Jones and Condit Redux in High Dynamic Range and Color

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Abstract

In a classic 1931 paper[1], Jones and Condit measured the luminance range in 130 natural scene "... to determine the perfection with which the tonal characteristics of a given scene can be reproduced by the photographic process". And while their data served photography well over 70 years, their results in no way represent what we see every day in both dynamic range and color. Yet, today's media are approaching such a standard, and it seems as important as it was then to revisit the Jones and Condit study in this larger context through the auspices of Fairchild's HDR photographic survey that captured and documented over a hundred natural scenes in their fullest range of luminance and color. Analysis of these scenes found contrast ratios or within scene dynamic ranges averaging 3 orders of magnitude approaching 6 orders at the 3 sigma limits of their distribution. By contrast, Jones and Condit found an average of 160:1 with a maximum value of 750:1, certainly less than 3 orders of magnitude in total. Perhaps not surprising, a large proportion of the distribution of color in these scenes were largely confined to in and around the neutral axis, However, a small, but significant portion was found that almost fill the gamut of all possible colors in CIE chromaticity space, certainly well outside the current digital cinema and video standards for color.

Introduction

Jones and Condit[1] measured the luminance range in 130 natural scenes taken in daylight of "… an object or a collection of objects of which a photographic reproduction is to be made." Their motivation was "… to determine the perfection with which the tonal characteristics of a given scene can be reproduced by the photographic process, [and in order to accomplish this,] it is necessary to know the brightness[1] scale of the scene." Their measurements served the science of photography well for over 70 years. Yet, their results in no way represent what we see everyday in terms of both luminance and, specifically, color which would not become pervasive in photography until some 25 years after Jones and Condit's paper was published.

Today, the media has progressed significantly over what was possible in a photographic print made in Jones and Condit's time. Dynamic range in luminance of up to five (5) orders of magnitude is now possible in high dynamic range (HDR) displays[2]. Color gamut approaching McAdams' locus of pure, spectral colors are achievable through the use of LED and laser primaries that are just beginning to appear in the marketplace. These media will soon be able to reproduce the entirety of our visual experience.

Just as in Jones and Condit's time and the photographic reproduction of objects, it is now necessary to know what they termed as the brightness scale of the scene in the context of what is now possible. And just as necessary is the extent of color in a scene. The bright, luminous colors of a sunset. The fiery, red leaves of a maple on a Fall day. The glaring red of a stoplight. Hence, revisiting the Jones and Condit study in this much broader context seems warranted. And through the auspices of a study by Fairchild[3] capturing and documenting over a hundred natural scenes in their fullest range of luminance and color, such a revisitation is possible.

Background

Jones and Condit determined contrast ratio or, in their terms, luminance ratio defined as the ratio of maximum to minimum brightness. They classified the scenes into five groups and their results for each of the groups are shown in Table 1. $B_{o,MIN}$ and $B_{o,MAX}$ are the minimum maximum luminance which Jones and Condit reported in foot-Lamberts and, as shown here, are converted to cd/m^2 (3.426 cd/m^2 per foot-Lambert). BS_o is their luminance ratio, and $B_o(M)$ the mean luminance as measured by an exposure meter also converted here to cd/m^2. Overall, they obtained an average contrast scale of 160:1 with a maximum of 750:1 occurring in Group 4 scenes – front lit in sunlight with the principle object in the shade.

Table 1: Jones and Condit Scene Summary by Group[1]

Group I: Front lit, distant, sunlit

	$B_{o.MIN}$	$B_{o.MAX}$	BS_o	$B_o(M)$
Min	68.5	5140	27	2,470
Max	548	39,400	285	19,500
Average	188	15,400	80	6,340

Group 2: Front lit, remote, sunlit

	$B_{o.MIN}$	$B_{o.MAX}$	BS_o	$B_o(M)$
Min	28.8	2,810	35	270
Max	260	31,500	99	11,600
Average	83.9	10,800	38	3,120

Group 3: Front lit, near-by, sunlit

	$B_{o.MIN}$	$B_{o.MAX}$	BS_o	$B_o(M)$
Min	19.2	2,120	42	685
Max	71.9	27,400	630	7,200
Average	18.8	8,220	190	1,990

Group 4: Front lit, near-by, sunlit, but with principle object of interest shaded

	$B_{o.MIN}$	$B_{o.MAX}$	BS_o	$B_o(M)$
Min	6.85	2,430	115	182
Max	39.7	13,700	750	2,470
Average	15.8	5,480	344	1,200

[1] Jones and Condit used the "brightness" to refer to what we now term as luminance and "brightness scale" to contrast ratio or dynamic range.

Group 5: **Heterogeneous scenes under haze, light cloud, and heavy cloud conditions**

	$B_{o.MIN}$	$B_{o.MAX}$	BS_o	$B_o(M)$
Min	2.81	188	27	130
Max	171	12,700	640	7,880
Average	21.6	3,600	165	1,100

Summary for all scenes

	$B_{o.MIN}$	$B_{o.MAX}$	BS_o	$B_o(M)$
Min	2.81	188	27	130
Max	548	39,400	750	19,500
Average	9.7	7,880	160	2,190

In 2007 Fairchild traveled across North America taking a photographic survey for the purpose of providing a significant body of high dynamic range, thoroughly documented images for research purposes. And unlike Jones and Condit, Fairchild's work consisted of both daylight and night scenes, indoors and outdoors, front lit and backlit scenes. The images where captured using a Nikon 2Dx digital SLR with a 12.4 mega-pixel CMOS sensor fully characterized to within an average ΔE^*_{ab} of 2.5 with a standard deviation of 2.5 over 18 stops of exposure using the scene depicted in Figure 1. The images were typically captured in a nine (9) stop exposure sequence within 2 seconds along with a number of scene specific measurements using a Konica-Minolta CS-100 spot colorimeter in absolute luminance (cd/m^2) and CIE 1931 chromaticity coordinates. Ultimately, each scene is available in OpenEXR format where each pixel in a scene can be represented in 32 bit, floating point, CIE XYZ. It is in this form that the following analysis is based consisting of over a trillion pixel values in over 100 scenes.

Figure 1: Luxo Double Checker, the camera characterization scene

Methodology

First, the scenes were processed for their respective luminance information then classified and presented in a similar framework as Jones and Condit[1]. Then, the scenes are process for their respective color information, and a distribution of CIE xy chromaticity presented at successive layers of relative scene luminance. The determination of relative scene luminance is made under the assumption that the world averages 20% gray (or 18% depending your persuasion). Hence, each luminance value in a scene is normalized to its average luminance presumed to be 20% gray. In this way, color information can be put on the common basis of relative luminance across all scenes.

Results and Discussions

Figure 3 illustrates the distribution of the log absolute luminance in cd/m^2 of the combined luminance values over all scenes and can be compared to Figure 2 that illustrates the light sensitivity of the human visual system. As such, the distribution of absolute luminance from the Fairchild's survey spans that shown in Figure 2 from 0.01 cd/m^2 (a log luminance 0f -2) night scenes through to 100,000 cd/m^2 (a log luminance 0f 5) scenes lit by bright sun.

Figure 2: The light sensitivity of the human visual system (HVS)

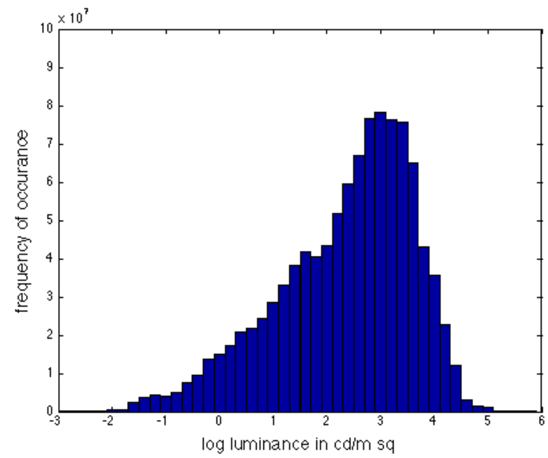
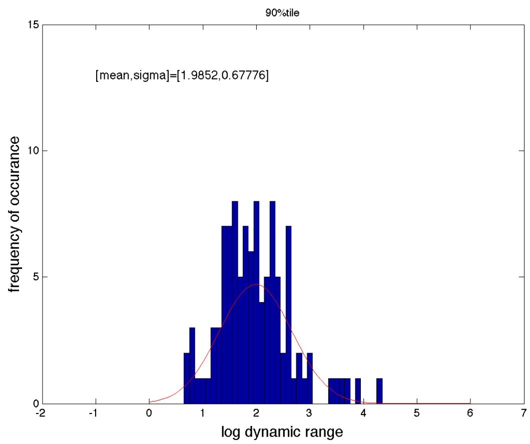


Figure 3: Overall distribution of luminance

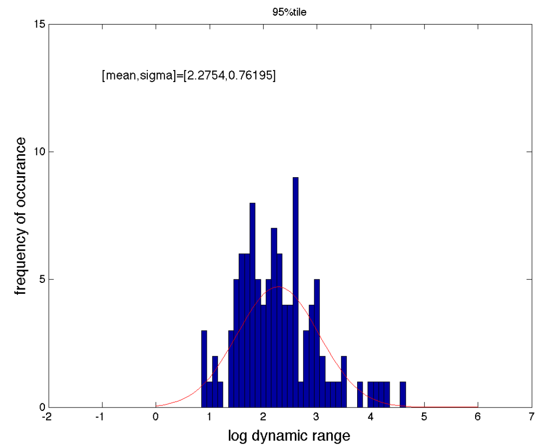
Dynamic Range

The determination of scene dynamic range in luminance (contrast ratio) depends on what selection criteria are used to pick the minimum and maximum luminance in a scene. In this analysis, dynamic range for each scene is computed as a function of the central percent of the histogram of luminance values for that scene. For example, if the computation is based on the central 95% of the values in a scene, then the minimum value is taken at the 2.5th percentile and the maximum at the 97.5th. Dynamic range is then the this maximum luminance value divided by the minimum value and is reported here as the log of this ratio.

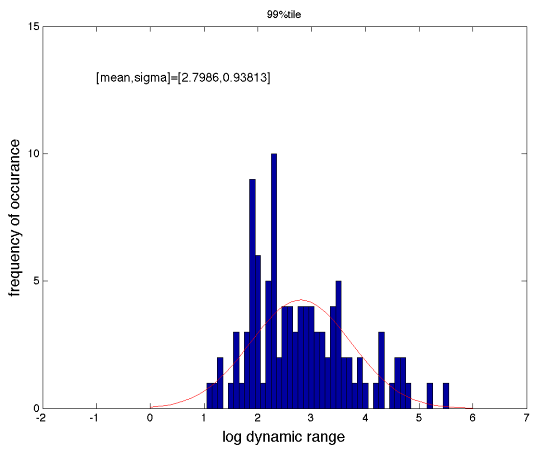
Figure 4 illustrates the histograms of log scene dynamic range for each of the 90th, 95th, 99.5th, 99,9th, and 99.95th percentile scene selection criteria. And as Jones and Condit, scene dynamic range is assumed normally distributed over a large number of scenes. Figure 4 then also includes the computed normal distribution over all scenes and their corresponding mean and standard deviation, and Figure 5 illustrates the three (3) sigma, log dynamic range of this distribution as a function of the selection criteria. For a criteria of 50% or the central half of the histogram of scene luminance is considered, the three sigma log dynamic range is approximately 2.6 or 400:1; of 90%, approximately 4 or 10,000:1; for 95%, 4.6 or 40,000:1; and so on. As the selection criteria approaches 100%, the three sigma dynamic range approaches six orders of magnitude.



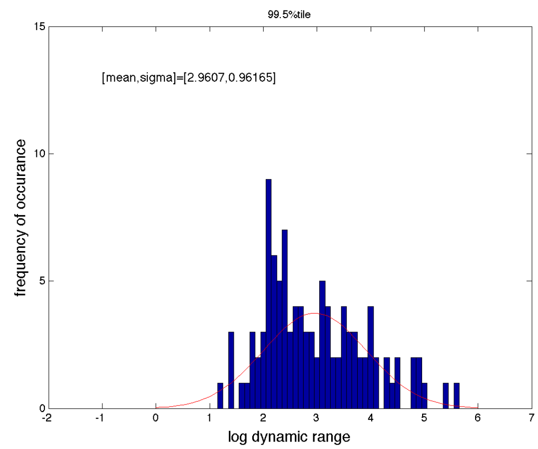
(a) 90th Percentile



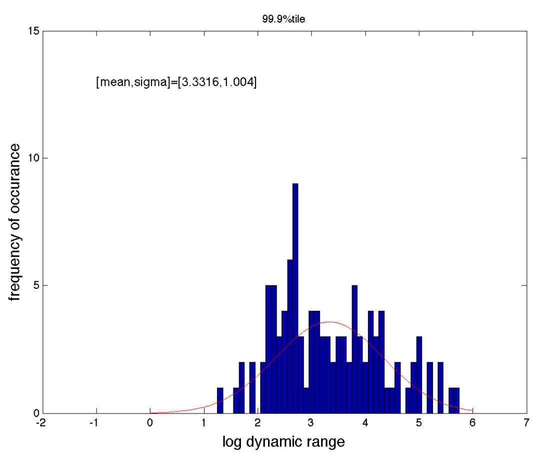
(b) 95th Percentile



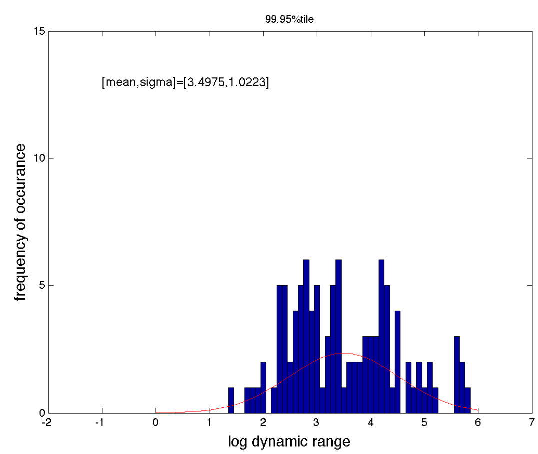
(c) 99th Percentile



(d) 99.5th Percentile



(e) 99.9th Percentile



(f) 99.95th Percentile

Figure 4: Distributions of scene luminance scale taken from the (a) 90th percentile of computed scale within a scene, (b) 95th percentile, (c) 99th percentile, (d) 99.5th percentile, (e) 99.9th percentile, and (f) 99.95th percentile

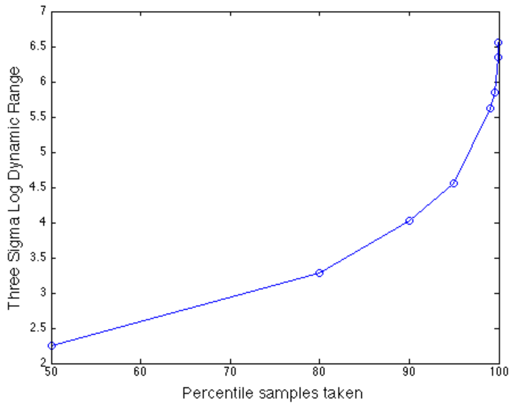


Figure 5: The log of the three sigma, maximum scene dynamic range as a function of the percentile of samples taken within a scene

The maximum value observed by Jones and Condit was 750:1, significantly less then the 90% and above selection criteria as Jones and Condit restricted their measurements to objects whereas this analysis includes everything. For example, the image illustrated in Figure 5 includes direct sun viewed through the leaves of a back lit tree and has a 99.5th percentile scene dynamic range of 11,100:1. The camera calibration scene illustrated in Figure 1 has a 99.5th percentile scene dynamic range of 252,000:1 approacing 1,000,000:1 at the 99.95th percentile, the highest dynamic range observed in this survey.

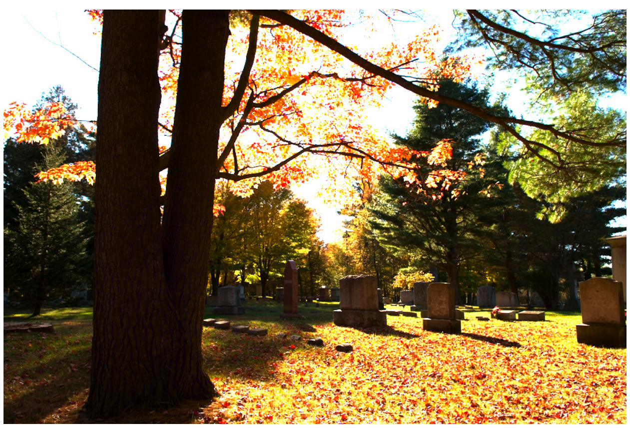


Figure 6: The Cemetery Tree, backlit, direct sun

Scene Classification

In concert with Jones and Condit, the survey scenes were classified into groups (Table 2), and Groups 1 through 4 of the survey scenes was intended to match Jones and Condit's groups. In Groups 1 and 2, this analysis reports scene dynamic range for the survey scenes at least two orders of magnitude greater than Jones and Condit for the reasons already mentioned. The remaining parameters for these groups show some likenesses, yet its difficult to make any definitive statement except that the Jones and Condit scenes are much more specific to the four groups. Hence, their members more numerous. In the case of Groups 3 and 4, clearly little can be said as the survey is very sparse, no members in Group 3 and only two in Group 3.

Table 2: HDR Scene Summary by Group for 99.5th Percentile

Group I: Front lit, distant, sun (16)

	$B_{o.MIN}$	$B_{o.MAX}$	BS_o	$B_o(M)$
Min	2.81	595	25.4	141
Max	359	33,100	3,040	6,650
Average	91	1,500	534	720

Group 2: Front lit, remote, sun (36)

	$B_{o.MIN}$	$B_{o.MAX}$	BS_o	$B_o(M)$
Min	0.7	1,290	14.2	106
Max	919	44,600	7,100	11,200
Average	105	11,900	687	4,200

Group 3: Front lit, near-by, sun (0)

	$B_{o.MIN}$	$B_{o.MAX}$	BS_o	$B_o(M)$
Min	-	-	-	-
Max	-	-	-	-
Average	-	-	-	-

Group 4: Front lit, near-by, sun, but principle object of interest shaded (2)

	$B_{o.MIN}$	$B_{o.MAX}$	BS_o	$B_o(M)$
Min	5	14,500	272	2,500
Max	52	21,200	4,400	4,790
Average	28	17,600	2,400	2,370

Group 5: Indoors (16)

	$B_{o.MIN}$	$B_{o.MAX}$	BS_o	$B_o(M)$
Min	0.015	1,450	2,150	12.3
Max	1.76	13,150	252,000	9,670
Average	0.380	4,940	62,000	64.5

Group 6: Outdoors, night (10)

	$B_{o.MIN}$	$B_{o.MAX}$	BS_o	$B_o(M)$
Min	0.0076	0.980	129	0.285
Max	5	1,240	10,700	310
Average	0.380	369	2,570	12.7

Group 7: Backlit (12)

	$B_{o,MIN}$	$B_{o,MAX}$	BS_o	$B_o(M)$
Min	0.5	2,960	396	247
Max	104	623,000	11,100	33,400
Average	33	118,000	4,080	6,760

Group 8: Sunsets (7)

	$B_{o.MIN}$	$B_{o.MAX}$	BS_o	$B_o(M)$
Min	2.5	1,210	113	268
Max	15	97,500	10,200	291
Average	8	22,600	3,310	90.4

Group 9: Cloudy (8)

	$B_{o.MIN}$	$B_{o.MAX}$	BS_o	$B_o(M)$
Min	0.5	242	64.9	89.4
Max	65	10,500	6,820	2,300
Average	14.9	4,300	1,760	688

Summary for all scenes (107)

	$B_{o.MIN}$	$B_{o.MAX}$	BS_o	$B_o(M)$
Min	0.0076	0.98	14.2	0.285
Max	919	623,000	252,000	33,400
Average	54.9	20,400	10,700	2,390

Flare

A large portion of Jones and Condit's paper was dedicated to a careful accounting of flare. And as noted in Fairchild's paper[3], their care and concern was well placed as "… their typical absolute levels of flare were about 6% or the scene maximum", whereas " In the *Luxo Double Checker* scene [shown in Figure 1], the absolute flare level was approximately 0.0001% in the image data and 0.00007% in the photometric measurements." A typical, low dynamic range scene in the Jones and Condit study having a dynamic range of 100:1 would be reproduced at 100:2.5 or 40:1 at their reported average flare factor of 2.5 whereas the *Luxo Double Checker* reported by Fairchild as having approximately 1,000,000:1 would reproduce in the survey HDR image at 800,000:1 (252,000:1 as reported in the above at a selection criteria of 99.5%).

Furthermore, Fairchild notes that flare is "… very scene dependent, measurement location dependent, and image composition dependent …". And while Fairchild made special effort to minimize the effect of these factors, surely they ultimately affect these results for dynamic range along with selection criteria as noted above. And with regards to flare, it should also be noted that the human visual system (HVS) is certainly not immune from its effect either[4]. All this is not to say that high dynamic range (HDR) imaging both in instruments like cameras or the HVS is impossible. A recorded dynamic range of 252,000:1 is certainly well beyond current media technology and can certainly be characterized as HDR.

Color

Of course, the means to reproduce color photographically was not available at the time of Jones and Condit's study. And furthermore, had it been available, their interest would most likely be limited, as in their measurements of luminance, to the color of objects in a scene. The Fairchild survey, on the other hand, makes color available to its fullest extent. And if it is accepted that the survey has captured images at dynamic ranges exceeding that of fully adapted HVS's ability to comprehend and assuming that the Nikon sensor's color filter array (CFA) approximates a linear combination of the HVS's color matching functions, it could be said that the survey represents certainly a significant portion of color we see everyday. Colors that exceed what is possible in real objects. Again, the bright, luminous colors of a sunset. The fiery, red leaves of a maple on a Fall day. The glaring red of a stoplight and so on.

Figure 7 illustrates the entire distribution of CIE xy chromaticity in the survey. Again, over a trillion colors clustered around the D65 neutral ($[x,y]=[0.31,0.33]$. Each succeeding contour of the distribution represents a 5% increment in the total. As such, colors at the 20 to 25% percentile in both the cyan-green-magenta and purple exceed the ability of either the BT.709/sRGB standard primaries (shown in magenta) and a typical set of LED primaries (shown in cyan) to reproduce. Yet, because this representation in the form of a chromaticity diagram is overly simplistic, such a statement is correspondingly simplistic. It does not, in any way, convey how all this color is distributed in luminance. How much of it occurring at such a low luminance that it is not seen? Or at such a high luminance where only bright white is seen?

To this end, Figure 8 illustrates how color is distributed in relative luminance where, as noted in the above, relative luminance is normalized to the scene average. For example, Figure 8(a) illustrates the distribution in CIE xy chromaticity of those samples whose log relative luminance is less -2.5 (0.00316 times the scene average). Each contour of the distribution represents a 5% increment of, in this case, 1.16% of the total samples in the survey.

The distribution shown Figure 8(a), because there are so few samples at such a low luminance, more than likely is just noise. Figure 8(b) representing a more substantial 9.4% whose log relative luminance is between -2.5 and -1.5 (0.00316 and 0.0316 times the scene average) begins to show some structure. While the bulk of the distribution is clustered around dark green characteristic of foliage (Many of the scenes in the survey are taken with dark foliage in the scene.), clearly the beginnings of a cluster is forming around the neutral axis ($[x,y]=[0.31,0.33]$). And this clustering around neutral is further exemplified in Figure 8(c) representing 37.3% of the total between -1.5 and -0.5 (0.0316 and 0.316 times the scene average).

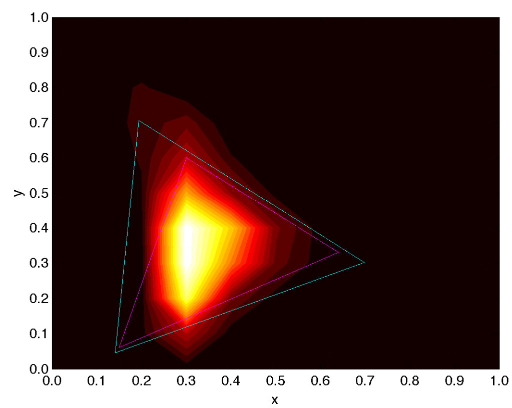
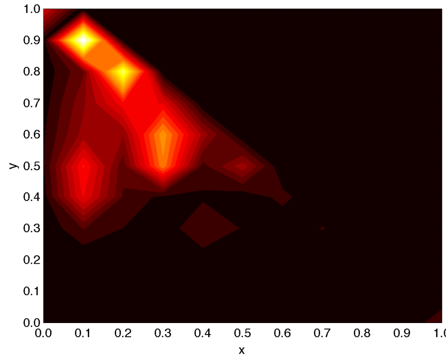


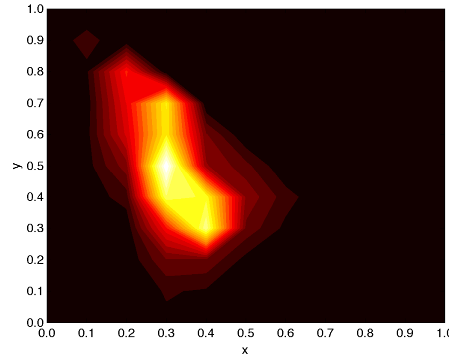
Figure 7: The distribution of CIE xy chromaticity for the survey images overlain with the BT. 709/sRGB standard primaries (magenta) and a typical set of LED primaries (cyan).

Figure 8(d) represents 46.8% of the total between -0.5 and 0.5 (0.316 and 3.16 times the scene average), and is further representative of object color as its central value of 0.0 (the scene average) is assumed to be 20% gray. Yet, the green-magentas at least at the 5% level approach the spectral limits of pure color[5], and it could be said that the purple surely exceeds the limit at least at the 5% level.

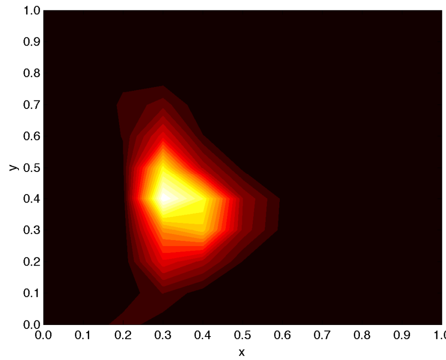
Beyond a log relative luminance of 0.5, Figures 8(e) – (g) and representing 5.3% of the total, the samples are clustered around neutral. And yet, a substantial portion are not that close to neutral. These, then, are clearly beyond object color as most are beyond diffuse white, a log relative luminance of 0.70 or 5 times the scene average of 20% gray, and these most likely are representative of the colors in the sunset scenes and scenes with bright blue sky, light sources, brightly colored Fall foliage, and the like.



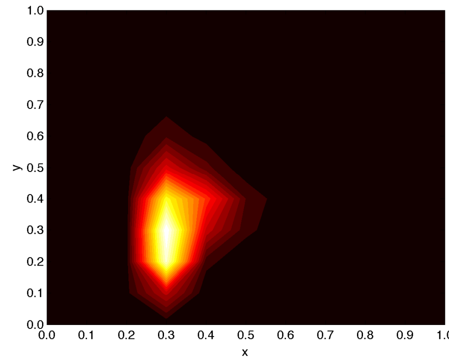
(a) $\log Y_{rel} < -2.5$ *(1.16% of the total samples)*



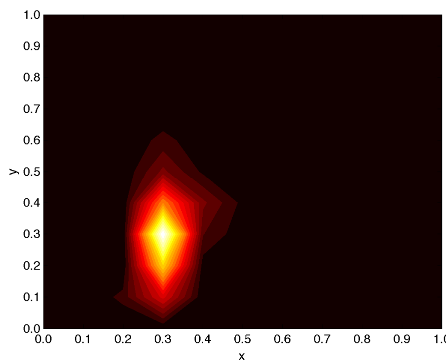
(b) $-2.5 \leq \log Y_{rel} < -1.5$ *(9.4% of the total samples)*



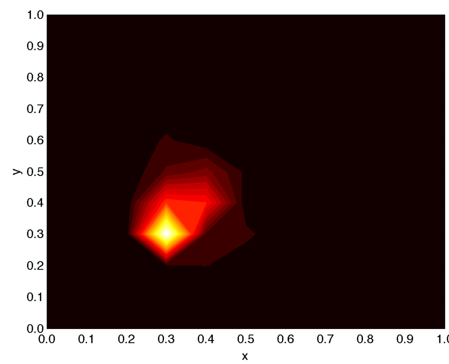
(c) $-1.5 \leq \log Y_{rel} < -0.5$ *(37.3% of the total samples)*



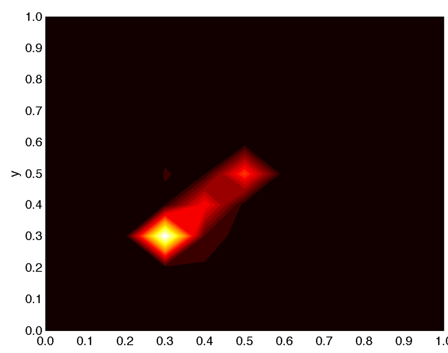
(d) $-0.5 \leq \log Y_{rel} < 0.5$ *(46.8% of the total samples)*



(e) $0.5 \leq \log Y_{rel} < 1.5$ *(5.3% of the total samples)*



(f) $1.5 \leq \log Y_{rel} < 2.5$ *(0.11% of the total samples)*



(g) $2.5 \leq \log Y_{rel}$ *(0.004% of the total samples)*

Figure 8: The distribution of CIE xy chromaticities according of the log of the relative luminance (Y_{rel}) on a scene-by-scene basis

Conclusions

The scope of Jones and Condit's work encompassed the luminance range of objects, at that time the photography of objects as its muse. Photography in color was simply not available in their time. Today's media technologies would have been difficult for them to envision, a media that is approaching the ability to reproduce the full visual experience of our daily existence. And so, by way of conclusion, it is worthy to ask whether all this is representative of what we see everyday.

It is argued that HDR capture, exceeding the dynamic range in luminance of the fully adapted HVS, and a sensor having a color filter array (CFA) that is a linear combination of the HVS color matching functions (CMF) is both necessary and sufficient for capturing the full visual experience. The first of these conditions, exceeding the dynamic range of the fully adapted HVS, is met. In viewing the *Luxo Color Checker* scene both in the real scene and its reproduction on an HDR display, the darker portions of the scene are not seen without covering the filament of the lamp. Hence, without the benefit of local adaptation, the range of luminance in such a scene cannot be totally comprehended by the HVS. Hence, depending on the selection criteria, dynamic ranges approaching six (6) orders of magnitude substantiate the first of these two conditions.

Once, the first condition is met, the second condition is answerable only to the degree to how well the device's CFA match, not just the CIE 1937 CMF, but an individual's CMF which we all know varies across individuals. Hence, it is not a question of capturing all of color. It's a question of once captured, does its reproduction match the original in the metameric sense. For each individual, they will not always match. Hence, *in lieu* of metamerism, such a device fulfilling both these conditions can, in fact, capture our entire visual experience. And this study only falls short in that the 100 or so natural scenes consisting Fairchild's HDR photographic survey cannot possibly represent all we have seen. But scene dynamic ranges approaching six (6) orders of magnitude and CIE chromaticity that come close to filling the entire space in xy at virtually all comprehendible levels of relative luminance are demonstrated.

References

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Biographies

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