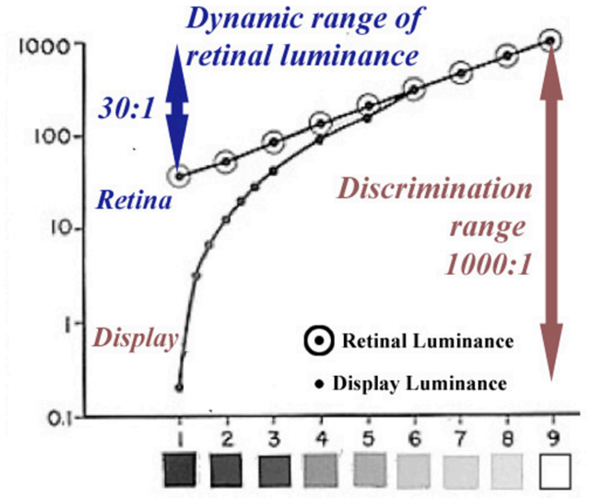

Figure 10 shows dots plotting the display luminance for the HDR transparent lightness scale. The circled dots plot the luminance on the retina, after intraocular scatter. Observers can discriminate display luminances over of 3 log units. This discrimination is made using calculated retinal luminances of only 1.5 log units.

5.2 Visual Appearance of HDR Displays

We asked observers to evaluate the appearance of the *4scaleBlack* and *4scaleWhite* displays using magnitude estimation. Observers sat 48 inches from the 24 inches wide display. The radius of each sector was 2 inches; subtending 2.4 degrees. Three observers were asked to assign 100 to the "whitest" area in the field of view, and 0 to the "blackest". We then instructed them to find a sector that appeared middle gray and assign it the estimate 50. We then asked them to find sectors having 25 and 75 estimates. Using this as a framework the observers assigned estimates to all 40 sectors. The data from each observer (ages 31, 64, 68) was analyzed separately. No difference between observers was found. The average results are shown in Figure 10.

The results of Figure 10 show very dramatically the role of spatial comparison and scattered light in vision. The *4scales Black* and *4scalesWhite* appearance estimates overlap for only the top 5 luminances. Below that, contrast makes the luminances in the white surround darker. The white surround makes the local maxima in scales C and D darker than in the zero-luminance surround. Scattered light from the white surround severely limits the discrimination below 2 cd/m^2.

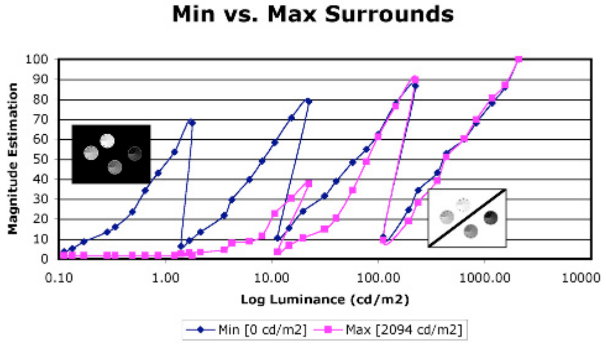

Figure 11 plots magnitude estimation of appearance vs. calibrated luminance for the 40 sectors in *4scales Black* and *4scales White* test targets. Although the luminances are exactly equal the appearances are not. With a black surround observers can discriminate all 10 sectors in all four displays. With a white surround observers cannot discriminate below 2 cd/m^2.

The *4scalesBlack* estimates are very different from those in *4scalesWhite*. Here, observers can discriminate all 40 test sectors. The pie-shaped sectors with the highest luminance in each scale all appear light (Estimates=100,90,80,69). As shown in other experiments, the local maxima generate appearances that change slowly with luminance. [18] Nearby areas with less luminance, change more quickly (contrast). This experimental data shows great similarity to Gerrit van Honthorst's faces in the painting in Figure 1. As the distance between the candle and the faces grew, the tones rendering the faces got slightly darker. Figure 10 just assigns numbers to 16th century observations. Chiaroscuro painters did not render luminances, rather they rendered appearances.

Image dependent intraocular scatter transforms the identical display luminances into completely different sets of retinal luminances. Contrast mechanisms using spatial comparisons further distort any correlation of scene luminance and appearance. Any attempt to find an appropriate "tone scale" relating camera digit to appearance is futile. HDR does not accurately render luminances, and appearances are controlled by spatial comparisons with other pixels in the image. Any function that uses a single pixel's luminance as input cannot account for both the physical image-dependent effects of scatter, and the physiological effects of spatial comparisons in contrast.

6. DISCUSSION

Veiling glare limits HDR imaging in two distinct ways. First, camera glare limits the luminance range that can be accurately measured (Section 4). Multiple exposures improve the quantization of digital records, but fail to accurately record scene luminance. Second, intraocular scatter limits the range of scene luminances falling on the retina (Section 5).

Accurate camera estimates of scene luminance are impossible for the 4.3 $\log_{10}$ dynamic range images studied here. The comparison of white and black surrounds shows dramatic scene dependence. In addition, the camera flux estimates, when compared with actual flux, show a different error with each exposure. It may be tempting to look for some type of average-flux curve that represents data with smaller errors, but that idea is in conflict with the fundamental aim of the process, namely recording accurate scene luminance. Multiple-exposure HDR is limited by veiling glare that is scene-, exposure-, lens-, aperture-, and camera-dependent. The accuracy of scene-luminances estimates vary with all these parameters.

Some HDR algorithms attempt to correct for glare. [19] Given the characteristics of the camera, they calculate the luminances in the scene. The glare spread functions of commercial lenses fall off very rapidly with distance to a very small value. We might think that such small glare values cannot affect distant pixels. However, there are millions of pixels that contribute glare to all other pixels. Each pixel is the sum of scene luminance plus scattered light from all other pixels. The sum of a very large number of small contributions is a large number. Sorting out these millions of scene-dependent contributions would be required to accurately correct for glare. ISO 9358:1994 Standard states unequivocally that: "the reverse [deriving luminance from camera response] calculation is not possible" [12].

Claims are made that recent multiple-exposure HDR algorithms capture wider scene luminances, or colors than previously possible. [20] These claims are severely limited by scene and camera veiling glare. Both camera and intraocular glare are image dependent and cannot be rigorously removed by calculation. As shown above, the designers of negative films selected a 4.0 $\log_{10}$ response range. That range exceeds the camera glare limit for almost all scenes. Further, the 3.0 $\log_{10}$ range of luminances of conventional transparency film equals the range of discriminable luminances in a display with a white surround. Nevertheless, the resulting HDR images are considerably better than conventional images with limited range. Since HDR imaging works so well, there must be reasons, other than accurate luminance, that explains the improved images. The multiple exposure technique does significantly improve digital quantization.

Veiling glare for human vision is much worse than for cameras. [16] Nevertheless, human vision has a much greater apparent dynamic range than camera systems. Humans can see details in highlights and shadows much better than conventional films and electronic cameras can record. Camera response functions are tuned for low-contrast, uniform-illumination scenes. They generate high-contrast renditions of low-range scenes. Early HDR algorithms [21] never attempted to determine actual scene luminance, since luminance is almost irrelevant to appearance. [22] Instead, these spatial algorithms mimicked vision by synthesizing HDR visual renditions of scenes using spatial comparisons. The intent of Land and McCann's electronic HDR imaging was to render high-dynamic range scenes in a manner similar to human vision. They made the case for spatial comparisons as the basis of HDR rendering in the B&W Mondrian experiment. [23] There, a white paper in dim illumination had the same luminance as a black paper in high illumination, but their appearances were strongly different.

Gatta's thesis [24] reviews many papers that combine HDR capture with a variety of tone-scale rendition functions. Tone scales cannot improve the rendition of the black and the white areas in the Mondrian with the same luminance. Tone-scale adjustments designed to improve the rendering of the black, do so at the expense of the *white in the shade*. As well, improvements to white make the *black in the sun* worse. When two Mondrian areas have the same luminance, tone-scale manipulation cannot improve the rendering of both white and black. Land and McCann made the case that spatial algorithms can automatically perform spatial rendering shown by Adams to compress HDR scenes into the limited range of prints. Such rendering is not possible with tone-scale manipulations in which all pixels are modified by a single tone–scale function.

The true benefit of high-dynamic-range image capture is improved quantization that can be used in spatial comparison algorithms. Spatial comparison images correlate with appearance, but not with scene luminance. By preserving the original scene's edge information, observers can see details in the shadows that are lost in conventional imaging. Spatial techniques have been used by painters since the Renaissance, multiple exposures and dodging and burning have been used by photographers for 150 years, and digital spatial algorithms, such as Retinex [9] and ACE [26] have been used to display high-range scenes with low-range media. HDR imaging is successful because it preserves local spatial details. This approach has shown considerable success in experimental algorithms, [25-27] and in commercial products. [28]

7.0 CONCLUSIONS

This paper measures how much veiling glare limits HDR imaging in image capture and display. Glare is the scene- and camera- dependent scattered light falling on image sensors. First, glare limits the range of luminances that can be accurately measured by a camera, despite multiple exposure techniques. We used 4.3 $\log_{10}$ dynamic range test targets and a variety of digital and film cameras. In each case, the camera response to constant luminances varied considerably with changes in the surrounding pixels. HDR image capture cannot accurately record the luminances in these targets. Second, we measured the appearance of the same targets. Appearance did not correlate with luminance: it depended on physical glare and physiological contrast. The improvement in HDR images, compared to conventional photography, does not correlate with accurate luminance capture and display. The improvement in HDR images is due to better digital quantization and the preservation of relative spatial information.

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REFERENCES

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[1] J. J. McCann and A. Rizzi, in *Proc ADEAC/SID&VESA*, Atlanta, 155-158, 2006

[2] J. J. McCann and A. Rizzi, "Veiling glare: the dynamic range limit of HDR images", in Human Vision and Electronic Imaging XII, eds. B. Rogowitz, T. Pappas, S. Daly, Proc. SPIE, Bellingham WA, , 2007, **6492-41**, 2007.

[3] Clair-obscur (French) and chiaroscuro (Italian) both mean "light-dark". The two terms are used to denote sharp contrasts of light in paintings, and prints.

[4] T. Mulligan & D. Wooters, eds, *Photography from 1839 to today, George Eastman House, Rochester, NY*, Taschen, Koln, 360, 1999.

[5] C. E. K. Mees, *The Fundamentals of Photography*, *Kodak Research Laboratory*, Rochester, p.82, 1920.

[6] C. E. K. Mees, *An Address to the Senior Staff of the Kodak Research Laboratories*, *Kodak Research Laboratory*, Rochester, 1956.

[7] A. Adams, *The Negative*, New York Graphical Society, Little, Brown & Company, Boston, pp.47-97, 1981.

[8] E. Land and J. J. McCann, "Lightness and Retinex Theory", *J. Opt. Soc. Am.*, **61**, pp. 1-11, 1971.

[9] J. Frankle, & J. J. McCann, Method and apparatus of lightness imaging, U.S. Patent, 4384336, May 17, 1983.

[10] J. J. McCann, "Calculated Color Sensations applied to Color Image Reproduction", in *Image Processing Analysis Measurement and Quality*, Proc. SPIE, Bellingham WA, **901**, pp. 205-214, 1988.

[11] P. E. Debevec, J. Malic, "Recovering high dynamic range radiance maps from photographs", *ACM SIGGRAPH'97,* 369-378, 1997.

[12] ISO 9358:1994 Standard, "Optics and optical instruments. Veiling glare of image forming systems. Definitions and methods of measurement", (ISO, 1994).

[13] C. E. K. Mees, *Photography*, The MacMillan Company, New York 1937.

[14] L. A. Jones and H. R. Condit, *J. Opt. Soc. Am.* **38,** 1-11, 1948.

[15] C. E. K. Mees and T.H. James, *The Theory of the Photographic Process*, 3rd ed., The MacMillan Company, New York 1966.

[16] W.A. Stiehl, J. J. McCann, R.L. Savoy, "Influence of intraocular scattered light on lightness-scaling experiments", *J. opt Soc .Am.*, **73**, 1143-1148, 1983.

[17] T. Cornsweet and D. Teller, "Relation of Increment Thresholds to Brightness and Luminance", *J. Opt. Soc. Am.* **55,** 1303-1308**,** 1965.

[18] J. J. McCann, "Aperture and Object Mode Appearances in Images", in Human Vision and Electronic Imaging XII, eds. B. Rogowitz, T. Pappas, S. Daly, Proc. SPIE, Bellingham WA, **6292-26**, 2007.

[19] E. Reinhard, G. Ward, S. Pattanaik, P. Debevec, *High Dynamic Range Imaging Acquisition, Display and Image-Based Lighting*, Elsevier, Morgan Kaufmann, Amsterdam, chap 4, 2006.

[20] < http://www.cs.nott.ac.uk/%7Eqiu/jvci/Call-for-Papers.html>

[21] J. J. McCann, "Capturing a Black Cat in Shade: The Past and Present of Retinex Color Appearance Models", *J. Electronic Img.*, 13, 36-47, 2004.

[22] G. Wyszecki and W. S. Stiles, *Color Science: Concepts and Methods Quantitative Data and Formulae*, 2nd Ed, Wiley, New York, chap 6, (1982).

[23] E. H. Land and J. J. McCann "Lightness and Retinex Theory", *J. Opt. Soc. Am.*, **61,** 1-11, 1971.

[24] C. Gatta "Human Visual System Color Perception Models and Applications to Computer Graphics", PhD thesis, Università degli Studi di Milano, Dottorato di Ricerca in Informatica, XVIII ciclo, 2006.

[25] J.J. McCann, ed., *Retinex at Forty*, Journal of Electronic Imaging, **13**, 1-145, 2004.

[26] A. Rizzi, C. Gatta, D. Marini, "A New Algorithm for Unsupervised Global and Local Color Correction", *Pattern Recognition Letters*, Vol. 24, No. 11, July 2003, pp. 1663-1677.

[27] J. J McCann, "Rendering High-Dynamic Range Images: Algorithms that Mimic Human Vision", in *Proc. AMOS Technical Conference*, Maui, p 19-28, 2005.

[28] HP cameras with Digital Flash or Adaptive Lighting (Models 945, 707,717,727) use spatial comparisons to improve image rendering.