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Modeling Perceived Brightness in HDR Displays

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Abstract

This article presents an enhanced mathematical framework that builds on the existing XCR model to more fully account for the increase in perceive display brightness as saturation rises. By integrating modifications to the CIECAM16, our toolkit allows for intuitive graphical exploration of color appearance attributes across a display's full gamut.

Introduction

The Helmholtz-Kohlrausch (H-K) effect is a fascinating visual phenomenon in which a color's perceived brightness is influenced not only by its luminance - the amount of light it emits - but also by its saturation. This means that highly saturated colors often look brighter to the human eye than less saturated ones, even if their objective luminance is identical. This effect is especially noticeable with hues like reds and blues.

the H-K visual phenomenon, a cornerstone in display technology, illustrates that a brighter image isn't achieved solely by increasing luminance. This effect is especially relevant for modern displays boasting wider color gamuts, such as OLED and QD-OLED (Quantum Dot) technologies. Thanks to the H-K effect, these displays can leverage their ability to produce highly saturated colors, which, in turn, boosts the perception of brightness and vividness without needing to increase the display's overall luminance.

Display engineers and color scientists are actively working to incorporate the H-K effect into Color Appearance Models (CAMs). This integration is crucial for more accurately predicting how users perceive brightness on wide color gamut High Dynamic Range (HDR) displays. In a previous article by Hellwig [1], it was highlighted how a television with a wider chromaticity gamut appeared brighter to consumers in side-by-side comparisons, even when its measured luminance was the same as another set. This phenomenon, often seen in HDR displays, is attributed to the H-K effect. This discrepancy between objective physical measurements and subjective human perception poses a significant challenge for accurately characterizing modern and emerging HDR display technologies.

This article presents a mathematical toolkit that builds on the existing XCR (eXperienced Color Range) model, described in [1], providing a deeper understanding of why displays with wider chromaticity gamuts are perceived as brighter. Our purpose in this article is to survey in an unbiased way several 2D and 3D tools available to HDR industry for display color characterization and suggest a future that embraces progress likely by the CIE over the next few years. Our toolkit integrates modifications to the CIECAM16 [2], enabling graphical analysis of color and lightness across display's achievable range. To set the stage for our mathematical framework, we first revisit the existing XCR model. Then we'll explain how to implement this framework to examine the perceived H-K compensated brightness for HDR displays.

XCR Mathematical Framework

Our developed XCR framework is based on a calculus-based model of the H-K effect, as defined by Hellwig [3], along with improvements to CIECAM16, referred to as modCAM16 [4]. These upgrades simplify the model into essential pieces that make the model easier to implement for HDR displays analysis. We chose CIECAM16 color appearance model due to the lack of HDR support in CIELAB [5], and aligning with CIE's adoption of CIECAM16 (CIE 248:2022).

Hellwig's analysis of the H-K effect across twelve evenly spaced hues demonstrated that colors with higher chroma appear equally bright as their paired counterparts of the same physical luminance, evidenced by negatively sloped data lines connecting equally bright color pairs. These data, shown in Figure 1, generally align with the model's "blue loci," though deviations in slope reveal that shallower slopes indicate the model overpredicts and steeper slopes underpredict the effect's strength. Both the data and model slopes are steepest at low achromatic lightness and become less steep with increasing lightness, confirming slope as a direct measure of the H-K effect's strength. Building on these insights, a mathematical model, expressed in Equation 1, was formulated by Hellwig where J_A is a solely achromatic term and C is chroma.

$$J_{HK} = \sqrt{J_A^2 + 66C} \tag{1}$$

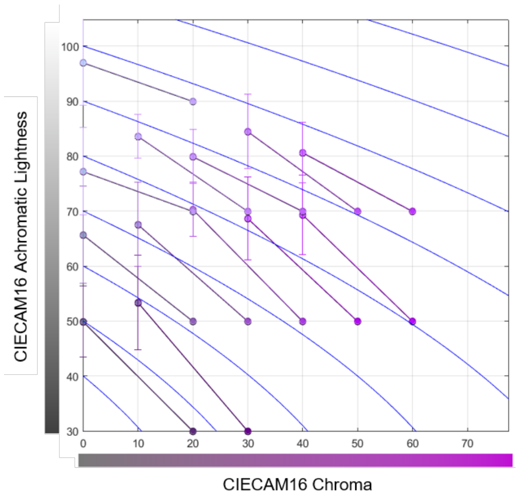


Figure 1. *Experimental brightness matching results: purple lines connect colors that, on average, were perceived as equally bright by observers. The blue lines represent lines of equal brightness as predicted by Equation 2 (fit to all experimental data).*

Additionally, Equation 2 was derived to evaluate the absolute perceived brightness, which is compensated by the Helmholtz–Kohlrausch effect, and we refer to it as H-K compensated brightness.

$$Q\_HK = (2/c)(J/100)\ A\_W \tag{2}$$

Where small c - set by the viewing condition at 0.525 - and A_W is the achromatic signal for reference white measured in cd/m^2. It's worth noting that the perceived lightness and perceived brightness have been observed to have a linear relationship. The modCAM16 model corrected brightness to be

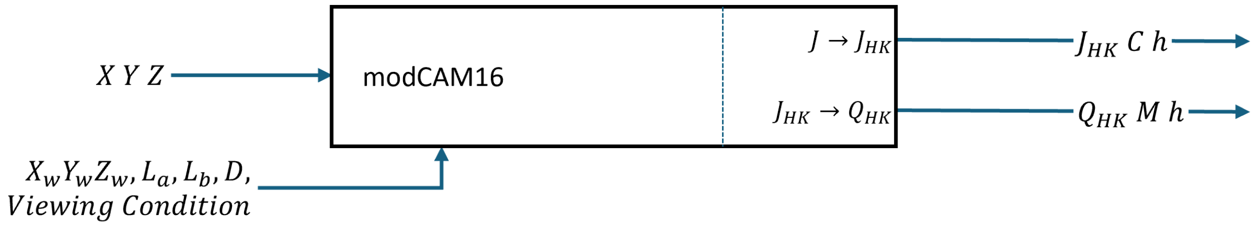


***Figure 2.** XCR model flow where H-K compensation is integrated into modCAM16 for 2D analysis*

linearly dependent on lightness, as reflected in Equation 2. For HDR applications, modCAM16 describes both relative lightness and absolute brightness, where luminance above reference white represents HDR highlights. This capability differs from CIELAB, which takes the peak luminance as the reference white and only delivers L*, relative lightness, neglecting the absolute brightness.

Computational Experiments

The XCR model can examine the perceived H-K compensated brightness not only in each primary but also all other achievable color mixtures within the display color gamut, representing variation in hue, saturation and luminance. To effectively illustrate the XCR behavior, we utilized a 2D plot of XCR to demonstrate the perceived H-K compensated brightness. The flow in Figure 2 indicates where absolute XYZ along with the input parameters for the modCAM16, listed in Table 1, are fed into the XCR model.

Table 1. Test conditions used throughout this article unless noted

Input condition	Value	Units
HDR peak luminance	1000	cd/m2
SDR peak luminance	200	cd/m2
Reference white	200	cd/m2
Background luminance	20	cd/m2
Degree of adaptation, D	1 (fully adapted)	n/a
CAM16 viewing condition	‘dark’	n/a

Figure 3 illustrates H-K compensated lightness, J_{HK}, versus chroma, C, for an HDR display calibrated to P3 color space. The figure shows a few sample points from two bands of constant J at various hues, “x” and “◇” represents J equal to 30 and 60, respectively. The hue angle is the same between like colored pairs and labeled. The H-K compensation is the slope for each example hue. In the case of h equal to 114, a chroma change equal to 18.8 boosted the H-K compensated lightness, by 37.5 even though the difference in lightness, J, is only 30. The figure shows four examples where J_{HK} increases more so than J driven by a change in chroma. The figure is a readable sample of over 2000 data points.

A second way to reveal H-K compensated effects plots Q_{HK} and Q (uncompensated) versus luminance. In fact, gradually increasing the RGB—range 0 to 1—of an image from [0, 0, 0] to, for example, [1, 0, 0], transitions the color from achromatic black to pure red. This process boosts luminance by adding more light and simultaneously increases chroma as the color becomes highly chromatic and saturated. Figure 4 is a composite with all primaries shown. In each case, the dashed loci are uncompensated.

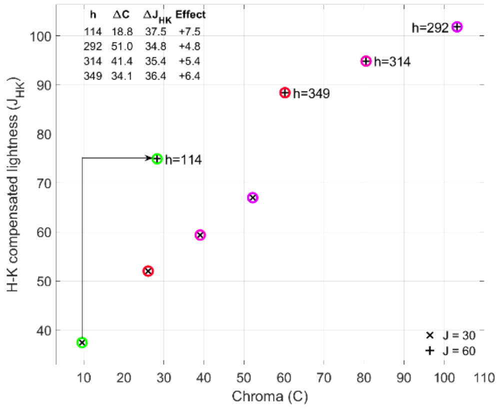


***Figure 3.** Model results showing H-K compensated lightness vs Chroma at two bands of constant lightness (J). Circles around markers show the sample’s hue and the data table shows the magnitude of the H-K effect.*

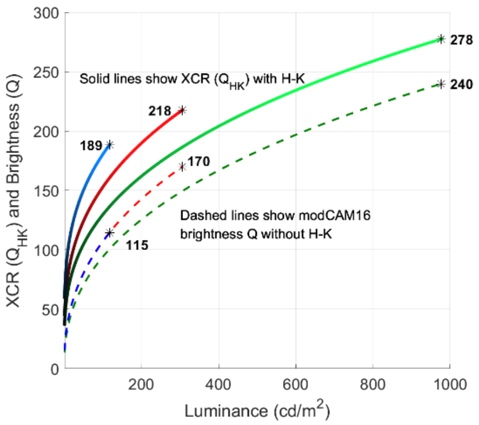
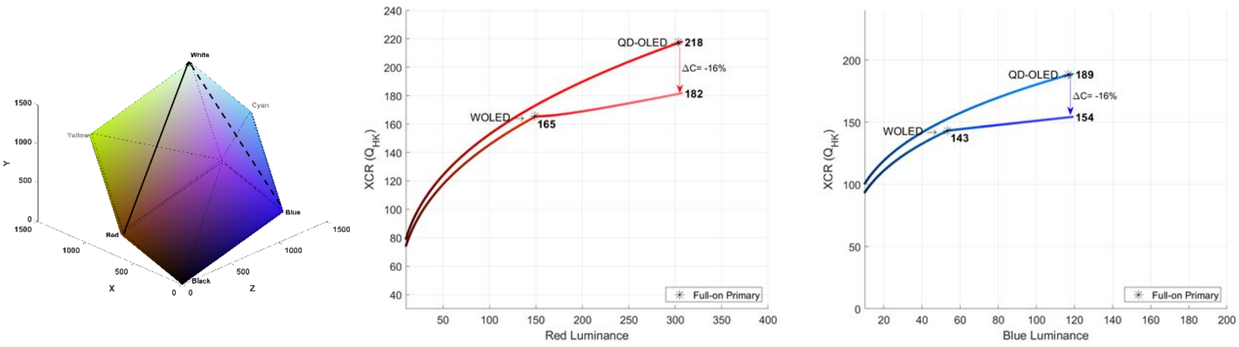


***Figure 4.** A composite graph showing the overall H-K compensated brightness (solid line) versus non-compensated brightness (dashed line) as luminance increases. The numeric labels show the brightness value for each full primary.*

The XCR framework is also useful to compare technologies where color primaries differ. To illustrate, we compared a QD-OLED with only red, green and blue primaries with a white OLED with color filters, we will refer to the panel as WOLED. As is often the case, the chromaticity and luminance of the primaries between these panels are different. The XCR model output shown in Figures 5a and 5b demonstrate the brightness of the red or blue full-on primaries, the most relevant colors with respect to the H-K effect, to predict how each set benefits from H-K compensation. However, since one set reaches full-on primaries at a lower luminance and the primaries cover a smaller gamut, the Q_{HK} is correspondingly lower.



(a) (b) (c)

Figure 5. *XCR brightness of red and blue comparing two display technologies, where one primary drives less color gamut and less luminance, e.g., QD-OLED vs WOLED. (a) XYZ cube illustrating red plus white color desaturation (solid arrow) and blue plus white color desaturation (dashed arrow); (b) Red XCR comparison to primary followed by color desaturating by ΔC = -16% to reach equal luminance, (c) Blue XCR comparison to primary followed by color desaturating by ΔC = -16% to reach equal luminance.*

The brightness for each full-on primary is noted in the figures. However, some content represented by a full-on primary by the QD-OLED will render differently on the WOLED due to brightness and colorfulness differences. The extended WOLED locus at luminance above the full on-primary shows what could happen if the set boosts the luminance to match the QD OLED set by increasing luminance output either by mixing with white or a combination of its alternate primaries. In either case, as the colors mix by moving along an *XYZ* prism from the red or blue primary toward white, the color desaturates. The comparison at the QD-OLED primary luminance shows the decrease in chroma, ΔC, by -16% for red and blue. The chroma loss was derived by the XCR model. The XCR toolkit draws upon a number of research papers from academia and industry. Table 2 outlines the CIECAM16 modifications required to replicate our work.

Table 2. XCR modifications of CIECAM16

CIECAM16	modCAM16	Literature References
Eccentricity for hue, in degrees: $e_t = \frac{1}{4}\cos\left(\frac{\pi}{180}h + 2\right) + 3.8$ Applied using α $\alpha = f(e_t, n)$	Defined a more accurate eccentricity for hue, according to our data sets, and apply to *M* (colorfulness); *h* is in degrees $e_t = -0.0582\cos h - 0.0258\cos 2h$ $- 0.1347\cos 3h + 0.0289\cos 4h$ $- 0.1457\sin h - 0.0308\sin 2h$ $+0.0385\sin 3h + 0.0096\sin 4h + 1$ Applied hue eccentricity to *M* (colorfulness) $M = 43N_c e_t\sqrt{a^2 + b^2}$	Hellwig & Fairchild [4]
$C = \alpha\sqrt{\frac{J}{100}}$ $s = 50\sqrt{\frac{\alpha c}{A_W + 4}}$ $Q = \left(\frac{4}{c}\right)\sqrt{\frac{J}{100}}(A_W + 4)F_l^{0.25}$	$C = 35\frac{M}{A_W}$ $s = 100\frac{M}{Q}$ $J = 100\frac{A}{A_W}^{cz}$, $where\ z = 1.48 + \sqrt{\frac{Y_B}{Y_W}}$ and c (no change) $Q = \frac{2}{c}\frac{J}{100}A_W$	Hellwig & Fairchild [4]
No H-K effect.	Add compensation for the H-K effect: $J_{HK} = \sqrt{J_A^2 + 66C}$ $Q_{HK} = \frac{2}{c}\frac{J_{HK}}{100}A_W$	Hellwig, Stolitzka & Fairchild [5]

Conclusions

Several limitations in traditional color models and metrics have become increasingly evident as display technologies evolve. The widely used chromaticity diagrams, such as CIE 1931, is now considered inadequate for representing HDR displays due to its two-dimensional structure and lack of luminance modeling. Similarly, the CIELAB color space, while once a significant advancement, does not account for the high luminance levels characteristic of HDR displays and fails to capture important perceptual effects like the Hunt Effect, Stevens Effect, and the Helmholtz–Kohlrausch Effect. Another concern arises with the ΔEITP color difference formula defined in ITU-R BT.2124, which has been adopted by Dolby and RTINGS.com to assess a product's color volume relative to reference gamuts like P3 at 1000 cd/m² [6-8]. This metric has been derived under viewing conditions that may not reflect typical home environments. Consequently, colors that register as significant differences (e.g., ≥1 ΔEITP) may not actually be perceptible to a viewer adapted to watching content in a gently lit room, which can potentially lead to overestimation of visible color differences in practical scenarios. And finally, XCR has evolved to indicate how chroma plays a role in elevating perceived brightness of a display. However, 2D analysis, such as XCR are relatively new, thus, usage is nascent. In summary, given the range of available color models and metrics, none has achieved universal acceptance for modeling HDR displays. Each method has its critics, leading to a stalemate within the industry.

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Author Biography

Farnaz Agahian received her PhD in Color Science from Tehran Polytechnic (2009). She began her career at Apple Inc, where she focused on ALS calibration, and later joined Google contributing to color management of Pixel displays. She's currently with Samsung Display America Lab, focusing on the standardization of HDR displays.

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