Determining the color appearance of Helmholtz-Kohlrausch effect for self-emissive displays

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ABSTRACT
The correlation between the measured luminance of a stimulus and its perceptual brightness, which varies with saturation and color, has been studied extensively. The increase in the colorfulness of the stimulus generates a Helmholtz-Kohlrausch (H-K) effect, which appears ‘bright’. This study aims to quantify the H-K effect of a highly saturated self-luminous display and to apply it to the CAM16 model. It also attempts to quantify the H-K effect by using the ratio of lightness and luminance values obtained from the modified CAM16 model. Future research objectives include the accurate prediction of color attributes to develop a model of high saturation displays in order to compare conventional displays.

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1. Introduction
Self-emissive displays with very high luminance and a wide color gamut are generally mass produced. A typical example of this is the OLED display, in which the high dynamic range (HDR) is hardware implemented with a white value similar to that of the existing LCD-based displays by developing materials/driving with a near-zero black self-emissive. Several studies have been conducted in order to improve the contrast and image quality as the color gamut expands with the expansion of the range of luminance (HDR) for large OLEDs [1–3].

The single-wavelength red, green, and blue (RGB) is the ideal pixel for large-gamut displays, as it presents 100% purity and the largest color gamut for the human eye. The saturation (purity) of the RGB quantum dot (QD) materials of the primary pixel increases with the reduction in the half-width of each pixel [4]. The display color gamut has been developed to reach the Rec. 2020 in recent years [5], which includes Pointer’s gamut [6] of real surface colors for accurate reproduction. A large color gamut has an added advantage in that highly saturated colors have smaller lightness limits. The lightness limit for achromatic colors is 100. In the case of chromatic colors, it depends on the chromaticity of the color, which is the maximum visual efficiency shown on a color locus [7]. This phenomenon is known as the Helmholtz-Kohlrausch (H-K) effect, and it is predicted to have a high impact on new emerging displays, such as the OLED, LED, and QD displays [8].

This study aims to modify the color appearance model (CAM) in order to predict the H-K effect caused by a highly saturated self-emissive display. Due to this highly saturated display, we are looking at a brighter display. However, the H-K effect is not predicted by a color appearance model, such as CIECAM02 or CAM16. This paper first conducted a magnitude estimation experiment on the perceptual brightness caused by highly saturated colors. The latest color appearance model, CAM16, was then modified in order to analyze the color appearances reflecting the existing H-K effects and predict lightness. Finally, the H-K effect of self-emissive light displays is investigated by examining the relationship between perceptual lightness and prediction using actual measurements by CAM.

2. Background
The H-K effect, which is a typical color appearance phenomenon, appears brighter as the colorfulness of the stimulus increases. It refers to how the color stimulus lightness changes as the purity increases while the luminance factor remains constant. Therefore, the H-K effect is quantified by using the ratio of lightness and luminance as L/Y, where L is an abbreviation for lightness...
and Y for luminance. Previous studies have reported that the correlation between the measured luminance of the stimulus and perceptual lightness varies based on stimulus saturation [9–12]. An experiment was conducted in order to obtain the L/Y ratio data by using 43 ceramic tiles to acquire a relational expression for lightness against order to obtain the L/Y ratio data by using 43 ceramic tiles to acquire a relational expression for lightness against CIE chromaticity coordinates [12]. The results indicated that the colored stimulus pair appeared brighter than an achromatic stimulus with equal luminance reflection. In addition, previous research has demonstrated that the L/Y ratio is independent of the luminance reflection level. The H-K effect is a well-studied phenomenon that explains the relationship between perceived lightness and luminance of a reflective surface. However, the H-K effect has not been widely used in transmissive color displays, LED, and lightning areas. The demand has increased as highly saturated materials are used in the display field.

CIELAB [13] and CIECAM02 [14] are color affordance models for reflective colors. Other models for translucent colors have also been proposed, such as the CAM15u [15] and CAM18sl [16]. These two models represented the absolute brightness as a function of coloration level. The H-K effect is a well-studied phenomenon that explains the relationship between perceived lightness and luminance of a reflective surface. However, the H-K effect must be expressed as a function of colorfulness (M), considering the H-K effect for unrelated colors that cannot extend to related colors.

Fairchild [17] has developed CIELAB to implicate the H-K effect. According to Fairchild, the H-K effect is used to fit an object’s color data set by several previous studies and the basic equation is as Equation (1). In the data reported by Wyszecki [12], k = 0.143. Below shows the resulting lightness (L*) from the H-K effect addition of the chroma (C*) of the stimulus.

\[ L_{1}^{*} = L^{*} + kC^{*} \]  

(1)

However, the H-K effect must be expressed as a function of the hue angle as a hue dependency. Therefore, hue-related function replaced the constant in Equation (1) shown as Equation (2). The hue-related function is Equation (3) and fitted by several color data sets.

\[ L_{2}^{*} = L^{*} + f_{1}(h^{*})C^{*} \]  

(2)

\[ f_{1}(h^{*}) = 0.116 \left| \sin \frac{h^{*} - 90}{2} \right| + 0.085 \]  

(3)

The H-K effect was much larger at low luminance factors than at high luminance factors. To correct this phenomenon, the following function was added to L:

\[ f_{2}(L^{*}) = 2.5 - 0.025L^{*} \]  

(4)

\[ L^{**} = L^{*} + f_{2}(L^{*})f_{1}(h^{*})C^{*} \]  

(5)

For \( L^{*} = 60 \), \( f_{2} \) was set to 1.0, and the maximum chroma (C*) value of the set was 86.70. Kim compensated for the H-K effect by using this equation as a basic frame in order to universally apply CIECAM02 to display devices with a wide color area [18]. The lightness (L*) and hue angle (h*) of CIELAB correspond to the lightness (J) and hue angle (h) of CIECAM02. CIELAB provides only one color-related attribute (C*, chroma), whereas CIECAM02 provides three attributes: colorfulness (M), chroma (C), and saturation (s). Colorfulness (M) is used instead of C* in Fairchild’s study in order to apply it to CIECAM02 in Kim’s study. The use of colorfulness (M) is more appropriate than chroma or saturation because M presents luminance-dependent properties, such as C*. Equation (6) presents a formula optimized for CIECAM02 in order to compensate for the H-K effect.

\[ J^{*} = J + k_{f}f_{2}(J)f_{1}(h)M \]  

(6)

J* represents the final lightness, including the H-K effect in CIECAM02. J, M, and h represent the lightness, colorfulness, and hue angle calculated using CIECAM02, respectively. The stimulus with the highest chroma (C*) is 135.73 based on Kim’s study. The display used in the previous study was a 15-inch LCD. This paper is quantifying the H-K effect by using a highly saturated self-emissive display.

### 3. Experimental setup

#### 3.1. Display

Two types of 65-inch OLED displays with a large color gamut were used in this study: a QD OLED and a white (W) OLED. All the measurements were for a 5.5% window size, which was also the size of the experiment stimulus. The measurements were taken with a Minolta CS-2000 spectroradiometer at a distance of 50 cm from the display. The primary and secondary colors were converted by using the CIE xyY measurement values to CIELAB values (L*, a*, b*, C*) using the white of each display. The measurement values of the primary colors for each display were similar, as shown in Table 1; however, a slight difference can be observed between red and green. Tables 1 (QD OLED) and 2 (W OLED) present the measurement values of the primary and secondary colors of each display, such as lightness (xyY, L*), redness–greenness (a*), yellowness–blueness (b*), and chroma (C*). The color gamut for QDs was 166% against sRGB and 88% for REC2020, and W was 140% and 74%, respectively. Figure 5 shows the color gamut using measured CIE xyY values of red, green, blue, cyan, magenta, and yellow for QD and W OLED. The luminance for the white stimulus was 601 cd/m² for QD and 435 cd/m² for W.
### Table 1. Measurement Values of QD OLED.

|          | x (QD) | y (QD) | Y (QD) | L    | a*   | b*   | C*   |
|----------|--------|--------|--------|------|------|------|------|
| Cyan     | 0.174  | 0.292  | 401.47 | 85.37| −67.15| −11.00| 68.04|
| Green    | 0.224  | 0.737  | 375.88 | 83.17| −138.02| 115.34| 179.87|
| Yellow   | 0.422  | 0.555  | 475.18 | 91.23| −37.65| 128.97| 134.35|
| Red      | 0.708  | 0.291  | 105.74 | 48.98| 99.31 | 83.70 | 129.88|
| Magenta  | 0.301  | 0.110  | 144.93 | 56.18| −64.70| 142.02|
| Blue     | 0.144  | 0.041  | 39.15  | 30.66| 106.79| −108.84| 152.48|

### Table 2. Measurement Values of W OLED.

|          | x (W)  | y (W)  | Y (W)  | L    | a*   | b*   | C*   |
|----------|--------|--------|--------|------|------|------|------|
| Cyan     | 0.187  | 0.278  | 357.58 | 92.65| −53.87| −13.49| 55.54|
| Green    | 0.261  | 0.688  | 324.95 | 89.24| −122.23| 115.75| 168.34|
| Yellow   | 0.414  | 0.553  | 393.80 | 96.21| −40.03| 128.62| 134.70|
| Red      | 0.683  | 0.317  | 97.84  | 54.54| 92.51 | 93.69 | 131.67|
| Magenta  | 0.292  | 0.121  | 136.24 | 62.77| 120.57| −62.31| 135.72|
| Blue     | 0.146  | 0.047  | 42.35  | 37.36| 108.12| −112.18| 155.81|

The C* values for the green in each display are 179.87 for QD and 168.34 for W, which are the highest chroma values reported in color appearance studies thus far. Additionally, the H-K effect is implemented for color appearance modeling for high-chroma stimuli.

### 3.2. Stimulus

A total of 100 stimuli (10 repetitions) were used in the experiment, including red, green, blue, cyan, magenta, and yellow. These were configured to be evenly distributed throughout the CIExY color space. Figure 1 shows all the measured stimuli on CIExY color space for QD.

### 3.3. Procedure

Each stimulus was displayed on a mid-gray background along with a white and colorfulness reference, as shown in Figure 2. The experiment was conducted in a dark room with the help of 10 normal non-color-blind female participants with Asian ethnic background on one display at a time. In advance, the participants were trained in the magnitude estimation experiment with known values. The definition of each color attribute was sufficiently informed prior to the actual experiment. The color stimuli were displayed randomly. Three color attributes, i.e. lightness, brightness, and colorfulness, were quantified for all the stimuli. The lightness was estimated against the white reference with a value of 100 and ideal black with a value of 0. The participants were asked to estimate the values in numerical scaling. Example of instructions were ‘Estimate the lightness of the stimulus on the right side against the reference white having the lightness value as 100 and the ideal black as 0.’ The brightness was estimated against a white (N 9.5) painted paper under an indoor illuminant of 700lx. The brightness of the painted paper was assumed to be 100 and remembered, and then the display’s brightness of the white (Figure 2 reference white) is asked to be quantified. The brightness of the display at dark conditions was always higher than that of the paper white. The difference between lightness and brightness is that the white on the display is fixed at 100 for lightness and not fixed for brightness. The difference from other related previous experiments is that they were allowed to answer values above white lightness and brightness. The colorfulness was estimated against the colorfulness reference (Figure 2 colorfulness reference) with a value of 40 and a background gray value of 0. The colorfulness reference has not changed throughout the experiment.

### 3.4. Observer

The reliability of the observer’s quantitative data is important because the modeling is based on human perception. The reliability evaluation of the observer was carried out in the magnitude estimation experiment by calculating the intra-observer variability using the coefficient of variation (CV). The mean CV values for each attribute were 16.1% for lightness, 12.7% for brightness, and 15.0% for colorfulness. The brightness CV value reported by Withouck [19] was 13%, which is similar to the results obtained in this study.

### 3.5. Color appearance model

The CAM16 [20] model was developed so as to improve the colorimetric cone response function in CIECAM02...
in order to remove the negative lobes for mathematical problems. CAM16 was used to predict the color appearance of the two OLED displays. The measured values of the stimulus, white color, colorfulness reference, and background were used as input values. The surround condition was Dark Surround, and the adaptation luminance $L_A$ is 128 cd/m$^2$ for QD and 93 cd/m$^2$ for W. J is used for lightness, Q for brightness, and M for colorfulness. The brightness data were scaled against the outer white reference stimulus with a value of 100, and colorfulness was scaled against the colorfulness reference with a value of 40.

4. Results

4.1. Color appearance

4.1.1. Lightness

The lightness color attribute is analyzed in this study. As previously explained in the Introduction section, the existing CAM must be modified as it appears brighter resulting from the highly saturated display. The difference from the previous studies is that the display has higher saturation and brightness. Additionally, there was a few stimuli beyond the lightness of reference white, which seems to ‘glow’. In the color application of the
reflective stimulus, there is no case beyond the brightness of white; however, in the transmissive type, a stimulus that appears brighter than white can exist due to its high saturation. There were three stimuli for the QD display and one stimulus (green) for the W display, which exceeded 100 lightness.

CAM16 was used as a color appearance model to predict lightness (J). Figure 3 presents the predicted lightness (J) values corresponding to the estimated values. The slope in Figure 2 should be 1 if the model and the psychophysical data coincide perfectly. The resultant slope for QD OLED display is 1.134 and 1.124 for W OLED, thus indicating that the stimulus appears brighter than the value predicted by CAM16. Therefore, this shows that CAM16 cannot sufficiently predict the lightness of a high chromatic stimulus, which causes the H-K effect. The $k_1$ and $k_2$ constant values were derived from fitting the magnitude estimation values against CAM16 lightness values using Equation (6).

The maximum chroma ($C^*$) value was 135.73, and $k_1 = 1.84$ in Kim’s study [18] that was previously mentioned. The highest chroma values for this study were 179.87 for QD and 168.34 for W. The $k_1$ constant value decreased from 1.84 in Kim’s study to 1.107 for this study because the colorfulness (M) value increased 1.5 times due to the wide gamut display, while the resulting lightness should not exceed the highest of 100. Therefore, the constant $k_1$ should decrease if the display’s saturation increases. Note that the constants would vary with the surrounding conditions and characteristics of the display in future studies.

In previous studies mentioned in the Background section, the color appearance model considering the H-K effect was derived by varying only the constant value while the frame of the function remains fixed. Furthermore, the lightness values that exceed 100 (white) must be determined. Two colors on QD and one color on W were over 100. Both colors were stimuli with high luminance and saturation, making them appear fluorescent. The existing equation adds a value proportional to the saturation to lightness (J) but includes a function that does not exceed 100. Unlike reflective colors, some colors can be seen as fluorescence; therefore, the $k_2$ constant of 1.05 was multiplied by the conventional equation (Equation [7]). In fact, the process is added because of one or two stimuli; therefore, it is safe to omit it. However, even if it is not white, there may be a stimulus exceeding 100; therefore, this is a process to consider in the future. The CV values were calculated against psychophysical data by using CAM J and J' from Equation (7) and shown in Table 3.

$$J' = k_2[J + k_1 f_2(J) f_1(h) M]$$ (7)

Table 3. CV Values for Compensation of H-K Effect Models.

|                | QD OLED | W OLED |
|----------------|---------|--------|
| $J$            | 18.5    | 16.8   |
| $J^*$          | 17.1    | 15.3   |
| $J'(k_2 = 1.0)$| 14.9    | 12.5   |
| $J'(k_2 = 1.05)$| 14.0   | 11.9   |

Figure 4. Brightness data predicted by CAM16; Q and modified Q’ plotted against magnitude estimation Brightness; (a) QD OLED (b) W OLED.
4.1.2. Brightness

Brightness (Q) was calculated by using the new J’ value in Equation (7). Figure 4 presents the results for Q and Q’, in which the slope indicates that the absolute value was not accurately predicted. Previous studies implemented models to predict the absolute brightness, but they were focused on reducing the variance rather than matching the value with a slope of one due to control conditions, such as unrelated colors.

The data obtained through the CAM16 and psychophysics experiments were plotted, and R² values and linear trend line were used to compare the variance. The R² value in the case of QD increased from 0.63–0.75 after modifying J’, and W increased from 0.60–0.73, thereby indicating a better prediction of brightness after the modification.

4.1.3. Colorfulness

Colorfulness (M) was used to calculate the lightness (J’) and brightness (Q’). The CAM16 predicted values were plotted against the psychophysical data presented in Figure 5. The data were fitted by using a linear line passing through zero. The slope for both displays is 1.0, and the R² value is 0.95, thereby indicating that the colorfulness predicted by CAM16 concurs well with the data provided by the participants.

4.2. H-K effect

The value of J’/Y for the H-K effect was calculated in order to observe the phenomenon in which it appears brighter as the colorfulness increases. The J, Q, and M values can be derived using CAM16. The lightness, brightness, and colorfulness data were obtained by using the data from each of the OLED displays. Among the 90 stimuli, the J’/Y values of stimuli with a value between lightness (L*) and 45–55 were calculated, and the contour lines were hand-drawn by connecting similar values as in the previous studies[7] mentioned in the introduction. Figure 6 shows the contour of the J’/Y

![Figure 5](image_url)

**Figure 5.** Colorfulness data predicted by CAM16; M plotted against magnitude estimation Colorfulness; (a) QD OLED (b) W OLED.

![Figure 6](image_url)

**Figure 6.** Lightness value (equal lightness for achromatic = 1; A) contour line for equal lightness stimulus of QD OLED.
values of mid-lightness on CIExy plane for the QD. (A) on the plane represents the achromatic stimulus with equal lightness. This is because the colorfulness value of the stimulus with a mid-lightness value was the largest.

A closed contour line is drawn based on mid-lightness (A). This aspect is identical to those reported in the previous studies. The increase in the brightness is parallel to the line connecting red and blue. Essentially, purple is primarily observed in the H-K effect. Additionally, a contour line is drawn toward green because there were no substances that could not produce high saturation in the middle brightness. Uchikawa [19] demonstrated that the lightness and brightness are similar at 560 nm, and the difference increases as they moved toward short or long wavelengths at 560 nm. The brightness decreases to 2.5 and 2 as it approaches 520-560 nm, as shown in Figure 5; therefore, the results are consistent with those of the previous studies. However, the difference with the previous studies is that the value of the contour is much higher for this study. As expected, the H-K effect is much stronger for self-emissive OLED displays.

5. Discussion

The H-K effect varies with luminance, thereby making it difficult to determine the overall brightness. Additionally, determining the absolute brightness value is difficult because the H–K effect varies with hue. The lower the luminance, the greater the H-K effect, and the lower the black color, the greater the contrast. When \( Y = 1 \text{ cd/m}^2 \), the calculated \( J'/Y \) is 72.7 for QD and 61.2 for W. The higher the white luminance, the greater the number of stimulus with \( J'/Y \) ratio of one or more (which appears brighter than the actual luminance) produced by the H-K effect, which spans a wider luminance range. On the contrary, if the white luminance is high but the saturation is low, the H-K effect is weak and the effect of bright appearance is low. For the H-K effect to show strongly, the luminance of the white should be high, and the primaries of the display should have a wide gamut.

The accurate prediction of the brightness is essential for describing the H-K effect. Withouck [15, 20] and Hermans [16] predicted the brightness. They both used self-luminance stimuli, and there was a difference when using black and gray in the achromatic colors. The resulting brightness was expressed as a function of saturation similar to this study, but it was expressed as an absolute value rather than a relative value. One limitation of this study is that the absolute value of the brightness was not accurately predicted. Unlike the previous studies, the relative value was used to explain the phenomenon with lightness because the background, stimulus size, and type of surrounding stimulus were not controlled.

The color attribute lightness must be accurately predicted in the future in order to develop a model that compares the lightness of conventional displays owing to high saturation and high luminance. The coefficient in the study of Fairchild [17] was 0.143, which is a small amount for fitting object colors. For this reason, the general CAM would not have included the H-K effect for its small impact in predicting the color attributes. However, perceptual values, such as lightness and brightness, must be improved and predicted based on the model developed in this study using only the existing luminance measurements when self-emissive displays with higher saturation are released. The quantification of stimuli beyond recognizing white as the maximum value of lightness is also a factor to be further analyzed in existing CAMs based on the object color appearance; therefore, it should be differentiated from the existing equation [21] Table 3.

6. Conclusion

The image quality of the next-generation displays has significantly improved, and they can reproduce colors that are close to real life due to the widening of the color gamut. In this study, highly pure materials were used as pixels to expand the color gamut and show the saturation of more than twice the color of the object. Self-emissive displays also have a wide range of luminance; thus, the H-K effect caused by saturation has become increasingly noticeable. This study attempted to predict the lightness and brightness corresponding to the H-K effect by conducting psychophysical experiments and modifying the existing CAM16 model.

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Notes on contributors

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References

[1] D. Tian, L. Xu, and M.L. Luo, El 2019 (10), 309–301 (2019).
[2] H.J. Shin, K.M. Park, S. Takasugi, Y.S. Jeong, J.M. Kim, H.S. Kim, and C.H. Oh, SID 48 (1), 1134–1137 (2017).
[3] D. Stolitzka, J.H. Chong, C. Lee, and J. Kwag, SMPTE 2020, 1–15 (2020).
[4] R. Zhu, Z. Luo, H. Chen, Y. Dong, and S.T. Wu, Opt. Express 23 (18), 23680–23693 (2015).
[5] Series, B. T, Recommendation ITU-R 500-13 (2012).
[6] M.R. Pointer, Color Res. Appl 5 (3), 145–155 (1980).
[7] D.L. MacAdam, J. Opt. Soc. Am 40 (9), 589–595 (1950).
[8] R. Donofrio, J. Soc. Inf. Disp 19 (10), 658–664 (2011).
[9] R.M. Evans, and B.K. Swenholt, J. Opt. Soc. Am 58 (4), 580–584 (1968).
[10] R.M. Evans, J. Opt. Soc. Am 49 (11), 1049–1059 (1959).
[11] D.L. MacAdam, J. Opt. Soc. Am 25 (8), 249–252 (1935).
[12] G. Wyszecki, JOSA 57 (2), 254–257 (1967).
[13] C.I. de l’Eclairage, (CIE, Paris, 1978).
[14] N. Moroney, M.D. Fairchild, R.W. Hunt, C. Li, M.R. Luo, and T. Newman, CIC 2002 (1), 23–27 (2002).
[15] M. Withouck, K.A. Smet, W.R. Ryckaert, and P. Hanselaer, Opt. Express 23 (9), 12045–12064 (2015).
[16] S. Hermans, K.A.G. Smet, and P. Hanselaer, J. Opt. Soc. Am. A Opt. Image Sci. Vis 35 (12), 2000–2009 (2018).
[17] M.D. Fairchild, and E. Pirrotta, Color Res. Appl 16 (6), 385–393 (1991).
[18] M. Kim, J.H. Jo, Y. Park, and S.W. Lee, Displays 56, 1–10 (2019).
[19] K. Uchikawa, et al., J. Opt. Soc. Am. A 18 (4), 737–746 (2001).
[20] M. Withouck, K.A. Smet, W.R. Ryckaert, M.R. Pointer, G. Deconinck, J. Koenderink, and P. Hanselaer, J. Opt. Soc. Am. A Opt. Image Sci. Vis 30 (6), 1248–1255 (2013).
[21] C. Li, Z. Li, Z. Wang, Y. Xu, M.R. Luo, G. Cui, M. Melogsa, M.H. Brill, and M. Pointer, Color Res. Appl 42 (6), 703–718 (2017).