Evaluation of Color Encodings for High Dynamic Range Pixels

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ABSTRACT

Traditional Low Dynamic Range (LDR) color spaces encode a small fraction of the visible color gamut, which does not encompass the range of colors produced on upcoming High Dynamic Range (HDR) displays. Future imaging systems will require encoding much wider color gamut and luminance range. Such wide color gamut can be represented using floating point HDR pixel values but those are inefficient to encode. They also lack perceptual uniformity of the luminance and color distribution, which is provided (in approximation) by most LDR color spaces. Therefore, there is a need to devise an efficient, perceptually uniform and integer valued representation for high dynamic range pixel values. In this paper we evaluate several methods for encoding colour HDR pixel values, in particular for use in image and video compression. Unlike other studies we test both luminance and color difference encoding in a rigorous 4AFC threshold experiments to determine the minimum bit-depth required. Results show that the Perceptual Quantizer (PQ) encoding provides the best perceptual uniformity in the considered luminance range, however the gain in bit-depth is rather modest. More significant difference can be observed between color difference encoding schemes, from which $\mathrm{YD}_u\mathrm{D}_v$ encoding seems to be the most efficient.

Keywords: Quantization Artifacts, HDR , Color Difference Encoding, Bit-Depth, Perceptual Transfer Function

1. INTRODUCTION

Traditional Low Dynamic Range (LDR) color spaces, such as BT.709[1], encode a small fraction of the visible color gamut for luminance values ranging from 0.1 to 100 cd/m^2. These color spaces cannot represent the range of colors and luminances that the human vision system can perceive. High dynamic Range (HDR) imagery aims at overcoming these limitations by capturing, storing and reproducing all that the human eye can perceive[2]. However current HDR pixel representation format uses floating point values which are inefficient to encode. They also lack perceptual uniformity of the luminance and color distribution, which is provided (in approximation) by most LDR color spaces. Therefore, there is a need to devise an efficient and perceptually uniform integer-valued representation for HDR pixels.

Following the interest that HDR video brought in recent emerging technology shows (CES, NAB, etc.), several standardization groups, such as the Society of Motion Picture and Television Engineers (SMPTE) and the Motion Picture Expert Group (MPEG), are currently working on HDR pixel representation for production and international program exchange. Their primary focus is on deriving color difference encodings that fit the requirement of video compression standard. Such requirements include encoding both the luminance and chrominance channels in a approximately perceptually uniform space and representing HDR content with a minimum bit-depth without impairing its visual quality. Based on psychophysical studies[3,4], several Perceptual Transfer Functions (PTFs) have been proposed to encode perceptually HDR luminances[5]. However, less work has been devoted to encoding chrominance channels that can represent the full visible gamut.

In this paper, we evaluate the minimum bit-depth at which quantization artefacts remain invisible for any luminance level. Unlike other studies[6], our experiments test both luminance and chrominance encoding in a

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rigorous 4AFC threshold experiments to determine the minimum bit-depth required. In Section 2, we present the difference between LDR and HDR color pixel encodings before describing the evaluated HDR color difference encodings. Then we describe our experiments along with the result in Section 3. Finally we conclude our paper in Section 4.

2. BACKGROUND

In this section, we describe LDR color pixel encodings along with their limitations to represent HDR color pixels. Then we present several proposition to encode HDR color pixels, some of them still under development.

2.1 LDR Color Pixel Encodings

Digital color pixels can be represented in two ways: additive color system which combines several primaries, usually three: Red, Green and Blue (RGB) and luminance/chrominance decomposition which removes the luminance information from the chrominance channels. LDR color pixels are represented using integer values whose distribution is optimized for human observers. Thus, images are encoded in a perceptually linear domain which has two goals: removing information that would be invisible after decoding (visual noise) and optimizing the limited bit-depth to minimize the visual loss due to quantization. Perceptually encoded and quantized luminance channel is denoted luma while chrominance channels chroma.

In LDR imagery, the perceptual encoding is performed by a non-linear transfer function called gamma encoding[7] and was designed through psychophysical studies for luminance level ranging from 0.1 to 100 cd/m^2 (capacity of CRT display technology). The gamma encoding is either applied on the three color channel (non-constant luminance) or only to the luminance channel (constant luminance). The High Definition TeleVision (HDTV) for production and exchange recommendation is described by the ITU-R Recommendation BT.709[1] (also known as Rec.709). This recommendation describes the location of the three primaries, the white point, a bit-depth (8 or 10 bits) and a luma/chroma decomposition (YC_bC_r). The color gamut boundaries and sampling of such a representation depends on the location of its primaries and on the bit-depth respectively. Note that the YC_bC_r representation is commonly referred to as a color difference encoding because it adds an offset to the chroma channel so as to center it in the middle of the used bit-depth. Color difference encoding are favored for video compression as they remove correlation between the luma and chroma channels.

Due to recent improvement in display technologies (local dimming, OLED, etc.), this standard has become outdated and hence another recommendation has been drafted in 2012 (BT.2020[8]). This recommendation enlarges both the color gamut and the bit-depth (10 and 12 bits) but the gamma encoding function remains the same. It also supplies an updated transformation matrix for the luma/chroma decomposition. Figure 1 illustrates both the proportion of the full visible gamut that the BT.709 and BT.2020 color spaces cover along with a representation of the C_bC_r plane.

2.2 HDR Color Pixel Encodings

Despite the improvement brought by the BT.2020, these encodings still cannot encompass all the color gamut and luminance ranges that the human eye can achieve. HDR imagery, through the use of the CIE 1931 XYZ color space[9] and floating point values, matches and can even surpass the human vision system limitations[2]. However, such a representation requires too much in term of storage capacity, computations time and throughput to be considered for consumer devices. Furthermore, image and video processing are devised to process integer valued images. To this end, perceptual encoding functions are used to convert floating point physical values to integer perceptually encoded values, commonly referred to as Perceptual Transfer Functions (PTFs) or Electro-Optic Transfer Functions (EOTFs).

One of the first perceptually uniform coding of HDR luminance was derived from the threshold versus intensity (t.v.i.) models[10]. The derivation involved rescaling luminance values so that the difference in code values corresponded to the detection threshold throughout the entire encoded range of luminance. The encoding was shown to require between 10 and 11 bits to encode the range of luminance from $10^{-4}\,cd/m^2$ to $10^{9}\,cd/m^2$. However, these numbers were based on the visual models rather than actual measurements made with images or video. In later work, the peaks of the contrast sensitivity function were used instead of the (t.v.i.) to derive

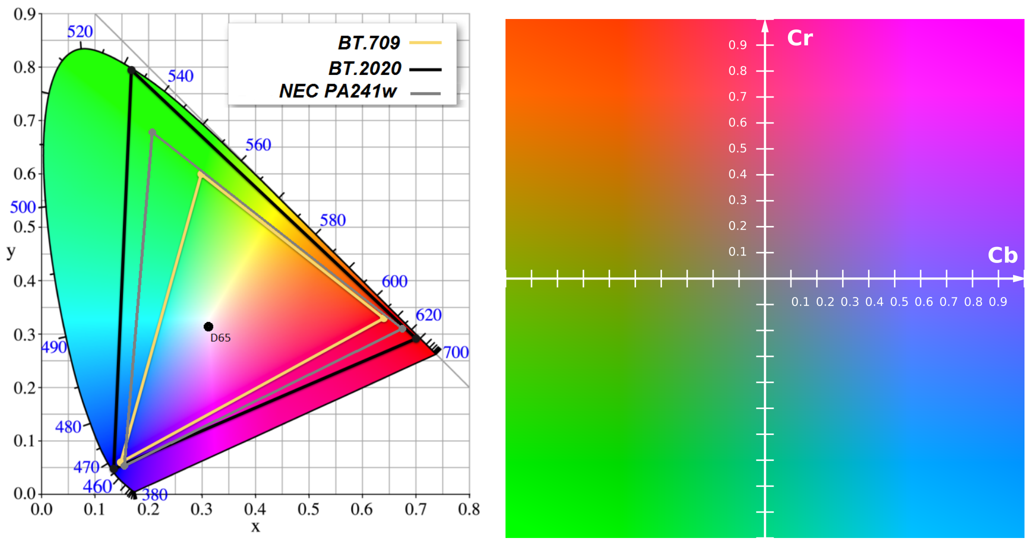

Figure 1. Left: CIE 1931 xy chromaticity diagram[9] with the primaries and boundarie of the color gamut of the BT.709[1], BT.2020[8] and the NEC PA241w display. Both recommendations use Illuminant D65 as white point. Right: C_bC_r chroma plane at constant luminance.

PTF	Equation
PU-HDRVDP[14,15]	lookup table
Perceptual Quantizer (PQ)[6]	$\mathbf{V} = \frac{c_2\mathbf{L}^{m_1}+c_1}{1+c_3\mathbf{L}^{m_1}}^{m_2}$
Gamma-Log[16]	$\mathbf{V} = \begin{cases} \mathbf{L}^{\gamma} & \text{if } \mathbf{L} \leq f \\ a \cdot log(\mathbf{L}+b)+c & \text{if } \mathbf{L} > f \end{cases}$
Rho-Gamma	$\mathbf{V} = log(1 + \frac{(\rho-1)\frac{\mathbf{L}}{L_{max}}^{\frac{1}{\gamma}}}{log(\rho)})$
Log-Linear	$\mathbf{V} = log_{10}(\mathbf{L})$
Arri Alexa	$\mathbf{V} = \begin{cases} max(0, e \cdot \mathbf{L}+f) & \text{if } \mathbf{L} \leq f \\ c \cdot log_{10}(a \cdot \mathbf{L}+b)+d & \text{if } \mathbf{L} > f \end{cases}$
S-Log	$\mathbf{V} = (a \cdot log_{10}(b \cdot \mathbf{L}+c)+d)+e$
PU based on Barten's CSF[4]	lookup table

Table 1. PTFs considered with the corresponding equations. **L** is the HDR luminance in cd/m^2 while **V** is the luma (perceptually encoded luminance). The results of the PTFs are normalized to the range [0;1].

the luminance encoding[11]. Another example of luminance encoding (PTFs) is the Perceptual Quantizer (PQ)[6], which was derived using a similar procedure as in[11], but from a different CSF model. This encoding was reported to require less than 10 bits to represent natural images without visual loss, however, smaller luminance range from 10^{-3} cd/m^2 to 10^4 cd/m^2 was considered. Several such PTFs, some of them currently considered in the ad hoc MPEG group on High Dynamic Range and Wide Color Gamut Content Distribution[12], are listed in Table 1. Figure 2 plots the luminance encoding of values ranging from 0.005 to 10,000 cd/m^2 on 12 bits along with the associated maximum quantization error. The optimum encoding should require the smallest number of bits per pixel and at the same time it should minimize the visibility of contouring artefacts due to quantization into integer values. The PQ has been standardized by the SMPTE[13] and is intended to enable the creation of video images with an increased luminance range. Note that the studied PTFs (and color difference encoding) correspond to display-referred encodings, that is to say encodings that aim at avoiding quantization artifacts when a content is reproduced on a display.

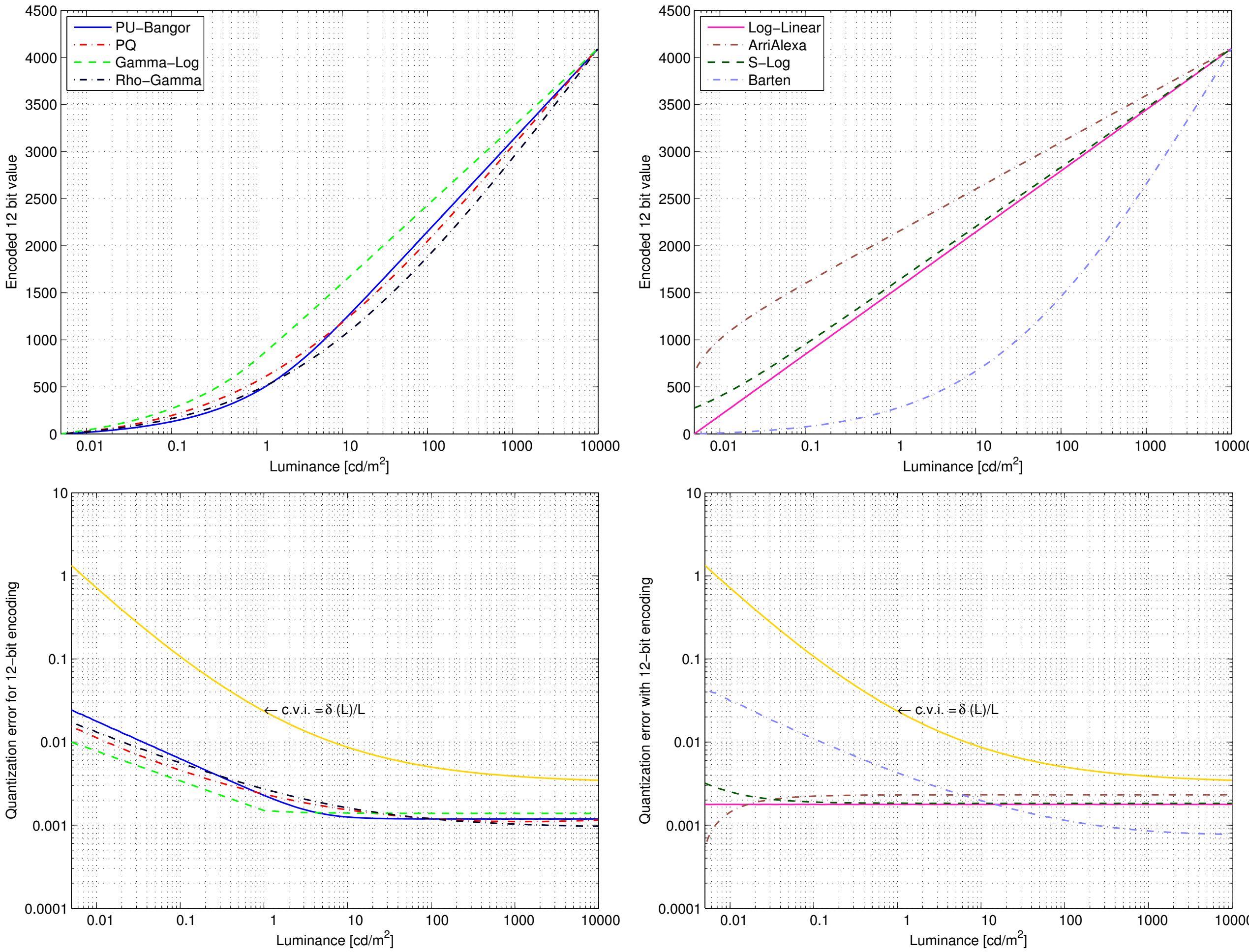

Figure 2. Top: luminance value encoded with different PTFs on 12 bits. Luminance range considered: [0.005; 10,000] cd/m^2. Bottom: quantization error for 12 bit-encoding. The bottom plots correspond to the legend of the top plots. The contrast versus intensity (c.v.i.) function has been added in the two bottom plots (yellow continuous line).

Regarding color difference encoding, three main approaches have been formulated so far: the BT.2020 YC$_b$C$_r$[8], YD$_z$D$_x$ and YD$_u$D$_v$. The YC$_b$C$_r$ encoding cannot represent the full visible gamut and is obtained by converting RGB tri-stimulus value using the transformation matrix described in the BT.2020 recommendation[8]. The YD$_z$D$_x$ converts pixels represented in the CIE 1931 XYZ color space[9] using a transformation matrix currently considered by the SMPTE[17]. Finally, the YD$_u$D$_v$ is based on the CIE Lu′v′ color space[18]. Table 2 summarizes the transformation for the color difference encoding considered in this paper. The quantization on a targeted bit-depth follows the Recommendation ITU-R BT.1361[19]:

$$\begin{bmatrix} \mathbf{D_Y} \\ \mathbf{D_{C_a}} \\ \mathbf{D_{C_b}} \end{bmatrix} = INT\left(\begin{bmatrix} (219\mathbf{Y}+16)\cdot 2^{n-8} \\ (224\mathbf{C_a}+128)\cdot 2^{n-8} \\ (224\mathbf{C_b}+128)\cdot 2^{n-8} \end{bmatrix}\right), \tag{1}$$

where $\mathbf{Y}/\mathbf{D_Y}$ and $\mathbf{C_a}/\mathbf{D_{C_a}}$, $\mathbf{C_b}/\mathbf{D_{C_b}}$ represents the unquantized/quantized luma and chroma channels respectively while n is the bit-depth.

Representation	Input	$\mathbf{Y}$	$\mathbf{C_a}$	$\mathbf{C_b}$
$\mathrm{YC}_b\mathrm{C}_r$	RGB	$\mathbf{Y} = 0.2627\mathbf{R} + 0.6780\mathbf{G} + 0.0593\mathbf{B}$	$\mathbf{C_b} = \frac{\mathbf{B-Y}}{1.8814}$	$\mathbf{C_r} = \frac{\mathbf{R-Y}}{1.4746}$
$\mathrm{YD}_z\mathrm{D}_x$	CIE XYZ	$\mathbf{Y} = \mathbf{Y}$	$\mathbf{D_z} = \frac{\frac{2763}{2800}\mathbf{Z}-\mathbf{Y}}{2}$	$\mathbf{D_x} = \frac{\mathbf{X}-\frac{2741}{2763}\mathbf{Y}}{2}$
$\mathrm{YD}_u\mathrm{D}_v$	CIE L′u′v′	$\mathbf{Y} = \mathbf{L}$	$\mathbf{D_u} = \frac{\mathbf{u'}}{0.62} - 0.5$	$\mathbf{D_v} = \frac{\mathbf{v'}}{0.62} - 0.5$

Table 2. Transformation matrix for the $\mathrm{YC}_b\mathrm{C}_r$, $\mathrm{YD}_z\mathrm{D}_x$ and $\mathrm{YD}_u\mathrm{D}_v$ color difference encodings.

3. EXPERIMENTS

The goal of this paper is to evaluate the different PTFs and color difference encoding considered in MPEG activities with respect to two criterions: the minimum bit-depth and the perceptual uniformity. The minimum bit-depth is the value at which quantization artefacts remain invisible for any luminance level. Perceptual uniformity is achieved if a small perturbation to a component value is approximately equally perceptible across the range of values (or luminance)[10,20]. Perceptual uniformity is an important criterion for every digital processing that rely on a weighting average of pixel values, for example filtering, motion estimation, distortion metric, etc. For example, HDR pixel values are linear physically (linearly related to the luminance) but are not linear perceptually (non-linearly related to brightness). If we consider a difference of 10 $\mathrm{cd/m^2}$ at 10 $\mathrm{cd/m^2}$ and 1000 $\mathrm{cd/m^2}$, obviously the perceived difference at 10 $\mathrm{cd/m^2}$ is higher than at 1000 $\mathrm{cd/m^2}$. However, a distortion metric, such as the Sum of Absolute Difference (SAD), would weigh both distortion similarly, hence giving the same importance to both distortion although the perceived difference is not the same.

To assess the minimum bit-depth and perceptual uniformity, we conducted a series of psychophysical experiments. This section first describes the experimental procedure before reporting and analyzing the results of our experiments.

3.1 Experimental Procedures

In all our experiments, the observers were presented four patches with smooth gradients in which only one was quantized at a targeted bit-depth. Examples of such a patches are shown in Figure 4. On the left, such a smooth gradient, presented on a gray background of the same luminance as the average luminance of the patch, provides possibly conservative case for the detection quantization artefacts. The artefacts are less likely to be visible in complex images and video, in which contrast masking, glare and small size of the features and motion reduce the detection thresholds. Note that the slope of the gradient may affect the detectability of the quantization artefacts. For that reason, we experimented with different slopes and used the one that maximized the visibility of banding or contouring. On the right of Figure 4, two chrominance gradients have been added on top of the luminance one.

The observers were asked to select one of the four patches that appeared different from the others (4AFC)[21]. The NEC PA241W display was addressed using a 10-bit signal whose bit-depth was further enhanced to 12-bits by spatio-temporal dithering. The average luminance of the patches varied from 0.05 to 150 $\mathrm{cd/m^2}$. We assumed that the measurements above 150 $\mathrm{cd/m^2}$ can be extrapolated as the Contrast Sensitivity Function (CSF)[4] does not vary much above that level. To achieve luminance levels lower than 5 $\mathrm{cd/m^2}$, the observers wore a pair goggles with attached neutral density filters (Kodak Wratten 96, 1.0D and 2.0D). The gamut of the NEC PA241W display is plotted on top of the BT.709 and BT.2020 in Figure 1. The QUEST procedure[22] was used to determine the detection threshold in terms of fractional numbers of bit used for encoding.

3.2 Experiment 1: Luminance Encoding

As human observer are more sensible to luminance than color variations, introducing artefacts in the luminance channel has more impact than in the chrominance ones. Furthermore, most image and video processing are performed on the luminance, for example, in video compression, the motion estimation is only performed on the luma channel and the same motion vectors are used to compensate both chroma channels. These processing rely on perceptual uniformity. Hence having an encoding that is not perceptually uniform will impair the

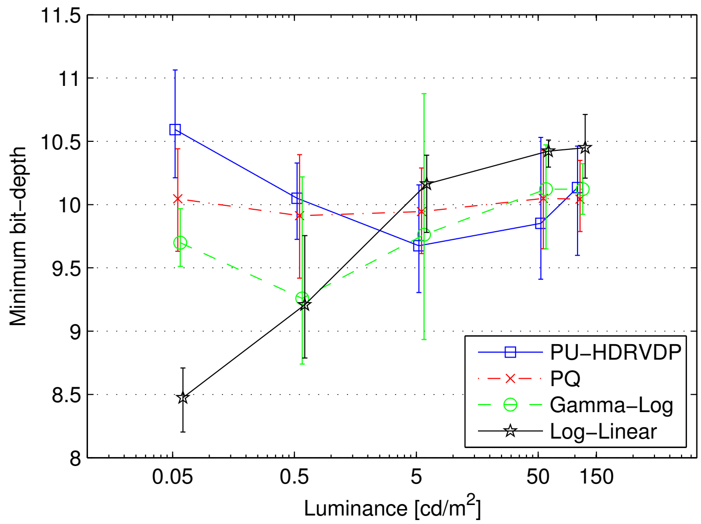

Figure 3. Minimum bit-depth required to encode HDR luminance values using several PTFs. For improved legibility the location of the error bars have been shifted along the x-axis. The error bars denote 95% confidence intervals describing the variance between observers. Note that, even though fractional bit quantization was measured in the experiment, in all practical applications the number of bits need to be rounded up.

quality of these processing and provides sub-optimum results. Finally, most color difference encoding base their decomposition on the luma channel. For all these reasons, our first experiment focus on the perceptual encoding of only the luminance channel.

Figure 3 shows the result of an experiment in which observers determined the minimum number of bits required for encoding luminance using four different PTFs (from Figure 2). The PTFs were designed to encode the luminance ranging from 0.005 to 10,000 cd/m^2, and the measurements were made for luminance levels ranging from 0.05 to 150 cd/m^2. Results show that the encoding using the logarithmic function (Log-linear) requires different number of bits for dark (8.5 bits) and bright (10.5 bits) regions. The number of bits is more steady for the perceptually uniform encoding based on the HDR-VDP-2 CSF model (PU-HDRVDP)[14,23] and the Gamma-Log function[16], but the bit-depth is the most uniform across the luminance levels for the Perceptual Quantizer (PQ)[6,24]. Note that the PQ was reported in[6] to require less than 10 bits for natural images while with our test patch, more than 10 bits are required. This results prove that our experimental setup is more conservative than using natural images.

The results for the minimum bit-depth of luminance encoding show that for all PTFs considered, the luminance from 0.005 to 10 000 cd/m^2 can be encoded without perceptual loss using 11 bits or more. If only the bit-depth is considered, then all PTFs are equivalent since fractional bit-depth cannot be implemented in hardware. The logarithmic encoding offers the advantage for uncalibrated HDR images as the same relative quantization error is introduced across the encoded lumiance range. The shortcomming of the logarithmic encoding is not only the poor perceptual uniformity, but also that it is likely to reveal more camera noise for darker tones. The cameras have similar noise characteristic as the visual system and they suffer from higher noise at low light levels. The stronger quantization at low luminance helps to reduce such noise. The other PTFs offer better perceptual uniformity with the PQ encoding being the most uniform in the tested range.

3.3 Experiment 2: Color Difference Encoding

Color difference encoding, similar to an opponent color space attributed to the human vision, is favored for video compression as it removes correlations between the luma and chroma channels. Indeed, achieving high decorrelation ensures that no redundant information is encoded. For that reason we first investigate the amount of decorrelation that the three color difference encodings presented in Section 2.1 can achieve. Table 3 reports the Pearson product-moment correlation coefficient[25] between the luma and chroma channels for 5 HDR images[26]. Results show that the $\mathrm{YD}_u\mathrm{D}_v$ achieves a higher decorrelation for three out of the five images. Furthermore,

Chroma	D_z	C_b	D_u	D_x	C_r	D_v
Balloon	0.033	0.098	0.014	0.272	0.052	0.190
FireEater2	0.950	0.740	0.391	0.909	0.790	0.375
Market3	0.226	0.176	0.379	0.189	0.289	0.224
Seine	0.413	0.407	0.245	0.445	0.390	0.262
Tibul2	0.933	0.860	0.086	0.912	0.540	0.027

Table 3. Pearson product-moment correlation coefficient[25] between the luma and the two chroma channels for each of the three color difference encodings. Those encodings were performed on 12 bits.

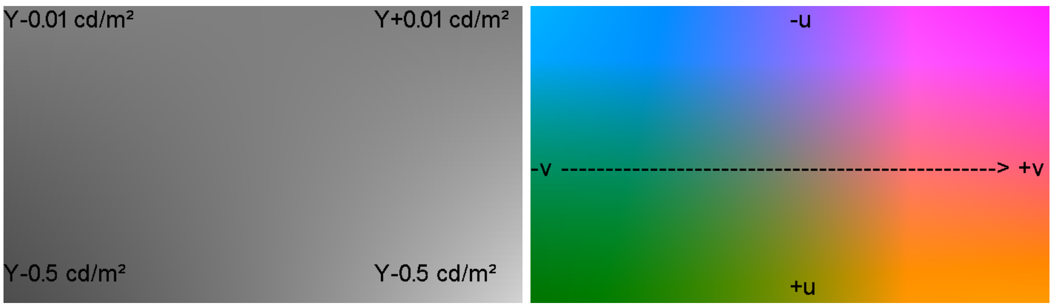

Figure 4. Left: test patch with luminance gradient used for the first experiment. Right: test patch with three different gradients: one along the luminance and two along the CIE u′ and v′ chrominances. The amplitude of the luminance gradient increases along the vertical axis from -/+0.01 to -/+0.5 in the log domain. The chrominance gradient ranges from -0.1 to 0.1 around the D65 white point.

for two images (FireEater2 and Tibul2), the YD_zD_x and YC_bC_r encoding have high correlation factor (close to one). The consequence of these results is twofold: firstly, information will be compressed twice, one time embedded in the luma channel and another in the chroma channel. Secondly, a higher bit-depth will most likely be required to encode chroma channels as more information is present. We propose to assess the validity of our second assumption by evaluating these color difference encodings with respect to the minimum bit-depth and the perceptual uniformity in a second psychophysical experiment.

We chose to evaluate the color difference encoding schemes associated only with the PQ PTFs as it was shown to be the most perceptually uniform. The test patch is built by combining three different gradients: one along the luminance and two along the CIE u′ and v′ chrominances[9] (Figure 4-right). The detection threshold for contouring artefacts was measured separately for quantization of luma and two chroma channels. The experimental procedure was similar to those used in Experiment 1.

The results of the second experiment are plotted in Figure 5. As expected, the results for luma quantization shown on the left are similar to those shown in Figure 3. However, the YC_bC_r encoding appears to require about 0.5 bit less of precision.

In case of chroma channel quantization (Figure 5-right), the difference in bit-depth precision between different chroma encoding schemes is much larger. The YD_uD_v encoding[18], based on the CIE u′ v′ chromatic coordinates, requires the fewest bits to encode, especially at low luminance levels. Given that two chroma channels need to be encoded, this can bring significant gains in compression efficiency. Note, however that the YD_uD_v is also the least perceptually uniform scheme and some adjustment in encoding may be required to address this problem. Otherwise, chroma channels will be represented with higher precision than needed, which may cause encoding invisible chroma differences at low luminance levels and lower coding performance.

The YC_bC_r encoding requires 9 bits and YD_zD_x requires at least 10 bits to encode. This makes them less efficient than YD_uD_v. Given that both YC_bC_r and YD_zD_x result in higher correlation with the luma channel, YD_uD_v encoding seems to be most efficient from those tested in terms of HDR pixel coding.

To summarize, encoding HDR color pixels can yield different results depending on the chosen color difference representation. When the amount of information is the main priority, experimental results indicates that the

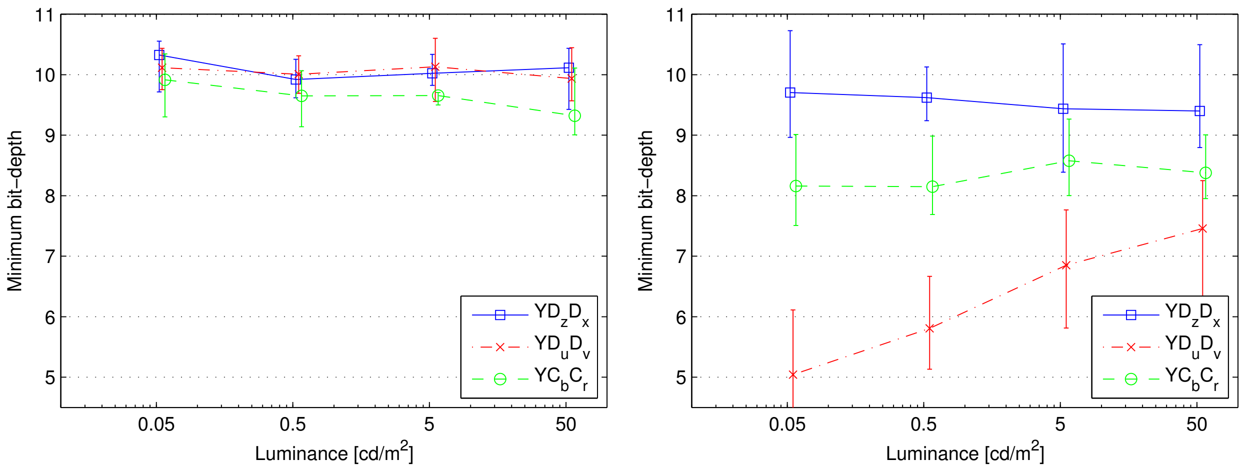

Figure 5. Minimum bit-required to encode color pixel using the three chroma encoding schemes: $\mathrm{YD}_z\mathrm{D}_x$, $\mathrm{YC}_b\mathrm{C}_r$ and $\mathrm{YD}_u\mathrm{D}_v$. Left: Results for luma channel quantization. Right: Results for the quantization of two chroma channels. For improved legibility the location of the error bars have been shifted along the x-axis.

$\mathrm{YD}_u\mathrm{D}_v$ coding requires only 8 bits to encode chrominance channel without visible distortions. If the application requires perceptual uniformity, then the $\mathrm{YC}_b\mathrm{C}_r$ representation outperforms the other two representation considered but requires at least 9 bits.

4. CONCLUSIONS

We presented an experimental evaluation of colour pixel encodings used to represent HDR pixel values. In particular, we have shown than the PQ encoding provides good perceptual uniformity in the considered luminance range, however the gain in bit-depth is rather moderate. In some applications, logarithmic encoding can prove equally effective, especially since it does not required HDR values to be calibrated in absolute units. A more significant difference can be observed between color difference encoding schemes, from which $\mathrm{YD}_u\mathrm{D}_v$ encoding[18] seems to be the most efficient.

The insights from this study are not only limited to compression of HDR content. In fact, perceptually uniform encoding of HDR luminance is a mandatory step for most image processing operations. To achieve high perceptual uniformity, the PQ PTFs could be used as it offers the best uniformity from the PTFs tested in this study. Although our experiments only tested low luminance values due to the limitations of our display, the contrast sensitivity experiments show little change in sensitivity above $50\,\mathrm{cd/m^2}$ when the cones are fully responsive. Consequently, results for higher luminance are expected to be close to ours results for $50\,\mathrm{cd/m^2}$.

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