Glare-limited Appearances in HDR Images

A. Rizzi, M. Pezzetti and John J. McCann; Dipartimento di Tecnologie dell'Informazione, Università degli Studi di Milano, 26013 Crema (CR), Italy and McCann Imaging, Belmont, MA 02478, USA

Abstract

Appearance in High Dynamic Range (HDR) images is controlled by intraocular glare and simultaneous contrast. This paper describes unique test targets that simulate real images. They change the HDR range by 500 times without significantly changing the veiling glare on the retina. As well, these targets have nearly constant simultaneous contrast. Using these test targets we measured the range of appearances possible from HDR images with different average luminances. The targets displayed a maximum luminance range of 5.4 log unit. Hoverever, the results show that the usable range of luminances for a full range of appearances (white to black) is much smaller.

Introduction

HDR imaging research has devoted considerable study to the use of tone-scale maps that render HDR luminance and color data [1]. Assuming that multiple exposures capture a wide range of scene radiances (camera flux digits) [2] , then the selection of an appropriate tone scale is important to render the HDR scene digits for humans.

HDR image formats [1] have been documented that encode dynamic ranges as large as 10^{76}. Even though some encode remarkably high dynamic ranges, the majority encodes around 3-4 log units. How much dynamic range is detectable by our visual system? The Human Visual System (HVS) is in fact an optical system, and, as all optical systems, is subject to veiling glare limitations. Glare is an uncontrolled spread of an image-dependent fraction of scene luminance caused by scattered light in the eye bulb by Tyndall scattering [3] by macromolecules. Recent experiments have pointed out that veiling glare is a physical limit to HDR image acquisition [4-9]. In this paper, we measure the usable limits of luminance range for HDR displays. We want to measure how veiling glare affects tone-scale functions (luminance to appearance in HDR images).

By limiting digital storage to the useful dynamic range we can utilize more precise image quantization. Since bits, even if used in large numbers, are a finite resource, using limited dynamic ranges can result in a better quantization of perceivable tones. In displays, the expansion of dynamic range comes at a cost of technology. Using only the useful, visible dynamic range allows us to implement the best possible quantization in relation to the available disk space, color depth and display technology.

Glare limits in HDR

Recently, to overtake the limited dynamic range of conventional displays, multiple exposure techniques [2] have been combined with LED/LCD displays that attempt to accurately reproduce scene luminances [10]. However, veiling glare is a physical limit to HDR image acquisition, display and viewing. It is scene-dependent, thus multiple exposures cannot accurately reconstruct scene luminances beyond the veiling glare limit [4-9].

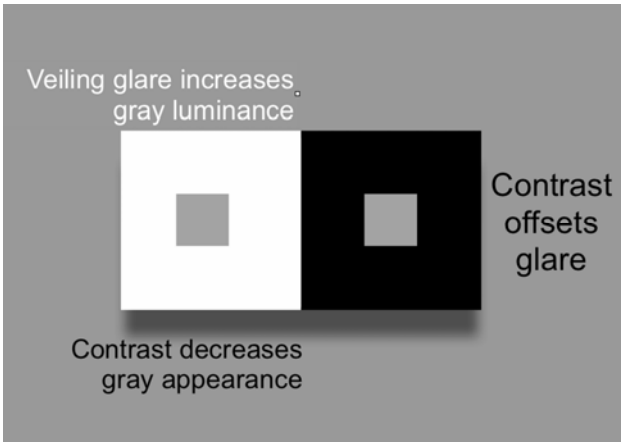


Figure 1 *In classic simultaneous contrast configuration two opposing visual mechanisms contribute to the final appearance of the gray patches.*

Human observer experiments show two independent and opposing visual mechanisms. Intraocular veiling glare reduces the luminance range on the retina while physiological simultaneous contrast increases the apparent differences [8,9]. Figure 1 shows the classic simultaneous contrast configuration. If we consider the gray patch surrounded by white, it will have much higher glare, due to the white surround. If retinal luminance predicted appearance, then it follows that this patch should appear lighter than the other on the black surround. However, simultaneous contrast makes the gray in white look darker. Glare distorts the luminances of the scene in one direction and simultaneous contrast works to counteract glare.

To test how the veiling glare limit can impact the HDR pipeline we recently ran some experiments [8-9]. We performed camera calibration and human observer experiments using a single test target with 40 luminance patches covering a luminance range of 18,619:1 (4.3 log units). In these experiments (Figure 2), we measured the appearance of four identical transparent targets with four levels of illumination in the same scene in a black surround [9]. Observers measured appearance by making magnitude estimates (MagEst) between white and black. They were asked to assign 100 to the whitest areas and 1 to the blackest areas in the scene.

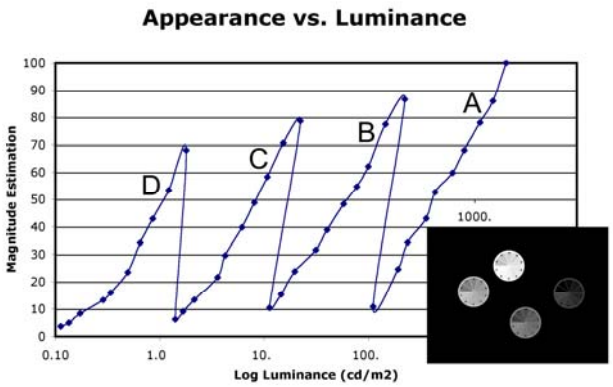


Figure 2 *Test target is in the bottom right. Four identical pie shaped transparencies with ten different transmissions were mounted on a light box. The top A had no neutral density filter behind it, B on the left had 1.0; C on the bottom had 2.0; D on the right had 3.0 ND filters. The surround was opaque. In total the target had 40 test areas with a luminance dynamic range of 18,619:1. The graph plots the average of observers' magnitude estimates of the appearance of the 40 test areas vs. luminance.*

Average observer estimates are plotted in Figure 2. The horizontal axis plots luminance measured with a spot photometer (cd/m^2). The vertical axis plots appearance (magnitude estimate value). The top target A has the highest luminance. It generates MagEsts from 100 to 11. The left target B, viewed through a 1.0 ND filter, has uniformly 10 times less luminance than A. It generates MagEsts from 87 to 10. The bottom target C, viewed through a 2.0 ND filter, has uniformly 100 times less luminance than A. It generates MagEsts from 79 to 6. The right target D, viewed through a 3.0 ND filter, has uniformly 1000 times less luminance than A. It generates MagEsts from 68 to 4.

If we look along the horizontal line at MagEst=50, we see that four different luminances (1.06, 8.4, 64 and 414 cd/m^2) generate the same appearance. If we look at luminance 147 cd/m^2 we see that it generated both MagEst = 17 (near black) in A, and MagEst = 87 (near white) in B. Similar examples of near white and near black appearances are found at luminance 15 (B&C), and 1.8 cd/m^2 (C&D). Magnitude estimates of appearance in complex images do not correlate with luminance.

In this target, nearly 80% of the total area is an adjustable surround; 20% of the area is luminance test patches. Removing the opaque background covering increased the glare to the maximum possible for this target configuration. With this new setup the ability of the observers to estimate the patch magnitude strongly decreased (see Figure 3). The range of discriminable patches decreased to less than 3 log units. In a black surround observers could discriminate all 40 luminance test areas over a range from [2049 to 0.11 cd/m^2]. When they replaced the black surround with a white (maximum glare) surround the observers were unable to discriminate appearances below 2 cd/m^2. Vision's simultaneous contrast mechanism further distorted any correlation of scene luminance and appearance. In the black surround, lower luminances appeared much lighter than in the white surround. They showed that both physical intraocular scatter and the HVS contrast processing influenced the appearances of darker test targets.

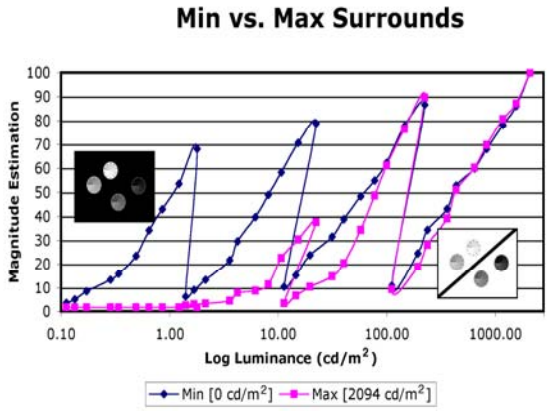


Figure 3 *Removing the opaque background mask increases the glare to the maximum possible for this target (bottom right). Now the ability of the observers to estimate the patch magnitude strongly decreases to a range of less than 3 log units.*

Then, McCann and Rizzi measured the dynamic range of a camera-negative-film-scanner system on the same target [9]. The film was capable of recording 4.0 $\log_{10}$ units of luminance. Glare from the 18,619:1 target surrounded by black reduced the range on the camera film plane to 3.5 $\log_{10}$ units in a single exposure. The glare from a white surround further reduced the range to 2.4 $\log_{10}$ units. The dynamic range of a single negative exposure exceeds the black surround scene (minimal glare) by 0.5 $\log_{10}$ units and white surround scene (maximal glare) by 1.6 $\log_{10}$ units. Conventional negative film can capture a greater range of luminances than falls on the camera image plane. For these test targets multiple exposures with negative films serve no purpose in measuring dynamic range. However, multiple negatives can provide better quantization, or digital segmentation, of details within the glare limited range. Since glare is image dependent then its effects can vary differently in each possible visual configuration.

Design of Appearance Scale Target

The main goal of this paper is to measure the usable dynamic range of luminance using targets with a fixed amount of glare and without changes in simultaneous contrast. To start, we set aside all the complexities introduced by gradients in illumination. We will just study patches of light that are uniform. We could begin with luminance patches that are surrounded by no light.

Bodmann [12] showed that magnitude estimates of brightness fit a 0.3 slope line, over 5 $\log_{10}$ units, similar to stellar magnitude. This data is inappropriate for typical images because it fails to account for the physical properties of scatter from normal images, as well as the physiological properties of simultaneous contrast. Bodmann's experiments also showed that areas darker than the surround changed in appearance at a much higher slope. Appearance functions derived from experiments using black surrounds are different from those derived from complex images. Thus, they are not appropriate to measure the tone-scale mapping of HDR images.

We could evaluate luminance patches in a white surround. Blacks appear blackest surrounded by white. However, veiling glare is greatest in white surrounds. The range of light, after scatter, from white surround luminances does not represent typical scenes that are made up of many different luminance areas. Appearance functions derived from experiments using white surrounds are also not appropriate. Nevertheless, we will measure appearance in a white surround as a control.

We could evaluate luminance patches in an average gray surround. Experiments compared lightness matches using a, white, gray, black, and complex-Mondrian surrounds. They showed that appearances in Mondrians are the same as those in a white surround, not gray surrounds [13]. Gray surrounds show a rate of appearance with luminance between the low-slope black and the high-slope white. Appearance functions derived from experiments using average gray surrounds are also not appropriate.

If we consider the global physical properties of glare, we would like to have a surround that is, on average, equal to the middle of the dynamic range. This can be achieved by making the surround 50% max and 50% min luminance. Further, if these surround elements are made up of different size min and max blocks we have energy over a wide range of spatial frequencies and can avoid the problem that simultaneous contrast depends on the size of the white areas [14].

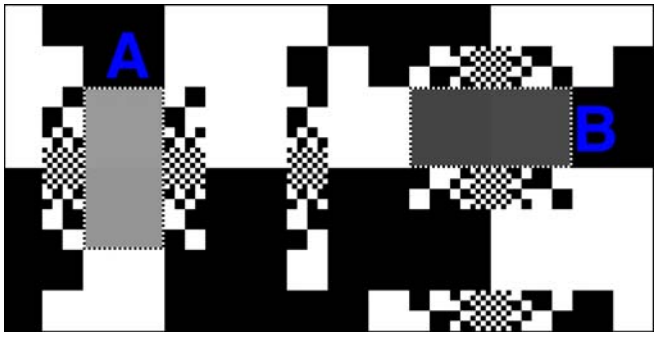


Figure 4 *Magnified view of two of twenty gray pairs of luminance patches. The left half (square A) has the same layout as the right (square B), rotated 90° counterclockwise. The gray areas in A have slightly different luminances, top and bottom. The gray areas in B have different luminances, left and right. The square surrounding areas are identical except for rotation. For each size there are equal numbers of min and max block.*

Targets Layout

Figures 4 & 5 shows the layout of our min/max test target. The display subtended 15.5 by 19.1 degrees. It was divided into 20 squares, 3.4 degrees on a side. Two 0.8 degree gray patches are within each square along with various sizes of max and min blocks. The two gray square length subtends an angle approximately the diameter of the fovea. The smallest block (surrounding the gray patches) subtends 1.6 minutes of arc and is clearly visible to observers. Additional blocks 2x, 4x, 8x, 16x, 32x, 64x are used in the surround for each gray pair.

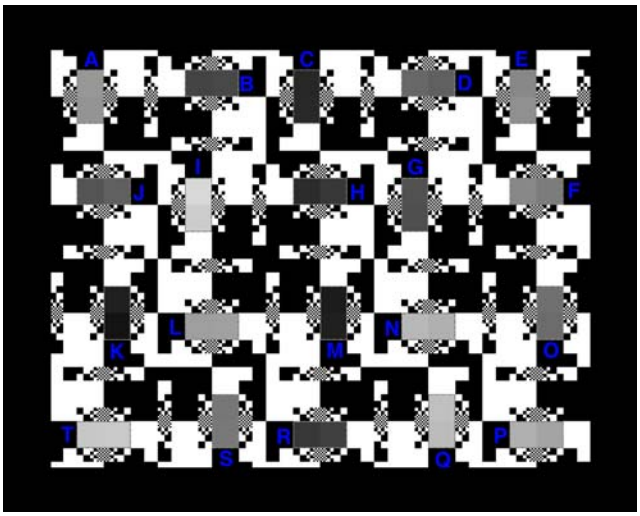


Figure 5 *Target with twenty gray pairs of luminance patches. All gray pairs are close in luminance, but some edge ratios are larger than others.*

Single- and Double-Density Targets

The observers made magnitude estimates of the appearance of patches in single- and double- density transparencies. The double- density target is the aligned superposition of two identical photographic 4 by 5 inch photographic (single-density) films. Two transparencies double the optical densities. The whites in each transparency have an optical density (O.D.) of 0.20; the blacks have an O.D. of 2.89. The double density images have a min of 0.40 and a max of 5.78 O.D (See Table 1). Both transparency configurations are backlit by 4 diffused neon bulbs.

Target	Max cd/m²	Min cd/m²	Range:1	%Average cd/m²	O.D. Min	O.D. Max	O.D. Range
Single Density	6,680	13.6	490	50.01%	0.20	2.89	2.69
Double Density	4,215	0.018	239,883	50.00%	0.40	5.78	5.38

Table 1 *List of the luminances and optical densities of the min and max areas in single and double density displays.*

Veiling glare for HVS is a property of the luminance of each image pixel and the glare spread function (GSF) of the human optical system. Surrounds made up of half-max and half-min luminances have very interesting glare properties for single- and double- density test targets. The average luminance of the single- density target is 50.10% of the maximum luminance, from a display with a range of ~500:1. The average luminance of the double- density target is 50.00% of its maximum luminance, from a display with a range of ~250,000:1. The effect of glare on the luminances of the gray test areas will be very nearly the same, despite the fact that the dynamic range has changed from 500:1 to 250,000:1. In other words, the black (min luminances) in both single- and double-density targets are so low they make only trivial contributions to glare. The white (max luminances) in both targets are almost equal and generate virtually all the glare. The layouts of both targets are constant, keeping simultaneous contrast stable. The physical contributions

of glare are very nearly constant. By comparing the magnitude estimates of appearance of these single- and double-density targets, we can measure the effects of constant glare on very different dynamic-range displays.

If the HVS can make use of the double- density image (range 250,000:1), then we expect to see a greater range of appearances in this image. If the veiling glare limit has been reached in the single- density image, then adding 500 times more range will have little, or no, effect on appearance.

Magnitude Estimation Experiments

The experiments were done in a dark room. The only source of light was the target. The lightbox had an average luminance of 10.6 cd/m^2 (chromaticities x=0.45, y=0.43).

Five observers made magnitude estimates of the appearance of the test patches between white and black. The observers were university students and workers between 18 an 23 years of age, with 20/20, or corrected 20/20 acuity. The five observers were asked to assign 100 to the "whitest" area in the field of view, and 1 to the "blackest" appearance, including the opaque surround. We then instructed them to find a sector that appeared middle gray and assign it the estimate 50 (or very near value). We then asked them to find gray squares having 25 and 75 (or very near values) estimates. Using this as a framework the observers assigned estimates to all sectors (A-T in figure 5). Each of five observers repeated the experiment five times, not consecutively. They gave estimates for each half of the gray areas. We repeated the experiment with the same observers with single- and double-density displays.

Average luminance = 50 % max luminance

The first experiment measured the target shown in Figure 5. The average results are shown in Figure 6. The plots for single- and double-density nearly superimpose. In the single-density image the highest luminance gray (Area I) has a relative optical density of 0.19, and an appearance estimate of 92. In that target the lowest luminance gray (Area K) has an optical density of 2.1 and an appearance estimate of 3.0. In the double-density image Area K has an optical density of 4.1 and an appearance estimate of 1.8 The average of all observers on both targets show the same asymptote to black at density 2.3.

The results are consistent with veiling glare determining the visible ranges. The effect of increasing the stimulus range has little or no effect because the single-density image is at, or near the maximum range possible on the retina for this scene. The plots in Figure 6 are the optimal tone scale function for these complex scenes.

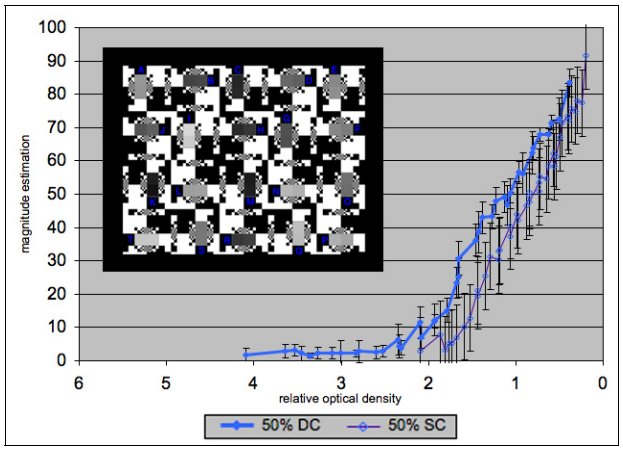


Figure 6 *Appearances of single- (SC) and double-density (DC) displays with 50% average luminance surround. Observers estimate the same range limit of 2.3 log units.*

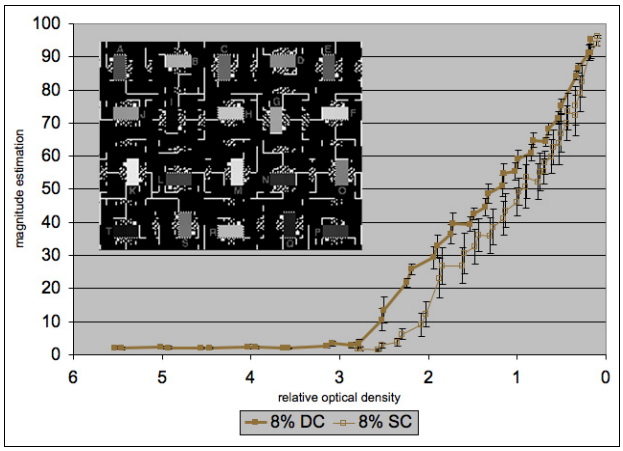


Figure 7 *Appearances of single- (SC) and double-density (DC) displays with 8% average luminance surround. Observers gave slightly different estimates for slope with the same range limit of 2.7 log units.*

Average luminance = 8 % max luminance

The second experiment studied another pair of single and double density targets with a different surround. We reduced the area of the white to 8% of the background, leaving the black to cover 92%. The effect of reducing the white area was to decrease the amount of veiling glare, while holding the dynamic range and the simultaneous contrast of the single- and double-density transparencies nearly constant. The results are shown in Figure 7. They show similar results to the 50% white background, but with an asymptote at 2.9 O.D.

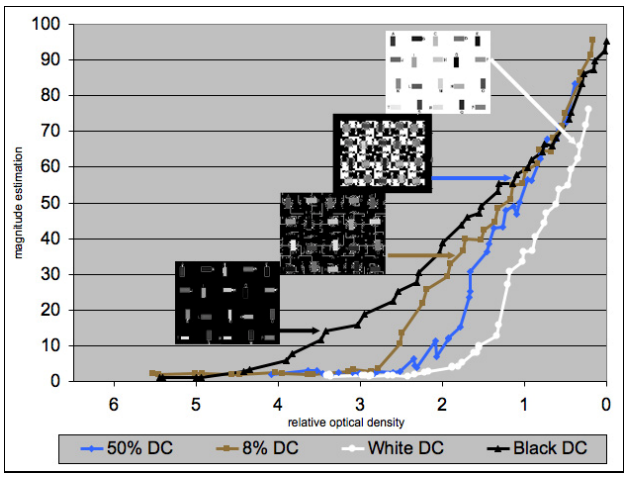


Figure 8 *Overall comparison of appearance slopes for double - density displays with 100%, 50% and 8% average luminance surround. Observers measured significantly different slopes and dynamic range limits.*

Discussion

As control experiments, we measured gray patches with a completely white, and a completely black background in single- and double-density. Figure 8 shows four magnitude estimates of appearance for the double density targets as a function of luminance.

For the three pairs of displays containing white (100%, 50% and 8%), we find that doubling the dynamic range shows only small changes in appearance. The slope of the transition from white to black depends on the amount of white in the background. Glare prevents the appreciation of most of the increase in dynamic-range information provided in the double density images.

For the black surround displays, we find that doubling the dynamic range shows changes in appearance. In the single-density target the optical density 2.7 has a MagEst=5.2. In the double density target the and optical density 5.0 has the darkest MagEst=1. In complete darkness observers can use densities between 2.7 and 5.0 to discriminate between different levels of black (MagEst=5.2 and MagEst=1).

The results with both black and white surround are consistent with changes in intraocular glare expected from these scenes.

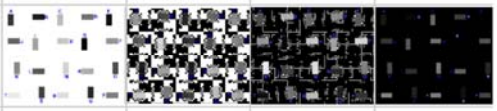
% White	100%	50%	8%	0%
				
Usable Range (log units)	2.0	2.3	2.9	5.0

Table 2 *compares the % White surround area with usable display dynamic range (log units).*

The figure 8 data shows that for four different backgrounds there are four different optimal tone scales. The data shown in Table 2 shows the maximum usable range of luminance for each target design. Each one of the background configurations generates a different amount of glare. Observer estimates show a usable range of 2.0 log units in the highest glare condition. Reducing the amount of white by half, increases the usable range to 2.3. We find usable range of 2.9 with 8% white background. In the case of the black background observers can discriminate luminances over a 5 log unit range; this can be obtained only with a completely black surround and total darkness in the entire room. These very strict constraints are inconsistent with common scenes and viewing situations.

All these displays held simultaneous contrast almost constant, while changing dynamic range. In the experiments described in Figures 2-3 [9], contrast and glare changed. Real scenes have variable amounts of simultaneous contrast and glare, and present a serious problem for tone-scale mapping. The table 2 experiments used uniform illumination and constant local surrounds around each patch, so as to have constant veiling glare. The results from Figure 8 show that each image requires a unique tone scale. That tone scale can only be calculated from spatial evaluations of the image incorporating corrections for both glare and contrast. ISO 9358:1994 Standard states that the glare correction is impossible to compute from image data. [15].

Many natural HDR scenes have non-uniform illumination. How can tone scaling HDR predict the effects of non-uniform illumination? Land's Black and White Mondrian [16] studied non-uniform illumination. They presented a configuration where two areas had the same luminance and hence the same camera digit, say 128, but one was a white paper in dim light and the other a black paper in bright light. Since the two patches did not appear as equal, to improve the rendering in mapping the image dynamic we need to increase the digit for white, and decrease it for black. This is impossible for a tone-scale curve to improve both whites and blacks, since input 128 can have only one output value.

Even more damaging is the data from Figure 2. Four areas have the same appearance from four very different luminances. Three different luminances have both white and black appearances. Luminance does not correlate with appearance.

Humans are very good at discriminating very small increments in luminance at edges. As Cornsweet and Teller showed, the ability to discriminate depends on the local stimulus on the retina (after glare) and not on the appearance [17]. Discrimination has to do with spatial comparisons.

There is a long history of rendering HDR scenes that does not depend entirely on tone scales. [6,8] Human vision, painting and photography use spatial comparisons to synthesize a new low-range image from HDR input. Although the retinal receptors have a measured dynamic range of more than 10^{10}, the retinal ganglion cells transmitting information to the visual cortex have a range only slightly greater than 10^{2}. Surface reflections from paintings and photographic prints limit their range to less than $10^{\wedge 2}$. Early electronic HDR algorithms synthesize new low-range images from HDR input [16]. The unifying principle is that these low-range images preserve edge information and highly distort luminance. Such spatial-comparison algorithms are scene dependent [18].

Conclusions

We have studied the effect of single- (0 to 2.7 log units) and double-density (0 to 5.4 log units) targets with almost no changes in glare and simultaneous contrast. HDR images are limited by scene-dependent intraocular glare. In a white surround, with the maximum glare, observers use an optical density range of 2 log units to cover the range of appearances from white to black. By using half-white and half-black surrounds we held simultaneous contrast constant and reduced the glare by half. Observers use a range of 2.3 log units for white to black appearances. In a third experiment we reduced the white to 8% white, decreasing glare further. Here, observers use a range of 2.9 log units for white to black. Observers estimated almost the same appearance in both single and double density displays. Optical densities between 2.9 and 5.4 did not substantially increase the range of appearance for all targets with white in the background.

References

* The term *contrast* has different definitions in photography and vision. In photography, it refers to the rate of change in reproduction luminance vs. scene luminance. It is the slope of the tone-scale function. In vision, it is the name of the spatial mechanism that enhances differences in appearance. A gray patch in a white surround is darker because of the physiology in the visual system, referred to as simultaneous contrast.

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Author Biography

Alessandro Rizzi took the degree in Computer Science at University of Milano and received a PhD in Information Engineering at University of Brescia (Italy). He taught Information Systems and Computer Graphics at University of Brescia and at Politecnico di Milano. Now he is assistant professor, teaching Multimedia and Human-Computer Interaction, and senior research fellow at the Department of Information Technologies at University of Milano. Since 1990 he is researching in the field of digital imaging and vision. His main research topic is the use of color information in digital images with particular attention to color perception mechanisms. He is the coordinator of the Italian Color Group.

Marzia Pezzetti has recently taken the degree in Computer Science at University of Milano, with an experimental thesis on the subject of this paper. She is a PhD candidate for the University of Milano.

John McCann received a B.A. degree in Biology from Harvard University in 1964. He managed the Vision Research Laboratory at Polaroid from 1961 to 1996. He has studied human color vision, digital image processing, large format instant photography and the reproduction of fine art. He is a Fellow of IS&T (1984). He is a past President of IS&T and the Artists Foundation, Boston. He is currently consulting and continuing his research on color vision. He received the SID Certificate of Commendation, Society for Information Display, 1996. He is the IS&T/OSA 2002 Edwin H. Land Medalist and IS&T 2005 Honorary Member.

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