HDR Displays: a Validation Against Reality[*]

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Abstract – *In the real world the contrast between bright areas, directly illuminated by the sun, and dark shadows can be of 6 or 7 orders of magnitude. Although such huge contrast ratio is common in the natural world when these luminance levels are to be displayed on a typical monitor, the range is far too large. Bright areas appear overly saturated and shadows are displayed as black. Until recently, the only approach to solve this problem was to compress the luminance component of a* High Dynamic Range *(HDR) scene. Such techniques are known as* tone mapping. *However, even tone mapping operators are not always capable of producing sufficient contrast reduction. In this paper we present the results of a psychophysical investigation to validate a novel HDR display which is capable of contrast ratios similar to what is present in the physical world. Images displayed on this device are an accurate representation of a* window *on a scene and may not be equivalent as standing in the* real *scene due to a lack of peripheral information. We describe three perceptual studies with the goal of validating the device against real scenes in terms of peripheral vision.*

Keywords: High dynamic range, psychophysics, visual perception.

1 Introduction

The natural world presents a wide range of luminance levels. Night scenes can have luminances of the order of 10^{-4} cd/m^2 or less, while daylight scenes can reach 10^6 cd/m^2 This huge range of luminance levels is known as *high dynamic range*. Generating high dynamic range imaging is straightforward. Lighting simulation packages such as Radiance for example, generate HDR rendered images of a scene. Not only virtual scenes can be in HDR, but even photographs can contain the entire dynamic range of the environment. Techniques proposed in [1] for example, allow a high dynamic range photograph to be generated from a series of photographs taken at different exposure times. Furthermore, digital cameras which capture high contrast ratios scenes are beginning to appear. A huge problem, however, still remains: displaying these scenes. Common displays and viewing environments limit the range of what can be presented to about two orders of magnitude between minimum and maximum luminance. A well-designed CRT monitor may do slightly better than this in a darkened room, but the maximum display luminance is only around 100 cd/m^2, which does not begin to approach daylight levels, see Figure 1. During the last decade, a great deal of work has been done by computer graphics researchers to find ways to map real world luminances to target display luminances. According to a framework proposed by Tumblin and Rushmeier [2], tone mapping operators (TMO) should generate images perceptually similar to a real scene by careful mapping to a set of luminances that can be displayed on a low contrast ratio display or even printed.

Figure 1: Reconstruction of a Pompeii building. The false-colored image shows the range of luminances present in the scene (red=high, blue=low). This vast range cannot linearly displayed on a typical monitor and unless tone mapping is applied, only a subset of the luminance range can be displayed at any one time. The large image is a tone mapped version.

Many algorithms have been developed aiming to compress the dynamic range of a scene to a displayable range. These operators can be classified according to the approach they use to achieve this goal. Models such as [3, 4] that apply the same mapping function across the image are known as *global* operators. Those operators in which the mapping

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varies spatially depending on a neighborhood of a pixel are known as *local*, see [5, 6, **?**]. Some operators can also be classified as *percpetual* as their mapping function is based on perceptual data which attempts to mimic the human visual system [7, 3, 8]. Although these tone reproduction algorithms can produce visually pleasing images that are easily displayable on common displays (or even printable), the result when compared to the actual scene is not always accurate. Also, the eye's physical response to the real scene can be extremely different since the luminance in the scene can be a few orders of magnitude higher than the maximum display luminance. Although perceptual operators mimic glare and veiling effects caused by the scattering of bright lights in the eye, the perceived sensation in reality is not comparable.

Recently, a few novel high dynamic range devices have been developed capable of displaying contrast ratio of approximately 4 or 5 orders of magnitude compared to standard display which are only capable of displaying a maximum of 2-3 orders of magnitude. These new devices allow us, for the first time, to display $linearly$ high dynamic range scenes without the need for complex tone mapping operators.

In this paper we present and discuss three perceptual studies aimed at validating images displayed on two novel high dynamic range devices against a real scene. Specifically our experiments investigate the influence of peripheral vision on the perception of an environment and what are the differences, if any, between standing in the real scene and observing it through a window. Firstly though, we give an overview of psychophysical measures used.

2 Psychophysical measures

Psychophysical methods and procedures are useful in determining thresholds. For an observer, the threshold is typically the point where a stimulus can just be detected. There are various methods that can be used to detect thresholds such as Methods of Adjustment or Staircase methods, all of which aim to determine the minimum amount of a stimuli required to perceive it. Thresholds measurements have been used in this work to determine difference in visibility in the different trials mentioned below.

When attempting to capture other human judgements such as preference or rating, the experimenter is trying to determine which of two or more stimuli is the preferred or "looks best" for example. Rating can be very useful, although it can lead to some erroneous results if the sample is not large enough or if the participants have not been trained, prior the trial, on a series of test images. In the third study presented in this paper, we ran a simple trial where subjects were asked to rate similarity of an image with respect to a reference.

Psychophysical methods and procedures are fairly new to the field of computer graphics. Rushmeier et al. [9] were amongst the first to attempt to make comparisons between virtual and real scenes. In more recent work, Rushmeier et al. [10] examined the perceived quality of various representations of texture and geometry simplification employing a rating system. Watson et al. [11] run a psychophysical investigation to determine perceptual differences of two model simplification algorithms. In their experiments, they used different techniques including rating and decision time. Other researches including [12, 13] have used other psychophysical measures to determine similarity between virtual images, real scenes and photographs.

3 High Dynamic Range devices

In this section we present two high dynamic range devices that we utilized for the three studies.

Figure 2: The HDR Display (left) and the HDR Viewer (right). Both devices are capable of contrast ratios in the region of four orders of magnitude.

3.1 Sunnybrook HDR display SBT1.3

The Sunnybrook Technologies SBT1.3 HDR Display is a rear-projection based dual-modulation display system capable of accurately portraying color video images over a dynamic range of 75,000 to 1 [14]. The SBT1.3 uses an Optoma EzPro737 DLP (Digital Light Projection) video projector with modified electronics, no colour wheel and a new internal light management system to create a grayscale video projection unit. Images from the projector are relayed through an array of lenses onto the back of a 15" XGA color Liquid Crystal Display (LCD) Sharp LQ150X1DG0 where the backlight and other electronics components of the LCD have been removed to create a transmissive image modulator.

3.2 A wide-field HDR stereo viewer

The stereoscopic high dynamic range viewer is a simple device developed by Greg Ward, consisting of a bright, uniform backlight joined to a set of LEEP ARV-1 stereo optics used in the original NASA virtual reality systems [15]. A pair of transparencies is placed on top of the diffuser in front of the ARV-1 optics. The optics allow a 120 degrees field of view in each eye for a complete stereo view. By combining these optics with an intense backlighting system and layered transparencies, the viewer is able to reproduce high absolute luminance levels and a contrast ratio of 10,000:1. A complete discussion and a schematic of the viewer can be found in [16] which also describes a series of psychophysical tests to validate the viewer against real scenes.

4 HDR display validation

In this paper we describe three experiments to validate our high dynamic range display. There are many properties and tests that we could run to determine the fidelity of the device. One important difference is that when standing in a real scene, our eyes can see information with approximately 120 degree visual field. Although the higher resolution is in the foveal area at the center of the retina, we are still capable of perceiving luminances and objects in the periphery of the eye. Peripheral vision is the ability to see objects and movement outside of the direct line of vision. The rods are predominantly responsible for this type of vision. Peripheral vision becomes even more fundamental at scotopic levels ($< 10^{-2}\ cd/m^2$) where vision is entirely rod-mediated. As shown in Figure **??**, the distribution of the eye's photoreceptors in the retina is not even. The vast majority of the cones are present in the foveal area providing our highest visual acuity. The rods are mainly situated in the outer regions of the retina and being much more sensitive to light, are very good motion detectors.

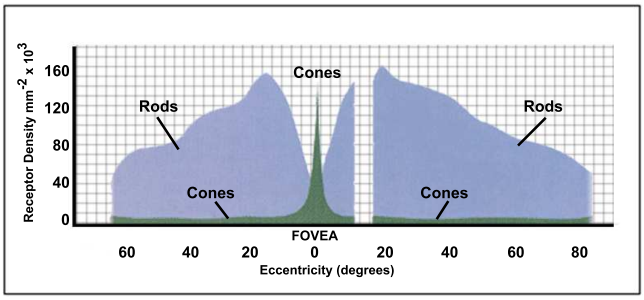

Figure 3: Cones and Rods distribution in the retina.

On the other hand, when capturing a scene with a typical lens, the visual field is greatly reduced as if we are looking through a *window* in the real scene. Looking through a window in the real scene is not the same as *being* in the actual environment. Therefore, displaying images on a high dynamic range monitor does not necessarily mean that the viewer's perception of the scene is identical to standing in the real environment. Although there are many parameters that have to be studied to validate the fidelity of this display, in this work, we were interested in determining how the lack of peripheral information and wide visual field affect the perception of a scene.

5 Study 1: Foveal vs Peripheral

The aim of the first experiment was to compare the difference in contrast detection between the real scene and a HDR photograph displayed on the high contrast ratio display. In particular, we wanted to study how visibility of a scene is affected by lights facing the viewer. We tested three scenarios as shown in Figure 4. In the first scenario (Figure 3), the lights sources were carefully positioned 10 degrees apart from the view point ensuring that foveal stimulation would be mainly responsible for vision (i.e. the lights were positioned centrally in front of the viewer). In the second case, we moved the lights along a semi-circle forming a 60 degrees angle. This light position allowed for a fairly even distribution of retinal illuminance. In the final scenario, the light sources were positioned to form a 120 degree angle and would be only visible in the periphery (i.e. would not be directly captured by the camera). In all three cases no other form of light source or ambient light was present and all walls and surfaces were black to reduce ambient reflections. We then asked 12 participants, with normal, or corrected to normal vision, to view a contrast sensitivity chart proposed by Ayres centrally positioned between the lights 2 meters away from the view point as shown in Figures 3 and 4.

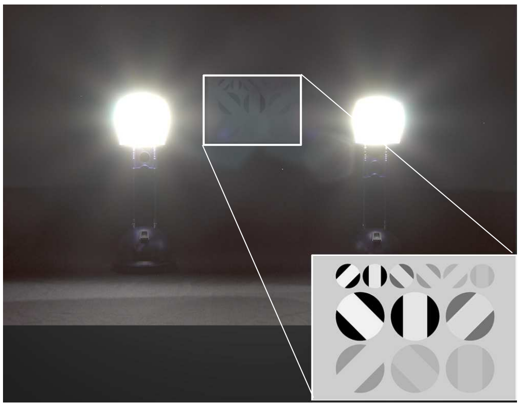

Figure 4: One of the test scenarios. A contrast sensitivity chart was positioned between the two lights. The different target sizes are to account for spatial frequency. Because of the light scattering in the eye, distinguishing various targets on the chart becomes a challenging task.

The subjects' task was to identify carefully selected targets from the Ayres chart in all three scenarios described above. In each case, a new, slightly modified chart was positioned in the scene, to avoid the possibility of any of the participants recalling the orientation of the targets in the previous scenario.

Since the aim of the experiments was to validate how accurately the HDR monitor *linearly* displays a range of luminances, it was preferable to create an environment with a contrast ratio within the maximum capability of the display. Filters had to be positioned in front of the lights to decrease the maximum luminance in the scene.

5.1 Experimental procedure

Prior to entering the dark room to take part in the actual experiment, each participant was shown the same contrast chart and was told about their task. During the experiment, the observers sat 2m away from the targets which were placed between the two bright lights making the task harder. The participants had to simply distinguish the direction of the target: either left, straight or right. A point was assigned for each correctly identified target (a score of 6 would represent complete accuracy in target detection). No time limit was given, although, each scenario took no longer than 1 minute to complete. All participants were given time to adapt to the environment.

Having completed this first experiment, each subject was then asked to repeat the three trials once more, however, instead of the real scene, they had to observe a representation on the HDR display.

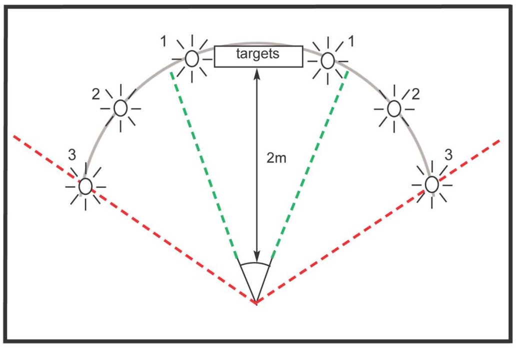

Figure 5: Scene setup. In the first scenario (1) two light sources were positioned centrally to stimulate the fovea. In the second (2), the light sources formed a 60 degrees angle. In the final scenario (3), the light sources were placed wide apart to stimulate peripheral vision.

5.2 Results

The results of the first study are presented in Figure 5. On the horizontal axis the three different angles (three scenarios) are compared. The first column of each pair shows the mean score obtained for a particular angle when observing the chart in the real scene. The second column shows the same condition displayed on the HDR monitor. From these results it can be seen that the mean visibility difference between observing the chart in the real scene and on the display is insignificant in the first two scenarios (see also Table I). This is important because it highlights similarity between reality and the display (providing that there is no clamping of the luminance channels when displaying the HDR photograph). However, the output from the t-test shows that in the third scenario (i.e. with the lights positioned such that the peripheral vision would play a major role) there are statistically significant differences between the two conditions (large targets: $T = 2.07, p < 0.05$). More specifically, the visibility on the HDR display is systematically higher than in reality. This is interesting as it emphasizes the effect of peripheral vision on our visual system. In the third scenario, when standing in the real environment, the presence of direct light sources causes light scattering in the retina (veiling effects) which lowers our contrast sensitivity decreasing the eye's ability of detecting the stimulus. When the same scene is captured with a camera, such light sources have very little effect as they are not directly visible, hence contrast detection is not affected.

As it can be seen from the inset of Figure 3, the contrast sensitivity chart used, contains target of two different sizes to account for spatial frequency. In all three trials of this study, we asked participants to observe firstly the large targets and then the smaller ones. The results for the small targets are represented by the red columns while the blue columns are the results for the larger targets. The visibility score for the smaller targets was usually lower, this is understandable since the eye's contrast sensitivity decreases at higher spatial frequencies. Even with the smaller targets the results had the same trend and statistically there are differences in visibility when the light sources are affecting peripheral vision (small targets: $T = 2.07, p < 0.05$). t-test results for Study 1 are shown in Table I.

Table 1: t-test results for Study 1.

1 (10 deg)	mean Real	mean HDR	t-test
small targets	3.08	2.83	$p = 0.34$
large targets	3.25	3.0	$p = 0.32$
2 (60 deg)	mean Real	mean HDR	t-test
small targets	3.91	3.75	$p = 0.57$
large targets	4.16	4.0	$p = 0.58$
3 (120 deg)	mean Real	mean HDR	t-test
small targets	4.0	5.16	$p < 0.05$
large targets	4.25	5.33	$p < 0.05$

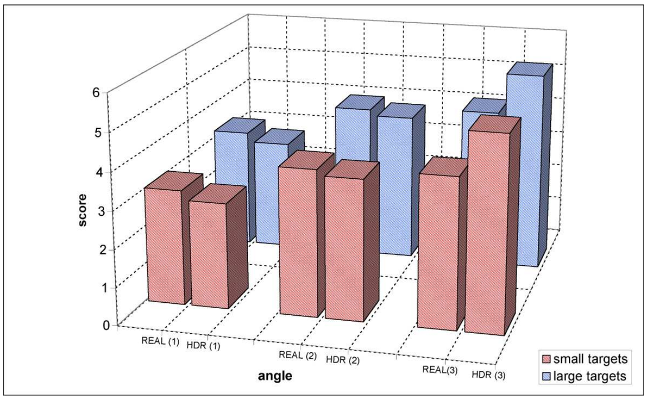

Figure 6: The results of Study 1. The red bars represent the mean score obtained when reading the small targets. The blue columns refer to the large targets. Each column-pair represent the score for the real and HDR scenes respectively.

The graph in Figure 6 clearly shows how the visibility is affected when standing in the real scene (red line) and observing a high dynamic range photograph on the display (green line). The visibility was calculated base on the mean score of all subjects with both target sizes. Note how the visibility is very similar for smaller visual fields, however, as the light sources are positioned further away from the foveal angle, the visibility in the real scene suffers whereas on the photograph it rises constantly.

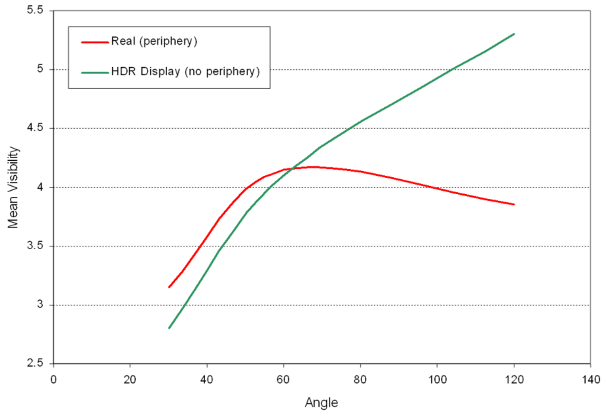

Figure 7: Comparing changes in visibility. As peripheral vision becomes more predominant, the visibility in the real scene is affected. When the same scene is captured with a camera and displayed on a monitor, important information is missing resulting in higher visbiilty which is not an accurate representation of reality.

Table 2: t-test results for Study 2 for scenario 3.

3 (120 deg)	mean Real	mean HDR	t-test
small targets	4.58	5.0	$p = 0.43$
large targets	5.41	5.48	$p = 0.12$

6 Study 2: Foveal vs Peripheral

In the first study we conducted the experiment in dark room having as the only source of light two spotlights. In a second experiment we wanted to determine whether the results obtained in the previous investigation would be affected by a more typical environment with a higher ambient level. The task was the same as in the previous experiment, however, in this case, we conducted the experiment in a bright environment which included still the two central lights. Once more, we wanted to determine how the visibility of the contrast chart would be affected as function of the angle.

6.1 Results

The mean scores and t-test results are shown in Table II. Note that we only present the t-test for the third scenario. Some important differences can be seen between Study 1 and Study 2. Firstly, the overall visibility is systematically higher when a higher ambient level is present. Secondly the scores of the three scenarios are much closer to each other. However the most interesting results are once more in the third scenario. From Table II it can be seen that although (as in Study 1) the visibility on the HDR is higher than in the real scene, statistically the mean differences are small enough to be insignificant ($p > 0.05$). These results are not surprising. The light sources, independently of their position, had a smaller influence on the overall visibility of the targets since the viewer's adaptation level was much higher. Therefore, we did except a close match in *all* three cases. This could probably be explained looking at the sensitivity of the eye. In particular the *threshold versus intensity* (tvi) function (see [17]). A vast majority of this function closely follows Weber's law demonstrating how our visual system is designed to distinguish objects from its background. The discrimination of luminances is strictly related to adaptation level. At the higher adaptation level of the second experiment, the spotlight (despite their position) had very little influence on visibility since the visual system is already adapted to such luminance levels.

7 Study 3: display vs viewer

In the previous two studies, the test scenes were very controlled allowing a precise and objective measure of the ability of our HDR device to linearly display a high contrast environment and the differences with reality. Although the results obtained for the two experiments are statistically significant and convincing, we further wanted to investigate the influence of a wider visual field when more natural scenes were shown. A possible approach would have been to compare once more real scenes with the HDR display. However, this is not always practical as we do not necessarily have access to interesting test scenes, furthermore, it may be difficult to run psychophysical experiments in certain environments. As mentioned in section 3.2, we own another HDR device which can be used as a good alternative to reality. Although both devices are capable of displaying huge luminance ranges there are some important differences. The main difference is that the HDR stereo viewer allows for 120 degrees field of view in each eye, which is close to human vision and has been shown to be a reasonable approximation of a real scene, see Ledda et al [16].

7.1 Experimental procedure

In the third study, we asked a sample of 8 participant (a group of computer graphics students) to observe 4 images images on both high dynamic range devices. Each observer was instructed to *rate* on a Likert scale from 0 to 5 the images in terms of how similar visibility and contrast were. A score of 5 indicated that an image displayed on both devices was perceived as identical. We gave each participant two practice trial allowing them to become familiar to the devices and rating system. We emphasized that we were interested in *visibility* and *contrast* rather than comparing based on more generic properties such a similarity of stimuli. The two devices are so different that comparing in terms of similarity could confuse some participants, while rating more specific properties such as color or contrast is more meaningful and simple.

Results show that the perception of the scene (in terms of contrast and visibility) is similar when observing an image in the HDR wide-field viewer and HDR display. Rating experiments require however a larger sample to obtain some statistically meaningful data. In the future we are planning to run a more extensive investigation. From these initial results however, it appears that in more common and natural scenes, peripheral vision has less of an effect than what the results show in the first study.

8 Discussion and Conclusion

In this paper we presented a series of psychophysical experiments to firstly validate a high dynamic range device against a real scene and secondly to determine how contrast discrimination of our visual system is affected by peripheral vision. From the results of our studies, it is clear that in most circumstances, there is a very close match in terms of visibility and contrast between observing or standing in a real scene and viewing a representation on the HDR display. This is significant if we are to use these devices as *tools* to simulate real scenes. When the same HDR photograph is displayed on a typical monitor, the visibility is very different from reality. However some discrepancies did occur. Of the three scenarios tested, in the first two the mean score was statistically equivalent between real and display. In the third scenario, where we specifically tested how peripheral vision affects visibility, the result was quite different. The contrast detection in the real scenes was systematically lower (particularly in the first study). This suggests that when light sources are present in our periphery, peripheral vision plays a major role in visibility.

The results obtained in the less controlled and more natural third study support the outcome of the previous two experiments. On average, participants did not perceive large visibility differences (apart from the obvious differences in visual field) when observing images on the HDR display or on the more realistic HDR wide-field viewer. From these results it appears that $information$ in the eye's periphery does not account greatly for visibility. This is because, the scenes tested were more natural environments with many light sources scattered over the scene, limiting the importance of peripheral vision. On the contrary in the third scenario of Study 1, we tested the extreme case where peripheral vision plays the major role in vision. Therefore when the scene is captured with a narrow-field lens, crucially important light sources, are not taken into account affecting enormously the visibility between peripheral and non-peripheral vision.

Understanding how these devices work and how the perception of a scene compares to reality is important if we are to use such displays as a reference. Future work will also consider developing tone mapping operators for high dynamic range devices in order to represent, in a meaningful and realistic way, the extremely large luminance variations of the real world.

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