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Heterochromatic Brightness Matching Experiments to evaluate Brightness Prediction Model including Helmholtz-Kohlrausch Effect

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Abstract

In this study, the brightness matching experiment was conducted to obtain the equivalent luminance between chromic and achromatic colors. Observers adjusted the luminance of achromatic colors until they appeared to have the same brightness as chromatic colors. A total of 285 chromatic colors with three different luminance levels (30cd/m^2, 95cd/m^2, and 300cd/m^2) were used as the test colors, and the experiment was repeated three times by 20 observers. The results showed that the equivalent luminance to luminance (L_{eq}/L) ratio, where equivalent luminance refers to the luminance of achromatic color, increases with CIE 1976 saturation increases at all luminance levels, reflecting the Helmholtz-Kohlrausch effect. Additionally, as the luminance level of chromatic color increased, L_{eq}/L ratio decreased. By using the newly collected equivalent luminance data, the existing color appearance models were tested. The findings indicate that existing color appearance models predicting the H-K effect can't predict the brightness well.

Introduction

The Helmholtz-Kohlrausch (H-K) effect is a color appearance phenomenon where two colors with the same luminance are perceived differently based on saturation changes. This effect has become increasingly important as the color gamut of displays has expanded. Displays with a wider color gamut appear brighter than displays with a smaller color gamut of the same peak luminance, due to the H-K effect.

In general, the H-K effect is studied through heterochromatic brightness matching experiments or brightness scaling using the magnitude estimation method. Although these two experimental methods should yield the same results, each data set has been used for different purposes. Brightness matching data is used to derive equivalent luminance, while magnitude estimation data is used for color appearance modeling.

For example, Sanders and Wyszecki [1] and Wyszecki [2] demonstrated the H-K effect through brightness matching experiments. Equivalent luminance sets collected from these experiments have been used to develop equivalent luminance-to-luminance (Leq/L) equations, such as the Nayatani model [3] and CIE200 [4], to predict the H-K effect.

The magnitude estimation method has also been widely used to investigate the H-K effect. Without et al evaluated the brightness of chromatic stimuli of the same luminance as a reference neutral color using the magnitude estimation technique, and the data was used to develop a brightness prediction model for unrelated colors, including the H-K effect [5, 6]. Park also used magnitude estimation to evaluate lightness [7]. Based on these experimental data, brightness models that can predict the H-K effect have been proposed as equivalent luminance and color appearance attributes. However, it is necessary to test H-K effect prediction models using brightness matching data sets and vice versa, as the models have the H-K effect in common. This study compares the H-K effect between different color appearance models using heterochromatic brightness matching data.

For brightness prediction modeling, the relationship between the H-K effect and color attributes, such as hue, saturation, lightness, etc., must be understood. In particular, this study compares the H-K effect and luminance, as most previous studies have compared chromatic stimuli with one reference neutral color. This study compares the brightness of stimuli with the same luminance and different hue and saturation at various luminance levels. The brightness matching experiment was conducted, and the results were used to evaluate the color appearance models.

Heterochromatic Brightness Matching Experiment

Experimental Setting

The experiment was conducted using the SONY BVM-X300 OLED display. The peak luminance was 713cd/m^2. The color gamut and gamma were DCI-P3 and 2.4 HDR. The display size is 3840x2160. Figure 1 shows the measured color gamut and gamma.

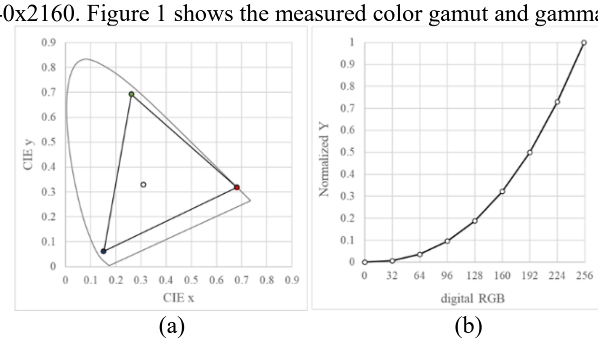

Figure 1. Display Characteristics (a) Color gamut (b) Gamma curve

The experiment was carried out in a dark room condition. The distance between observers and the display was 1m, and the field of view was about 10°

Experimental Stimulus

The circular stimuli were used in the heterochromatic brightness matching experiment. The stimulus was divided into two fields: an achromatic color field and a chromatic color field. The radius of the stimulus was 400 pixels. The achromatic color field was fixed as a neutral color with 6500K. Figure 2 illustrates example of the stimulus. The background luminance was 0cd/m^2.

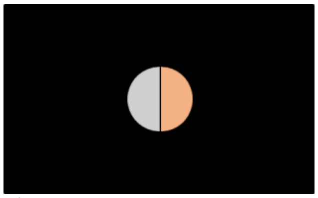

Figure 2. The example of experimental stimulus

Three different luminance levels were used for the test colors: 30cd/m^2, 95cd/m^2, and 300cd/m^2. The CIELUV saturation s_{uv} of the test color was kept the same at each luminance level. Figure 3 shows test colors represented on CIE 1976 u'v' color space.

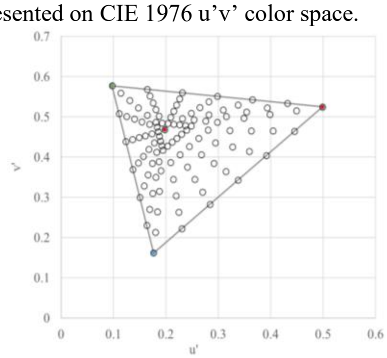

Figure 3. Test colors on CIE1976 u'v' color space

Since the number of colors that can be express by experimental display varies with each luminance level, the number of test colors was also different. The 109-, 107- and 69-stimuli were used in 30cd/m^2, 95cd/m^2 and 300cd/m^2 respectively.

Experimental Method

The heterochromatic brightness matching method was used for experiment. Before starting the experiment, an Ishihara test was conducted for checking the normal color vision. Observers adjusted the luminance of the achromatic color until it appeared equally bright to the test color. They used the right and left arrow keys for matching tasks. The black screen was displayed for two seconds between test colors. After finishing the brightness matching experiment for one luminance level, the next luminance level session was started. The order of luminance level was random. The matched luminance of the achromatic color was obtained as experimental data and is considered the equivalent luminance for each test color. All the session was repeated three times.

Participants

A total of 20 naïve people participates in this experiment. All the observers have a normal color vision, and they were all in the twenties.

Experimental Result

Observer Performance

The observer performance was tested by repeatability. Repeatability was calculated by using the coefficient of variation (CV). Table 1 shows the average CV value for each observer. The average CV value is 13.68%. The CV value on 300cd/m^2 session is lowest than other luminance levels. The maximum CV value is 27.53% in 30cd/m^2, and the minimum CV value is 5.80% in 300cd/m^2.

Table 1. Observer repeatability

CV (%)	*Luminance Level*		
Observer	30cd/m^2	95cd/m^2	300cd/m^2
1	20.46	14.27	7.27
2	16.33	12.01	5.8
3	13.23	10.96	7.58
4	13.6	11.4	8.03
5	20.3	16.54	9.47
6	25.53	17.56	12.26
7	15.52	13.35	9.27
8	15.15	10.63	6.98
9	24.62	22.92	10.58
10	21.85	13.41	9.5
11	17.15	13.94	8.23
12	10.62	9.31	6.11
13	27.53	17.58	10.97
14	14.55	10.67	7.5
15	16.94	11.86	6.95
16	18.33	12.16	7.71
17	21.56	13.95	7.89
18	27.23	18.85	14.14
19	12.84	12.27	8.62
20	16.71	13.28	8.87
Average	18.5	13.85	8.69

Result

The average matching luminance of achromatic colors is equivalent luminance (L_{eq}) which is experimental data. The luminance (L) refers to the fixed luminance of test colors. The logarithmic scale of average equivalent luminance to luminance was used for data analysis. If $\log(L_{eq}/L)$ is greater than zero, observers evaluated the luminance of test colors higher than its own luminance.

Figure 4 is a graph depicting the relationship between $\log(L_{eq}/L)$ and CIELUV saturation (s_{uv}). The x-axis represents saturation in the CIE LUV color space and the y-axis represents the $\log(L_{eq}/L)$, which is the experimental data. As shown in the Figure 4, the $\log(L_{eq}/L)$ increases as saturation increases, indicating that observers perceived the chromatic colors as brighter as saturation increases, as expected by the H-K effect.

The $\log(L_{eq}/L)$ also varies with the luminance level. As the luminance level increases, the $\log(L_{eq}/L)$ is decreases. Therefore, the 300cd/m^2 has the lowest $\log(L_{eq}/L)$.

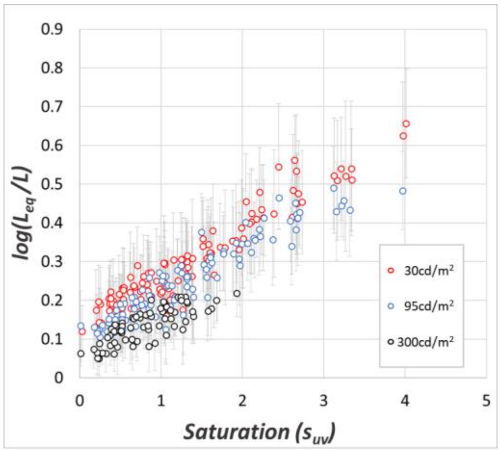

Figure 4. Comparison result between s_{uv} and $log(L_{eq}/L)$

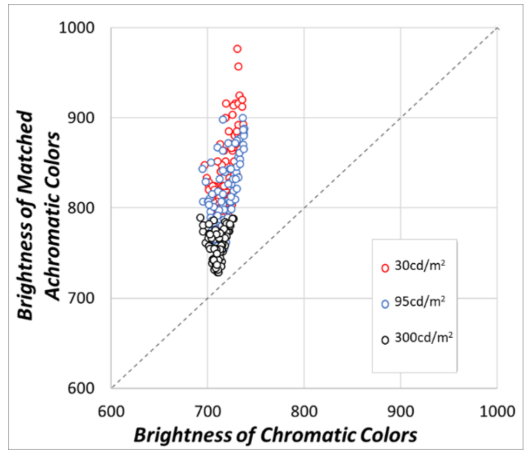

Figure 5. CIECAM16 test result

For the low-saturated colors that are nearly indistinguishable from the achromatic color, the offset is observed. The log scale of the lowest saturation stimuli is approximately 0.1. The equivalent luminance is around 1.4 times greater than the luminance which is due to the stimuli bias. It indicates that observers evaluated the brightness of test colors higher even low saturated colors.

Brightness Prediction Model including Helmholtz-Kohlrausch Effect Test

Test Method

The color appearance models are used for brightness prediction: CIECAM16, Hellwig et al. model, and CAM15u.

The brightness of matched achromatic colors was compared to that of test colors. Fig.6-8 show the results where the x-axis means the brightness of test colors and the y-axis represents the brightness of matched achromatic color. The dashed line in the Figure represents the y=x graph, and the closer the data points are to the line, the better the brightness prediction.

Test Result

CIECAM16

For predicting the brightness, the input data is XYZ tristimulus values of colors and reference white [8]. The reference white is set to the luminance of each test color: 30cd/m^2, 95cd/m^2, and 300cd/m^2 respectively. CIECAM16 brightness (Q) doesn't include any chroma and colorfulness that can predict the H-K effect.

Figure 6 displays the result of CIECAM16 test where all the data points for CIECAM16 are above the dashed line, indicating that CIECAM16 can't accurately predict the brightness of test colors.

Hellwig et al. Model

Hellwig et al. model is developed based on the CIECAM16. It calculates the lightness of CIECAM16 and applies chroma and hue functions, as shown in below equation 1-2 [9]. The reference white was set the same as in the CIECAM16 test. This model considers the H-K effect in its brightness prediction by using the lightness value.

$$Lightness_{HK} = Lightness + f(hue\ angle) \cdot Chroma^{0.565} \quad (1)$$

$$f(hue\ angle) = -0.160cosh + 0.132cos2h - 0.405sinh + 0.080sin2h + 0.792 \quad (2)$$

$$Brightness_{HK} = \left(\frac{2}{Surround\ factors\ (c)}\right) \cdot \left(\frac{Lightness_{HK}}{100}\right) \cdot Achromatic\ response\ for\ white \quad (3)$$

Figure 7 indicates the Hellwig et al. model test result. It is much better than CIECAM16, all the data is located near the dashed line. However, almost all the data points are located above the dashed line. It means that Hellwig et al. model predicts the brightness of matched achromatic color higher than the brightness of the test color. The model underestimates the brightness of chromatic color.

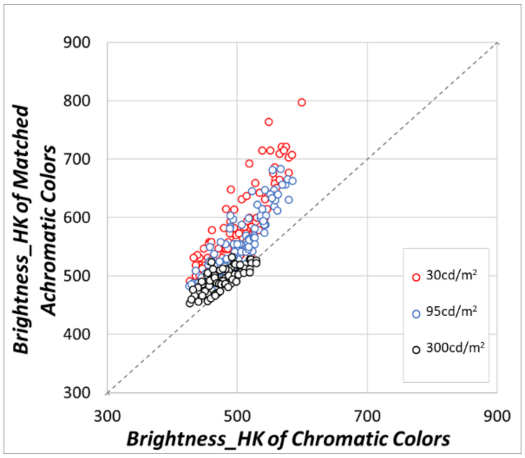

Figure 6. Hellwig et al model result

CAM15u

Withouck et al. proposed the CAM15u. CAM15u is the color appearance model for unrelated colors. The model includes the colorfulness as following Eq 2. The input value is spectral data of test colors and matched achromatic color.

$$Brightness = Achromatic\ signal + 2.559 \cdot Colorfulness^{0.561} \quad (4)$$

Figure 8 shows the results of CAM15u. This model predicts the brightness increases with an increase in chroma, but it overestimates the brightness. The data are located below the dashed line. It means that the model predicts the H-K effect to be greater than it was perceived by observers. CAM15u also can't predict the brightness well.

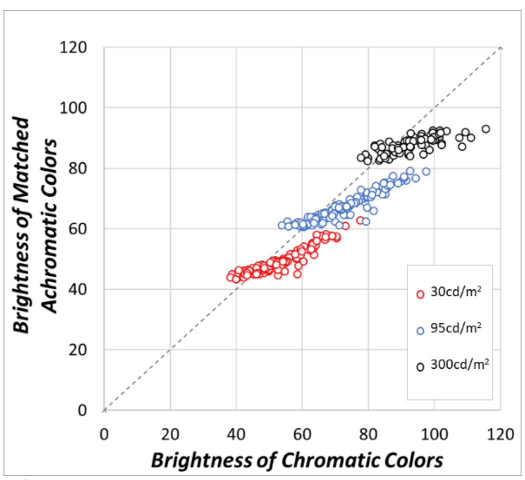

Figure 7. CAM15u test result

Conclusion

In this study, new heterochromatic brightness matching data set were obtained at various luminance level to investigate the H-K effect. Observers matched the brightness of test colors by adjusting the luminance of achromatic colors. The results showed that the luminance of achromatic colors increases as the saturation increases.

The existing color appearance models that include the H-K effect were tested using our equivalent luminance data set. The Hellwig et al. model and CAM15u which include the H-K effect can predict the brightness better than CIECAM16. However, both models also fail to predict well. Therefore, the further study is necessary to develop a new brightness prediction model that takes into account the H-K effect.

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Author Biography

Garam Seong received her BS in electrical engineering from the Ulsan National Institute of Science and Technology UNIST (2018) and her MS in human factor engineering from the UNIST (2020). She is PhD students in UNIST. Her work has focused on color appearance model and the image quality of the display.

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Hyosun Kim received her B.S. degree in Psychology and M.S. and Ph.D. degrees in Cognitive science from Yonsei University in 1997, 2003, and 2012, respectively. From 2003 to 2007, she was a Research Assistant with the Institute of Cognitive Science in Yonsei University, Seoul, South Korea. She is currently with Samsung Display, Yongin, South Korea. Her research interests include human perception and eye fatigue.