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Effect of Peak Luminance on Perceptual Color Gamut Volume

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Abstract

In this paper, two psychophysical experiments were conducted to explore the effect of peak luminance on the perceptual color gamut volume. The two experiments were designed with two different image data rendering methods: clipping the peak luminance and scaling the image luminance to display's peak luminance capability. The perceptual color gamut volume showed a close linear relationship to the log scale of peak luminance. The results were found not consistent with the computational 3D color appearance gamut volume from previous work. The difference was suspected to be caused by the different perspectives between the computational 3D color appearance gamut volume and the experimental color gamut volume/perceptual color gamut volume.

Introduction

The CIE has a defined color gamut as "volume, area, or solid in a colour space, consisting of all those colours that are either: (a) present in a specific scene, artwork, photograph, photomechanical, or other reproduction; (b) capable of being created using a particular output device and/or medium" [1]. The most well-known so-called color gamut is the chromaticity gamut area of a display in $u'v'$ or xy chromaticity diagram. In the recent decades, the 2D gamut in xy and $u'v'$ chromaticity diagrams has been widely utilized by display manufacturers to characterize the display's color reproduction ability. However, it is well known that at least a three-dimensional color space is necessary to describe a color precisely. This is also typically how color is encoded/recorded. Therefore, the 2D gamut is only an illustration of part of color rendition capabilities, but inappropriate for characterizing display's color appearance reproduction. Another interesting usage of the 2D gamut is that the $u'v'$ is generally more favored than the xy by the manufacturers due to it being slightly more perceptually uniform for threshold discrimination despite the fact that chromaticity diagrams do not describe perceptual appearance. This is based on CIE $u'v'$ having better uniformity performance based on MacAdam's experiment on the visual sensitivity to color difference in daylight experiments back in 1942, based on matching variability [2]. The experimental data demonstrated the better color threshold uniformity in CIE $u'v'$. However, the experiment was based on one observer with the colors on constant luminance level. Obviously, this is not sufficient as a strong evidence to support the superiority of CIE $u'v'$ over CIE xy as an approximation to the 3D color spaces, especially when neither describes color appearance directly. While the $u'v'$ or xy chromaticy diagram can be very useful in illustrating color stimulus capability in a convenient way, the lack of the higher dimensions of appearance and strong evidence of the well correlation between the 2D gamut and 3D color space limit the possibility of approximating 3D color volume using 2D chromaticity gamuts. Moreover, the area coverage by the primary of display on the chromaticiy diagram is either an interval scale nor a linear scale, i.e. the area coverage of one display can be said to be larger than the other but statements such as "30% larger or smaller" are meaningless in terms of color appearance.

Color appearance models, as proposed and tested by CIE Technical Committee 1-34, are required to have predictive correlates of at least the relative appearance attributes of lightness, chroma, and hue [3]. CIELAB is the widely used and well-known example of such a color appearance space though its original goal was supra-threshold color-difference uniformity. However, CIELAB does not take the other attributes of the viewing environment and background, such as absolute luminance level, into consideration. CIECAM02 is CIE-recommended color appearance model for more complex viewing situations [4]. In the years since adoption of CIECAM02, there are several new proposed color appearance models with some modifications and improvements, e.g. CIECAM02-UCS [5], CAM16 [6], CAM16-UCS [6]. CIECAM02-USC is an adjustment of the CIECAM02 aiming at reconciling color appearance scales with supra-threshold small color difference equations, noting that both perceptual phenomena cannot be predicted using the same perceptual scales. CAM16 includes a modification to solve occasional inconvenient negative values in CIECAM02 through a simple adjustment to the chromatic adaptation transform. CAM16-UCS is the similar as CIECAM02-UCS but based on CAM16. There is no significant change in perceptual predictions of these new color spaces from the current CIE recommendation, CIECAM02. Therefore, color gamut volume computed in CIELAB and CIECAM02 are representations for color appearance models.

Masaoka and Nishida reported an interesting finding about the RGB-primary display's 3D color gamut volume in CIELAB and JCh in CIECAM02 [7]. That work demonstrated a high correlation between the 3D color gamut volume expressed in CIELAB, CIELUV, JCh and the primary area coverage in the CIE xy chromaticity diagram, better than achieved using the CIE $u'v'$ chromaticity diagram. Later, Masaoka further analyzed the causes of these correlations and showed that it was due to the relative weighting of various chromaticity regions with respect to the display gamut volume in those regions [8]. Masaoka followed up that work by illustrating the importance of 3D color gamut volume in CIELAB for the comparison of High Dynamic Range (HDR) - Wide Color Gamut (WCG) displays [9]. In particular, this is critical when comparing RGB displays with RGBW displays or when comparing displays with disparate peak luminance levels or ratios between peak luminance and rendered diffuse white luminance. Jiang proposed a simple mathematical model for computing the 3D color gamut volume in CIELAB, JCh from CIECAM02 considering a wide peak luminance range, and different RGB primary, as well as different RGBW configuration [10]. The model predicts a close-to-linear relationship between the 3D color gamut volume and the peak luminance.

Along with the development and widespread use of the HDR WCG displays, there have been color spaces proposed specifically for HDR WCG. Fairchild and Chen proposed and evaluated hdr-LAB and hdr-IPT color spaces based on experimental data of lightness above the diffuse white level [11]. The extended CIELAB still showed a reasonable performance for predicting the lightness above the diffuse white. Recently, there are two interesting proposed color spaces for usage in HDR WCG applications, ICtCp [12, 13] and $J_za_zb_z$ [14]. ICtCp was developed on the perceptual quantizer (PQ) nonlinear function recommended by Society of Motion Picture & Television Engineers (SMPTE) [15]. The PQ is proposed based on Barten's Contrast Sensitivity Function (CSF) model [16] to avoid quantization artifacts. $J_za_zb_z$ utilizes the similar structure as ICtCp with a further optimization of some parameters based on a comprehensive experimental data. Both color spaces showed reasonable performances on micro color difference uniformity and hue linearity[14, 17].

Gamut volume can also be computed in such a micro-color-difference uniform space. Kunkel proposed an ICtCp-based adaptation hull to evaluate the color difference dataset from Pieri and Pytlarz [17]. Kunkel suggested a method of stacking disks with 1 unit just-noticeable-difference (JND) thickness of a certain adaptation level. Therefore, this is based on stacking volumes from multiple adaptation states, a way to model the best-case sensitivity to dynamic adaptation rather than the steady-state appearance to a fixed adaptation as is done with most implementations of CIELAB and CIECAM02. The study also showed the advantage of the adaptive hull of ICtCp in predicting micro color difference [17]. The good performance from ICtCp and $J_za_zb_z$ for the small color differences is not surprising given that is what the spaces were designed for. Certainly, within a certain small number of JND steps, the JND's additivity might be meaningful. However, it is well established that adding JNDs does not lead to a perceptual interval scale for describing large changes in color appearance, which is the goal of color appearance spaces such as CIECAM02. Also usage of JND scales requires some assumptions about adaptation, be it dynamic to the background or static, to make their scales valid. For example, the difference between one gray and (gray+10 JND steps) will likely not to be perceptually equal to that between the gray and (gray-10 JND steps) under a white adaptation background, which is far different from the JND measurement methodology. Therefore, simply adding JND steps straightly up does not produce a meaningful appearance scale. Considering the display presenting most image contents, very of the stimuli will not be within a few JND steps of the instantaneous adaptation level. Moreover, neither ICtCp or $J_za_zb_z$ includes the chromatic adaptation in the model. Therefore, the color gamut volume expressed in a color appearance model, with reasonable and necessary assumptions about the state of chromatic adaptation, is a more reasonable choice for characterizing the display color reproduction ability. Therefore, the JND-based color gamut volume method and the color gamut volume in ICtCp and $J_za_zb_z$ will not be used for analysis in this paper.

In addition to the computed 3D color gamut volume in certain color space, the perceptual color gamut volume is necessarily related to the ability to demonstrate colors from the perspective of the normal observers/consumers. Baek published the first study about the perceptional color gamut volume [18]. In Baek's experiment, observers were asked to evaluate the "rich" (originally in Korean for the observers in South Korean) in two side-by-side images. They examined the relationship between the perceptual color volume ("rich") and the mathematical 3D color gamut volume in three color spaces: CIELAB, QMh from CIECAM02, and ICtCp. They found the best correlation between the perceptual color volume and the computed color gamut volume in QMh. However, there is some question about the calculations used. For such a type of experiment design, single white point should be used for the entire display, i.e. for both images. Therefore, it is questionable to use two diffuse white levels for the two images presented simultaneously on the same display. The current work has aimed to address this limitation in perceptual evaluation of gamut volume.

Two psychophysical experiments were conducted to evaluate the effect of peak luminance on the 3D color appearance gamut volume. In these two experiments, the perceptual color gamut volume is defined by "colorful and detailed". The larger color gamut volume display is supposed to display the same image data more colorful and detailed, without additional color enhancement, tone mapping operator (TMO) or any other additional manipulation in the display pipeline. The two experiments follow two different diffuse white settings, a constant 200 cd/m^2 and a relative 20% to the peak luminance. The result is analyzed, and compared with different parameters.

Experimental Setup

In the two experiments, a professional 30-inch 4K OLED master monitor (Sony BVM-X300, Japan) was used for presenting images. The display is capable of reaching a stable 1000 cd/m^2 peak luminance level while accepting both HLG and PQ encoding format. Figure 1 shows the setup, with the display sided by the two black panels, blocking any possible ambient lighting. During the experiment, all room lights were turned off. All observers sat on the chair about 75 cm from the display. This meets the ITU-R suggestions on the viewing distance for 4K display [19].

Figure 1: The setup for the psychophysical experiments.

Both experiments adopted the same setup. Nine original HDR images were used for both experiments. Figure 2 demonstrates the preview of the 9 images. The 9 images includes indoor, outdoor, portraits and dark image with details (image #1), high contrast with details in the dark region (image #3). In terms of the types of object in scene, the 9 images include the ordinary reflective objects, direct lighting, highlights of objects. No synthetic images were used in either experiment.

Experiment I

In experiment I, each original image was clipped to four different peak luminances, 1000 cd/m^2 (original), 500 cd/m^2, 300 cd/m^2 and 200 cd/m^2. The clipping was conducted in the image digital data, resulting in the desired peak luminance when shown on the display. This is simulating displays with different peak luminance capabilities and assuming that these displays

Figure 2: Images used in the two experiments.

perform a clipping for image luminance data above their abilities. In terms of the clipping method, a hard clipping was applied. A soft clipping is something similar with a Tone Mapping Operator (TMO), which is more an optimized the usage of displays instead of presenting the fundamental color reproduction ability of a display. Since we are focusing on the fundamental color ability of the display, a hard clipping was used in the image processing. The processing generated nine sets of images, where each set includes four images with different peak luminances but almost the same content. The paired-comparison methodology was used for this experiment [20]. For each set of image content, there were six pairs to be compared, in a total of 54 pairs. Twenty-one observers with normal color vision participated in this experiment with ages ranging from 20s to 60s.

Experiment II

In experiment II, the same 9 original images were used. Each original image was physically filtered using three different ND filters. The reason for applying the physical filter instead of a digital filter is to prevent any artifacts, mainly banding effect from quantization, while producing reduced peak luminance levels. The transmittances of the three ND filters were 0.7, 0.5, and 0.35. Each original image thus generated a set of four images, including the original one. This process simulates the situation that the display would adjust the image data into its own peak luminance ability by linear luminance scaling of the whole image. This is how most displays render images without metadata. Paired comparison was used in this experiment as well, in a total of 54 pairs. Twenty observers participated in this experiment with ages ranging from 17 to 60s.

Experimental Procedure

Figure 3 illustrates the procedure. The experiment started with a black image, shortly followed by image#1 in first pair for 15 seconds observation time. A 10 second black image following that was designed to prevent the strong memory and/or afterimages of the first image. Following the black image, the image#2 of pair 1 will be presented for another 15 seconds. The whole screen would turn black after this 15 second presentation. A beep would remind the observers that they should make the choice based on which one in the pair was perceived to have more colorfulness and detail. The duration of each step was determined by balancing the fatigue of observers and the best performance in the pilot test. It would quickly proceed into next pair when the choice was recorded. The order of all pairs and the order of in each pair are both randomized for each observer. The experiment design of presenting the pair one by one is to mimic the perspective of an observer who is trying to compare two displays, not simultaneously but in succession. For example, one customer tries to compare the display he has been using with another display at a friend's home or in a store. Since human can adapt to the device and environment, a side-by-side setup would somehow exaggerate the difference between two displays by having a single adaptation point. Therefore, this one-by-one experiment setup was adopted from the perspective of a user.

Results & Analysis

The analysis of the psychophysical experiments followed case V by the law of comparative judgement from Engeldrum [20]. The 95% confidential interval was computed following Montag's work [21]. It should be noted that the result from the experiments is an interval scale, whose difference is meaningful while the absolute value and zero point have no intrinsic meaning. More details about the types of the psychophysical experimental result can be found in Engeldrum's book [20]. The result of the analysis is considered as the perceptual color gamut volume of the display conditions evaluated.

Figure 4 demonstrates the result of the two experiments against the linear peak luminance and the log10 scale of the peak luminance. Firstly, the perceptual volumes of the 1000 cd/m^2 peak luminance in the two experiments are different as they are not on the same scale, and the absolute value is meaningless as stated above. For both experiments, the perceptual color gamut volume shows a better linear relationship with the log10 scale of peak luminance than the linear peak luminance. The difference between the linear peak luminance and the log10 peak luminance is much larger for experiment I. The line in experiment II is much steeper than that in experiment I. This is reasonable as the ND filter would make the images darker compared with the same clipped peak luminance. The darker the image is, the less colorful the image becomes.

In addition to the peak luminance and log10 of the peak luminance, several more parameters were added for analysis, including 3D color gamut volume in LCh, JChDark, QMhDark, peak Q and the log10 scale of these. Some of these volumes can be easily computed following Jiang's work [10]. According the image processing of the two experiments, for experiment 1 (peak luminance hard clipping), a constant diffuse white level was adopted, and for experiment 2 (filters), a relative 20% diffuse white was used. A study about the perceptual diffuse white estimation supports these diffuse white settings [22]. R^2 values between the perceptual color gamut volume and these parameters are listed in Table 1. The gray cells indicate the best three parameters, log10(Peak Luminance), log10(QMhDark), and log10(Peak Q). The colorfulness of an image would increase as the absolute luminance level, the well-known Hunt effect [23]. LCh and JChDark do not predict colorfulness. Hence, LCh and JChDark did not demonstrate a good performance as expected. QMh takes the absolute luminance into account, and the M is the colorfulness attribute from the CIECAM02 model. It is not surprising that QMh performs better than the LCh and JCh. Figure 5 plots the best 3 parameters against the perceptual color gamut volume for both experiments. Firstly, the linearity is much better in experiment 2 than in experiment 1, the same as demonstrated by the R^2. For experiment 1, it can be found that the difference between the four different peak luminance levels is only around 5% for the log10(QMhDark) and log10(peakQ), but 25% for log10(peakLum). Very similar variance data of the normalized parameters in experiment 2. Another interesting result about the plots is the line of log10(peakQ) is above that of log10(QMhDark) in experiment 1 while the order is reversed for experiment 2. However, since the two experiments were con-

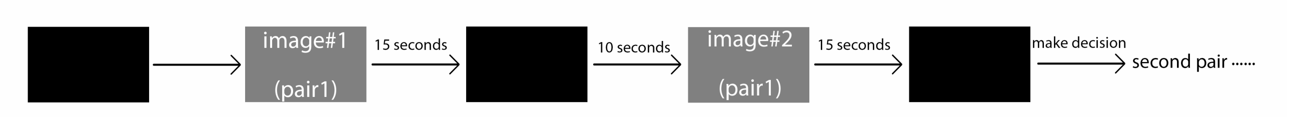

Figure 3: Schematic overview of the experiment procedure.

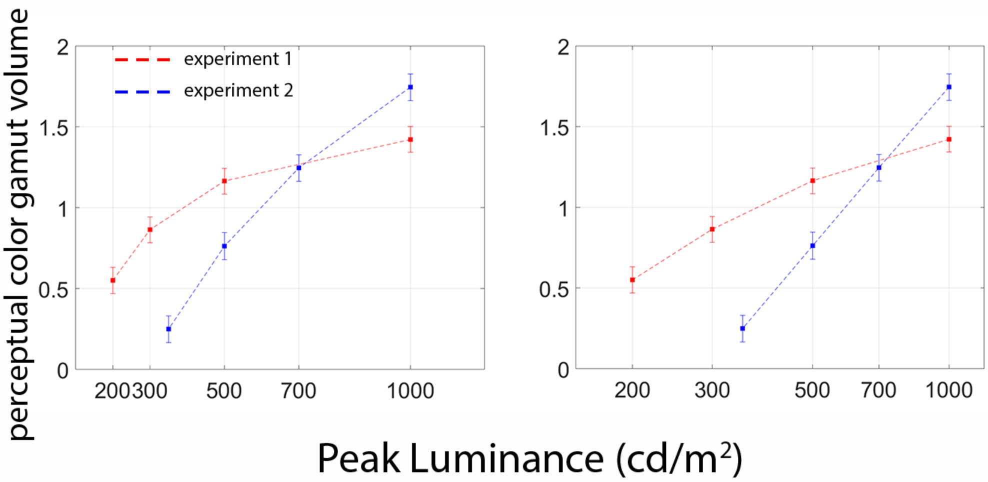

Figure 4: Perceptual color gamut volume against the linear peak luminance (left) and the log10 scale of peak luminance (right) for both experiments. The errorbar represents the 95% confidential interval.

ducted separately it is difficult to have a direct comparison of the two experiments. Therefore, the order of the lines is not that meaningful based on the current available experimental data.

R^2	Exp1	Exp2	average
Peak Luminance	0.862	0.974	0.968
log10(Peak Luminance)	0.974	1.000	0.987
LCh	0.861	0.000	0.431
log10(LCh)	0.975	0.000	0.788
JChDark	0.889	0.956	0.923
log10(JChDark)	0.976	0.956	0.966
QMhDark	0.914	0.989	0.952
log10(QMhDark)	0.975	0.999	0.987
Peak Q	0.957	0.992	0.973
log10(Peak Q)	0.974	0.998	0.986

Table 1: R^2 between the parameters and the perceptual color gamut volume.

Discussion

The two psychophysical experiments were designed and conducted to evaluate the model with varying peak luminance. The two experiments simulated two different image rendering methods, clipping and scaling. They are also corresponding with the two diffuse white settings in the model. The result of the experiment is not well consistent with the simulations. The 3D color appearance gamut volume model predicts a linear relationship between the 3D volume and the peak luminance. While the experimental result showed a better linearity between the perceptual color gamut volume and the log10(peak luminance). This is not a surprising result considering the difference between the model and the experimental methodology assessing the color volume. The perceptual color gamut volume can only be measured through experimental images on the displays. However, the pictorial images would not use the display's whole 3D gamut entirely. Actually, most of the images would be of reflective objects with some highlights, direct lights, the reflective objects close to lighting source, etc. Therefore, most of the content/pixels in a pictorial image are under a certain diffuse white level. Figure 6 illustrates the concept, where the gray lines represent two opponent color channels as in almost all color appearance spaces and the vertical axis (Z-axis) shows lightness/brightness. The colored 3D ellipsoid represents the volume used for reflective object and the three spikes above that are volume for highlights, etc. For experiment I, the hard clipping would mostly affect these spikes. Therefore, observers' response should be more similar to the impact on these spikes. The log scale of the peak luminance is obviously a better metric, than the linear peak luminance, to describe the observers' response, which is more linear to the log scale of luminance. It should be noted that this is based on a hard clipping image rendering. Utilizing a tone-mapping-operator (TMO)/soft clipping, which was designed to map a higher dynamic range image into a lower dynamic range display while preserves the details as much as possible, would probably be different from this experiment. A TMO would optimize the usage of a limited color gamut volume. A TMO is a mapping method of nonlinear compression from the dynamic range to the display's dynamic range while aiming at preserving more contrast information. An easy way to understand the TMO is that one TMO applies a slight compression over the 3D colored ellipsoid and a higher compression over the spikes over the 3D ellipsoid in Figure 6. The compression can be applied globally or locally according to the specific TMO algorithm. However, that is out of the scope of this paper but should be taken into consideration if any specific display is using TMOs in processing and display of high dynamic range image/video content. For experiment II, the ND filter was simulating the scaling processing. The filters reduce the whole image in the same scale. QMh from CIECAM02 model was designed to predict the well known Hunt effect [23]. It is not surprising that the 3D volume in QMh works better than LCh and JCh.

The only known study about evaluating the color gamut vol-

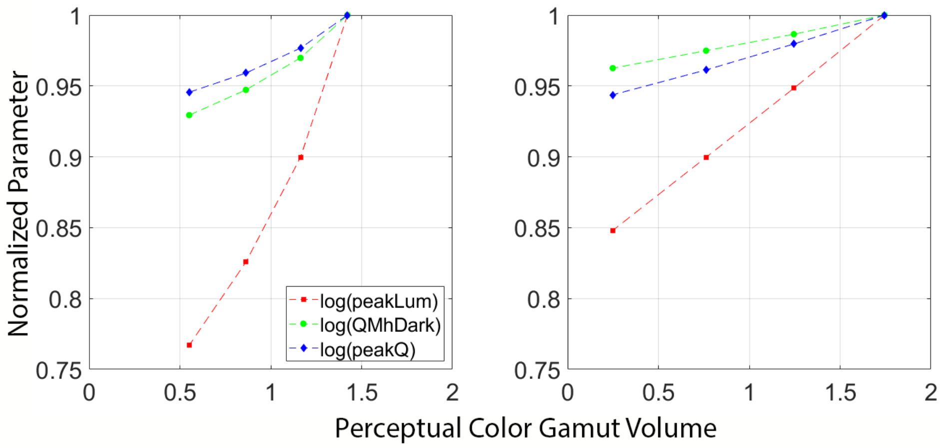

Figure 5: Normalized parameters against the perceptual color gamut volume for experiment 1 (left) and experiment 2 (right).

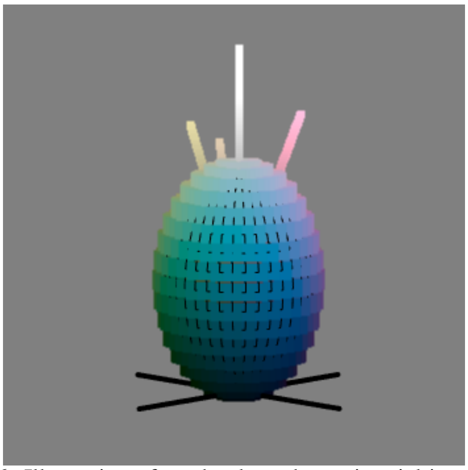
Figure 6: Illustration of used volume by a pictorial image. The two black lines present the two opponent channel in most color appearance models, and the vertical axis (Z-axis) stands for the achromatic channel lightness/brightness.

ume was reported by Baek [18]. However, as mentioned in the introduction, the calculation of the volume is questionable considering the chosen white levels. Therefore, we will not cross compare the results directly. However, the judging criteria/question for the observers in the psychophysical experiments is worth discussion. The question posed to the observers is critical for a psychophysical experiment. For example, there is a clear difference between color fidelity and observers' color preference in image. In these two experiments, a larger perceptual color gamut volume is supposed to demonstrate the image as more colorful and more detailed with the same image source data. The images were encoded in 10 bit HLG, which should be free of any artifacts as in the pilot test. This is also the main reason that ND filters were used instead of scaling the images digitally. Certainly, there is no standard definition of perceptual color gamut volume, and it could vary from application to application. For example, Baek's work using 'richness' in Korean word during their experiment [18]. Therefore, some variance would be expected for different questions. Moreover, for each image, 6 pairs were evaluated by all observers as a balance between the fatigue of observers and the efficiency. For R^2 analysis of the four points, the difference between different metrics in Table 1 is not that big. More pairs can be evaluated in the following study. Also, the two experiments are only assessing the displays with different peak luminance levels. Moreover, the primary set has a great impact on the 3D volume. It is necessary to explore the effect from the primary set and the joint effect of primary set and peak luminance. While difficult to implement and test, future studies of dynamic gamut computations considering spatially- and temporally-local adaptation would also give insight into more aspects of real-world display performance.

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