Perceptual Impact of Peak Luminance and Contrast in Direct View HDR Display

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Abstract

Characterization of a high dynamic range (HDR) display's performance can be largely defined by its contrast and peak luminance. Prior work has studied this question for virtual reality (VR) using a haploscopic HDR setup, but it is not obvious if those results are transferrable to a more traditional viewing setting, such as direct view. In this work, we conducted a study to measure user preference for different contrast and peak luminance parameters in this scenario, and develop a perceptual just-objectionable-difference (JOD) scale to quantify preference scores. This is accomplished by studying contrast and peak luminance conditions across several orders of magnitude, shown on a professional HDR display with peak luminance of 1,000 nits and 1,000,000:1 contrast. The data is used to develop a computational model that can drive display design and future standardization of the definition of HDR, in terms of human preference.

Introduction

The contrast and peak luminance of a display are the most important characteristics defining the quality of a high dynamic range (HDR) display. Industry standards for commercial displays define at which point a display can be considered HDR for these parameters and others, like color gamut and bit depth. However, standards such as DisplayHDR do not provide a perceptual rationale for how tiers were selected in their standard. We show that DisplayHDR is not spaced in equal perceptual units (see Figure 1), as defined by our model. Prior work has tried to answer this question, but have not studied the full range of parameters relevant for HDR displays.

Much of the prior work on characterizing preferences in HDR displays has focused on determining black level or highlight preferences, but not the two in combination. We compare different studies in Table 1. Furthermore, prior works have studied conditions specific to a certain application, such as virtual and augmented reality (VR/AR) or cinema. It is unclear whether the results of studies targeting these specific application scenarios can be translated to more traditional direct view conditions.

In our work, we develop a unified perceptual scale for quantifying user preference across different contrast and peak luminance parameters in a more traditional, direct view HDR scenario. We do this by following the study methodology of Chen et al. [1], with some modifications for direct-view displays. This scale allows us to make design decisions for display that can inform decisions on display power and more.

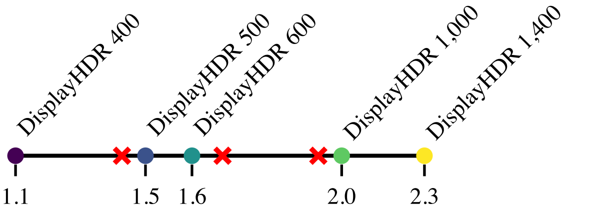


Figure 1. *In this plot, we show that the existing standard for HDR, DisplayHDR, is not spaced in equal perceptual units (JODs) as defined by our model. Red X marks are equally spaced as evaluated by this model (parameter values can be seen in Table 2).*

Background & Related Work

The term HDR can encompass the full pipeline of capture, processing, and display. HDR capture can include camera technologies with specialized sensors, and processing pipelines may include technologies that convert camera captures to HDR content. In this work, we focus on HDR display technology – specifically on how the performance of an HDR display can impact user preferences.

Kunkel and Reinhard [8] argued that the contrast capabilities of a high-end display could approximate the simultaneous dynamic range, i.e. the brightest and darkest features detectable under a given adaptation state, of the human visual system, which can span more than 4.7 log nits of luminance. Work on lightness perception [9] found that the human visual system is capable of distinguishing lightness values over a range of greater than 3 log nits of luminance. While these works studied the perceptual thresholds of absolute luminance perception, ours aims to study a more practical question of user preference across a range of relevant HDR contents.

The work of Chen et al. [1] forms the basis of this paper, and

Comparison of our work to prior studies.

Study	Peak Luminance	Contrast	Setting
Wanat et al. [2]	✘	✔	Direct View
Mantiuk et al. [3]	✘	✔	Direct View
Chen et al. [4]	✔	✘	Augmented Reality
Hammou et al. [5]	✔	✘	Direct View
Matsuda et al. [6]	✔	(✔)	Virtual Reality
Daly et al. [7]	✔	(✔)	Cinema
Chen et al. [1]	✔	✔	Virtual Reality
Ours	✔	✔	**Direct View**

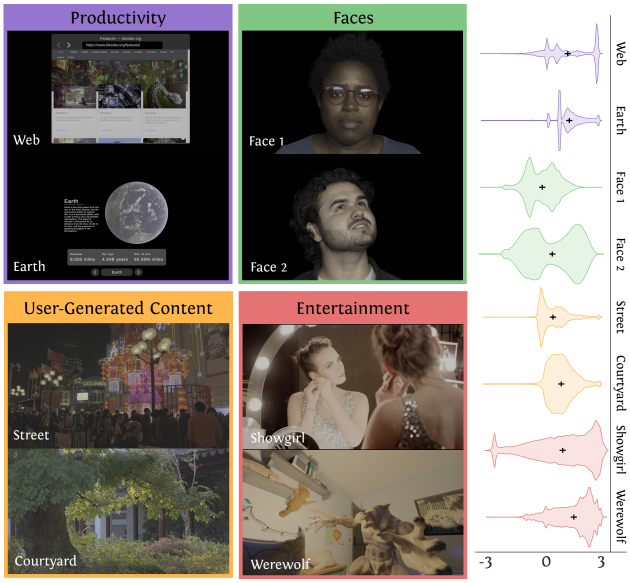


Figure 2. *User study stimuli (representative video frames) are shown here, grouped by content category and tone-mapped for display. The luminance distribution of each scene is shown to right, in logarithmic units. Note that the black background in Productivity and Faces scenes was excluded when plotting luminance distribution.*

is the only study that has defined a perceptual scale for HDR for a wide range of contrast and peak luminance parameters. However, their study focused on HDR VR, where they designed a haploscope testbed. Much of the prior work has studied one of either peak luminance or contrast, but not both. Matsuda et al. [6] used a prototype HDR VR headset [10] to study preferred peak luminance for different passthrough VR scenes. The work of Daly et al. [7] studied preferences for different exposure values in diffuse images, and highlight preference in images with specular regions. Their work focused on cinema, and even simulated exit sign lighting. Other works [2, 3] aimed to determine black level requirements of an HDR display, while some studied the effect of peak luminance on realism [4] or of the interaction of peak luminance and viewing distance [5]. Our work is the first to define a perceptual scale for HDR across several orders of magnitude for both peak luminance and contrast in a direct view HDR setting.

Experiment Methods

The goal of our user study is to determine preference scores across a range of peak luminance and contrast parameters in a direct-view HDR display. We base our study design on Chen et al. [1], but adapted it for our direct-view scenario. The main differences between the two studies is in the hardware apparatus and in the stimuli, both described in the next paragraphs.

Hardware Apparatus An EIZO CG3146 professional HDR monitor with a peak luminance of 1,000 nits and contrast ratio of 1,000,000:1 was used as our testbed for subjective studies. The display was calibrated with a spectroradiometer to a REC.2020 color gamut with PQ EOTF. Participants were seated 114.3 cm (0.88 diopters) away from the display, and the room lights were turned off.

Participants In total, 12 participants (6 men, 6 women) took part in the study. Participants had normal or corrected-to-normal vision, and completed the Ishihara test to assess color vision deficiency before beginning the experiment. The study was approved by an Institutional Review Board (IRB).

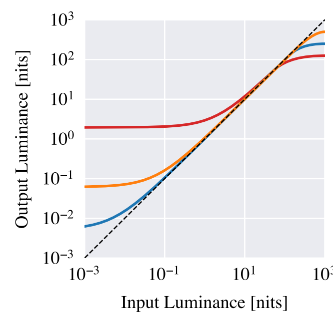
Stimuli Users were shown two scenes from each of four relevant content categories: faces, productivity, entertainment, and user-generated content (UGC). See Figure 2 for example frames taken from the stimuli videos, tone-mapped for display here. Productivity and faces content as well as the ”Werewolf” scene are from Chen et al. [1], ”Showgirl” from Froehlich et al. [11], and UGC scenes from Song et al. [12]. The luminance distributions of the videos is also displayed. Videos were encoded with HDR10 metadata (4K, 60fps, 10-bit, BT. 2100 primaries, PQ EOTF), and manually mastered to the range of the HDR display.

Five contrast and five peak luminance conditions were simulated using tone mapping:

- Peak luminances: 63, 125, 250, and 1,000 nits
- Contrasts: 64:1, 320:1, 1,600:1, 8,000:1, and 40,000:1

The reference condition was anchored at 1,000 nits peak luminance and 1,000,000:1 contrast, which is the maximum capability of our HDR display.

A visualization of different parameter configurations using our display simulation tone mapper is shown in the inset, to right. We applied a generic S-shaped tone curve [4], defined by the fixed tone mapper from Chen et al. [1], to simulate differences in peak luminance and black level. The peak luminance is modified by computing a smooth roll-off at a starting luminance value, defined by a spline. The goal of this tone curve is to preserve mid-tones, while modulating black level and highlights. A similar tone curve was described in an International Telecommunication Union (ITU) standard recommendation for HDR TV [13].



Procedure The method of pairwise comparison was used in this study, with a two-interval forced-choice design (2-IFC). To start each trial, participants first viewed the reference (1,000 nit peak, 1,000,000:1 contrast) video. Participants were then able to switch between the reference and two test videos using a standard keyboard. During stimuli switching, a grey blank screen is inserted to not allow direct comparisons while swapping stimuli. The study task was to select the test video that appears closer to the reference, in terms of both contrast and brightness. In order to reduce the number of total comparisons, we used an adaptive sampling algorithm to schedule the optimal trials to show users. The *ASAP* [14] algorithm is used for this purpose; the algorithm samples trials by maximizing expected information gain. In total, the data amounted to 2,400 total trials completed.

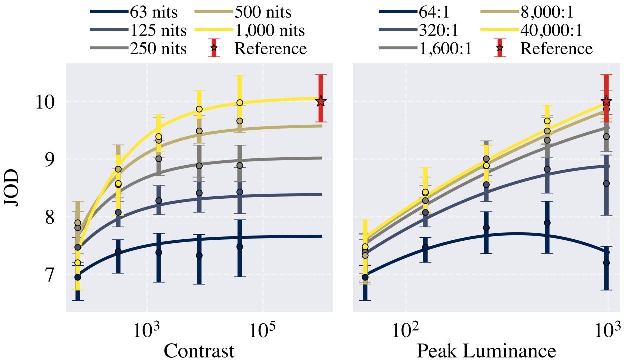


Figure 3. *Here, we show subjective study results (scatter points) and model fits (solid lines). The x-axis represents variable logarithmic contrast (left) or peak luminance (right), and the y-axis perceptual impact in JODs. The reference (red star) is pegged to 0 JODs. Single lines represent constant peak luminance (left) or contrast (right) conditions.*

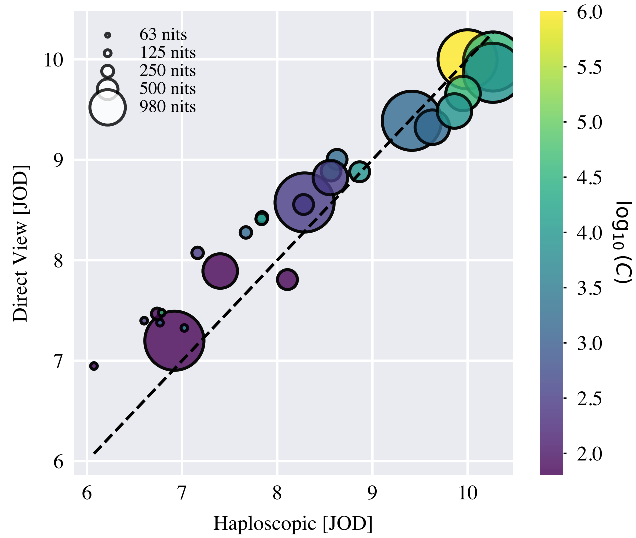


Figure 4. *We compare our direct-view results (y-axis) with the haploscopic (HDR VR) results from Chen et al. [1] (x-axis). Point color defines log-contrast, and point size defines peak luminance. The dashed line represents the identity line.*

Results The pairwise comparison responses were scaled to perceptual quality JOD scores assuming Thurstone's Case V assumptions using the *pwcmp* technique [15]. We show the scaled results in Figure 3 as scatter points, at constant peak luminance and contrast at left and right, respectively. Error bars, representing 95% confidence intervals, were simulated using 500 bootstrap samples via the same *pwcmp* algorithm. Inter-quartile normalized scores were computed, also using *pwcmp*, to detect outliers of which none were found.

We note that quality generally increases with contrast and peak luminance, but dips when contrast is extremely low (e.g. 64:1) and peak luminance is high (1,000 nits). The same effect was found to be true in Chen et al. [1] and Seetzen et al. [16].

An N-way analysis of variance (ANOVA) was conducted to determine the main effects of all study variables on JOD scores. The main effect of contrast and peak luminance on JODs was found to be significant ($p \ll 0.01$). The main effect of scene on JODs was not found to be significant, but the interaction effect of contrast and peak luminance with scene was ($p \ll 0.01$). The interaction effect of contrast and peak luminance was also significant ($p = 0.001$).

The closest related work to ours is the study from Chen et al. [1], where a perceptual scale was defined for HDR VR. We compared our results with those from Chen et al. [1] and computed correlations between the two datasets. We visualize this in Figure 4, where the x-axis are JODs from Chen et al. [1] and the y-axis JODs from our direct-view study. The Spearman rank order correlation was found to be $\rho = 0.97$ ($p = 1.41 \times 10^{-15}$), the Pearson correlation was $\rho = 0.98$ ($p = 2.38 \times 10^{-17}$), and the RMSE was 0.488. From this, we can conclude that there is high correlation between our results and the haploscopic ones from Chen et al. [1], suggesting that the two viewing conditions result in similar preference scores. We note, however, that direct view JOD scores are consistently higher (above identity line) for low-contrast conditions and lower for high-contrast conditions.

Model

We optimized the parameters of the polynomial model from Chen et al. [1] to our subjective study data. The model has the following form:

$$\mathscr{M}(L_{\min}, L_{\max}) = \left(k_1 - k_2\sqrt{L_{\min}}\right) \cdot \left(\log_{10}(L_{\max})^{k_3}\right) - k_4, \tag{1}$$

where $L_{\min}$ and $L_{\max}$ are black level and peak luminance, respectively, and k_i are parameters to be optimized. The model outputs JODs given these inputs. Note that we define contrast as $C = \frac{L_{\max}}{L_{\min}}$, so contrasts can be converted to black level $L_{\min}$. The optimized parameter values are

$$k_1 = 3423.04, k_2 = 0.00014, k_3 = 3426.64, k_4 = 0.68530. \tag{2}$$

The fitted model has RMSE of 0.134 and MAE of 0.110, in JOD units. Model fits plotted over study data are shown in Figure 3 as solid lines, and across the full range of peak luminance and contrast in Figure 5.

Applications

We apply the computational model to relevant applications, including display design and HDR standardization.

Display Design

The design of a display – the hardware components that affect its performance – influences factors like power consumption [17] and manufacturing/fabrication cost. In an LC display, power can be modeled as a linear function of peak luminance [17, 18]. Interpreting display power savings given the plot in Figure 5, the peak luminance axis (y-axis) can be taken to represent relative power savings. Iso-JOD lines then represent a tradeoff in display power (peak luminance) and contrast. More complex dimming schemes, e.g. local dimming, may boost contrast, thereby allowing lower peak luminance (and power consumption) at the same perceptual impact.

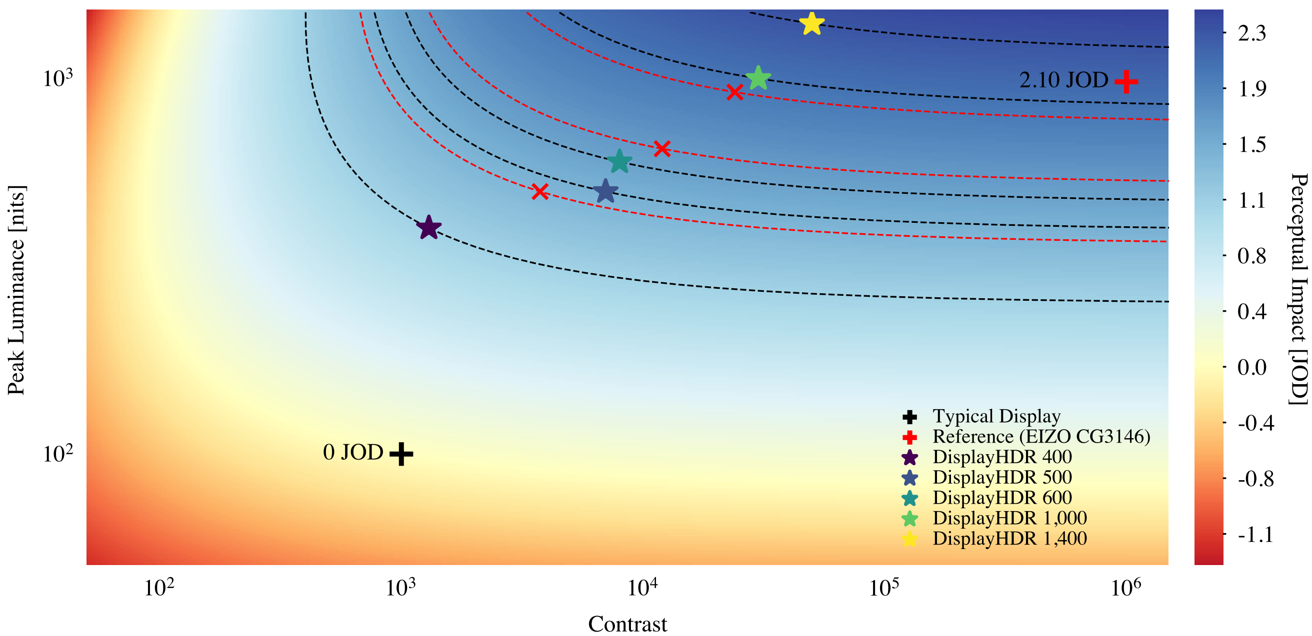


Figure 5. *We show a heatmap representing model evaluations for combinations of contrast (x-axis) and peak luminance (y-axis), both logarithmic. Colors represent perceptual impact in JODs, with the baseline set to a typical display with 100 nits peak luminance and 1,000:1 contrast. Star points are parameters of DisplayHDR, and the dashed lines represent iso-JOD lines. Red dashed lines (and X's) are equally spaced between the lowest and highest tiers in DisplayHDR.*

HDR tier list.

	DisplayHDR			*Ours*		
	Peak Luminance	Contrast	JOD	Peak Luminance	Contrast	JOD
Tier 1	400	1,300	1.08	400	1,300	1.08
Tier 2	500	7,000	1.46	500	3,750	1.39
Tier 3	600	8,000	1.59	650	12,000	1.67
Tier 4	1,000	30,000	2.01	920	24,000	1.95
Tier 5	1,400	50,000	2.25	1,400	50,000	2.25

HDR Standard

Given our model, we can define a new tier list for HDR displays that is perceptually-informed. In the DisplayHDR standard, tiers spacing is not perceptually uniform when computed using our model, as seen in Figure 1. Instead, we can use our model to interpolate between the lowest and highest tiers of DisplayHDR to sample JOD scores uniformly (shown with red crosses in Figure 5 and Figure 1). Peak luminance, contrast, and JOD values for DisplayHDR and our adjusted parameters are shown in Table 2.

Conclusion

In this work, we defined a perceptual scale across a wide range of peak luminance and contrast parameters, spanning multiple magnitudes, for a direct-view HDR display. We simulated these different displays using tone mapping, and conducted a study assessing preference for relevant content categories. Data was scaled to perceptual units, and compared to prior art. The data was fit to a model and applications in display design and perceptually-uniform display categories were explored.

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Alexandre Chapiro is an imaging architect and senior staff research scientist at Meta's Imaging Experiences Architecture team in Reality Labs. Previously, he worked in the Applied Perception Science team at Meta, Core Display Incubation team at Apple, the Applied Vision Science team at Dolby Laboratories, and the Stereo and Displays group at Disney Research Zurich. He earned a PhD from the Computer Graphics Laboratory at ETH Zurich, and holds MS and BS degrees in Mathematics. Alexandre is interested in solving novel problems for industry applications, touching on perception, computer graphics, computational display, and psychophysics. Prior work involved perceptual difference metrics, brightness and color, stereo 3D, the perception of faces, and display topics like virtual and augmented reality, frame rate, high dynamic range and more.