Prediction for the Helmholtz-Kohlrausch Effect of Natural Images under the Ambient Lighting Conditions

K.Nakagawa[1], H.Aoyanagi[2], H.Takamatsu[2], Y.Shimodaira[1], G.Ohashi[1]

nakagawa.kohta.15@shizuoka.ac.jp
[1]Shizuoka Univ., 3-5-1 Johoku, Naka-ku, Hamamatsu, Shizuoka 432-8561, Japan
[2]NEC Display Solutions, Ltd., 4-28 Mita 1-chome, Minato-ku, Tokyo, 108-0073, Japan
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ABSTRACT

This study predicts the Helmholtz–Kohlrausch effect of natural images under various ambient lighting conditions. The proposed prediction equation was obtained by incorporating the experimental values of International Display Workshop (IDW) 19 into the previous values obtained by IDW'18 to improve the accuracy of previous prediction equation.

1 INTRODUCTION

The Helmholtz–Kohlrausch (H–K) effect on human visual characteristics has been described by Hunt as follows "For colours of the same luminance, there is a tendency for the brightness to increase gradually as the colourfulness of the colour increases" [1]. Donofrio and others have argued that the H–K effect affects many displays, mobile devices and mobile phones, and contributes to a mesopic driving environment [2]. By quantifying the magnitude of this effect, we can improve the development and evaluation of displays.

Brightness sensations have been experimentally investigated in various environments [3]–[7]. Yujiri measured the perceived brightness of object colors under increasing illuminance using a color-naming method with color chips [3]. Yamada et al. measured the perceived brightness under high illuminance using the flicker method [4]. Many other studies have reported the brightness values of monochromatic colors perceived by humans [5]–[7].

In an International Display Workshop (IDW) based study, we previously assessed the prediction ability of the H–K effect in natural images [8]–[13]. Subjective evaluation experiments on natural images under various ambient lighting conditions have showed that illuminance influences the H–K effect [14].

In this study, we calculated the perceived brightness of natural images under various ambient lighting conditions. The experimental data confirmed that the change in lightness (L^* value in CIELUV color space) lessens as the saturation increases. Therefore, we used the ratio of the experimental value to the predicted value as a correction value to reflect the changing tendency of the lightness with increasing in saturation. After making the correction, the correlation coefficient between the slopes of the experimental and predicted values improved from negative to positive.

2 EXPERIMENT

2.1 Experiment Values

A subjective evaluation experiment on natural images under various ambient lighting conditions was performed in IDW'19.

Table. 1 Experience condition

Subjects	26 persons (age 20s: 25 persons , age 50s: 1 person)
Method	Adjustment method
Illumination (average)	Darkroom (0.00[lx]), Illuminant D_{65} (158[lx]), Illuminant D_{65} and indirect sunlight (1088[lx])
Display	LCD monitor (AdobeRGB 99%)
Viewing distance	9H (1.62[m])[15]

(a) "Autumn leaves" (b) "Sea" (c) "Tulip"

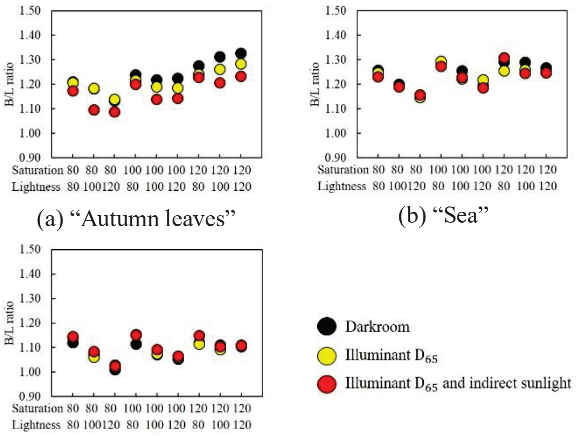
Figure 1 Natural

The conditions were set according to ITU-R BT 500-13 [15]. Experiments were conducted in three environments: a dark room, under illuminant D65, and under illuminant D65 and indirect sunlight. The experimental conditions are shown in Table 1. The original images were three natural images resized from Shutterstock [16] to a resolution of 800 × 600 pixels. As shown in Figure 1, the "Autumn leaves" and "Tulips" images are enriched in red, so are thought to exert a large H–K effect; in contrast, the "Sea" images dominated by cyan exerts a small H–K effect. The vertical surface illuminance level in front of the display was measured in each ambient environment and averaged over the subjects. The illuminance levels were 0 lx in the dark room, 158 lx under illuminant D65, and 1088 lx under illuminant D65 and indirect sunlight. The assessment was performed by the variable achromatic color (VAC) method assessment [17]. The perceived brightness was determined by adjusting the apparently same achromatic image luminance to a given chromatic luminance.

The experiments conducted under the different light conditions were focused on human light adaptation. The sunlight experiments were conducted on sunny days only. The experimental results are shown in Figure 2. The magnitude of the H–K effect is expressed as the brightness to luminance (B/L) ratio, defining the ratio of perceived brightness to luminance. Note that when the perceived brightness exceeds the luminance, the B/L ratio becomes larger than 1.0.

2.2 Prediction equation

Many models of visible colors have been proposed to date



(a) “Autumn leaves” (b) “Sea”

(c) “Tulip” (d) Usage guide

Figure 2 Experimental results

[18]–[21]. Nakano et al. derived the perceived brightness from physiological data, namely, from the L, M, and S cone responses [18]. The CIE200 equation, is based on the Nakano equation, which accounts for both the H–K effect and the Purkinje effect (the blueshift response of the eye to dark adaptation) [19]. These equations were derived from experimental data obtained by the variable chromatic color (VCC) method [20].

The CIECAM02 equation is also based on the color vision mechanism. Although this equation ignores the H–K effect, it is useful for calculating color adaptation from tristimulus values and for color management between image devices with different color information [21].

Meanwhile, the Nayatani equation expresses human perceived brightness by assigning numerical values to colors [22]. The Nayatani equation expresses the H–K effect in terms of parameters such as hue, saturation, lightness and adapting luminance dependency.

As this experiment uses the VAC method and the objects are simulated and presented on a high-resolution display, its results can be modeled using Equation (1):

$$\begin{aligned}\Gamma_{VAC} &= \frac{B}{L^*} \\ &= 1 + \{-0.134 \cdot q(\theta) + 0.0872 \cdot K_{Br}(L_\alpha)\} \\ &\qquad \times S_{uv}(u,v)\end{aligned} \tag{1}$$

where, $q(\theta)$ compensates for hue differences, $K_{Br}(L_\alpha)$ is the magnitude of the adapting luminance dependency relative to the background luminance L_α, and $S_{uv}(u,v)$ is the magnitude of saturation.

Shizume et al. extended Nayatani et al.’s prediction equation for the H–K effect to the prediction of natural images [9]. Specifically, natural images are regarded as a collection of monochromatic images, and the B/L ratio at each pixel is calculated using Equation (2):

$$\Gamma_{Natural} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}\Gamma_{VAC_{ij}}}{m \times n} \tag{2}$$

where, m and n are the width and height of the image, respectively.

We propose an additional term expressing the lightness change, which is absent in Nayatani’s equation. The estimation accuracy of the H–K effect was improved by correcting for lightness. The lightness correction is the second term of the prediction equation given using Equation (3):

$$\begin{aligned}\Gamma_{Corrected} &= \frac{B}{L^*} \times h(L^*, \theta) \\ &= 1 + \{-0.134 \cdot q(\theta) + 0.087 \cdot K_{Br}(L_\alpha)\} \\ &\qquad \times S_{uv}(u,v) \times h(L^*, \theta)\end{aligned} \tag{3}$$

where $h(L^*, \theta)$ is the lightness parameter, given using Equation (4).

$$h(L^*, \theta) = 1 + a(\theta)(L^* - L_s^*) \tag{4}$$

In this expression $a(\theta)$ is the increment of the compensation value for the lightness change in a hue, L^* is the lightness at a pixel, and L_s^* is the standard lightness in the Nayatani equation ($L_s^* = 47.58$).

3 RESULTS

To estimate the H–K effect under various ambient lighting conditions using Equation (3), we need the background luminance in each environment. To this end, the background luminance was measured by a spectroradiometer (TOPCON SR-3A) as shown in Figure 3. The luminance L_α in the dark room, artificially lit room, and artificially lit and sunlit room were 50.604, 51.056 and 53.650 cd/m^2, respectively.

After measuring the background luminance under each environmental light, the predicted results were combined with the experimental results in Figure 2, and are shown in Figure 4. In this figure, the horizontal axis indicates the saturation and lightness, and the vertical axis represents the B/L ratio or magnitude of the H–K effect (●: Experimental values, ✕:Predicted values). The estimation is considered correct if the predicted value lies within the 95% confidence interval of the experimental value. In the H–K effect, the B/L ratio tends to decrease with increasing lightness, and the prediction equation shows this trend. Therefore, most of the images were accurately predicted by considering the lightness changes.

4 DISCUSSION

As shown in Figure 4, the B/L ratio was well predicted, but the lightness change reduced with increasing saturation. For a quantitative analysis, first-order functions were derived from three points with different lightness values at the same saturation level in each environment, and their slopes were calculated using the least-squares method. The effect is shown in Figure 5. where the horizontal and vertical axis represent saturation and the mean slope of the approximated linear function, respectively. Black, yellow, and red circles indicate a dark room, an illuminant D65, and the slope at illuminant D65 and indirect sunlight, respectively. The slope of the lightness change increased with increasing saturation in all environments.

Therefore, to correct the predicted value, we multiplied it by the ratio of the experimental and predicted values. This correction reflects the decreased lightness change in the experimental values at high saturations. The ratio was calculated from the experimental and predicted values of

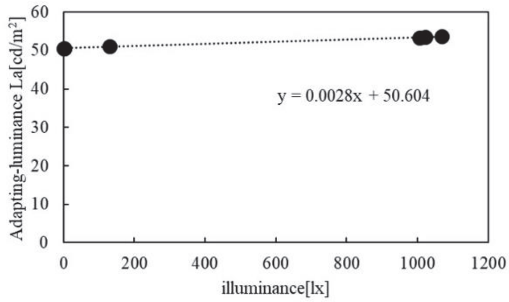
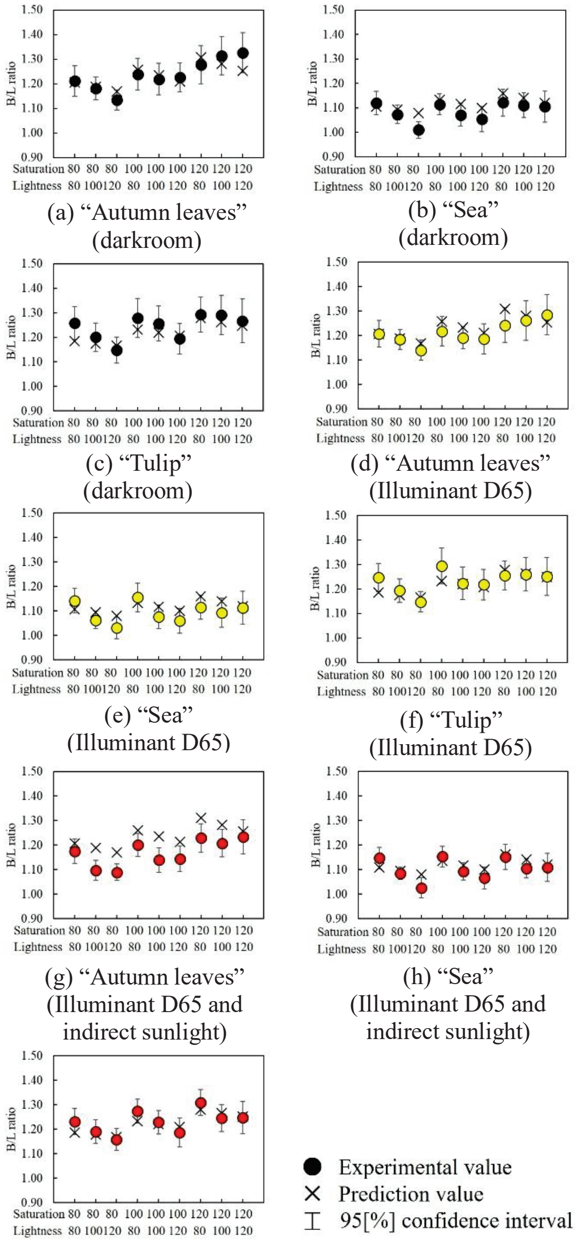


Figure 3 Adapting-luminance



(a) “Autumn leaves” (darkroom)

(b) “Sea” (darkroom)

(c) “Tulip” (darkroom)

(d) “Autumn leaves” (Illuminant D65)

(e) “Sea” (Illuminant D65)

(f) “Tulip” (Illuminant D65)

(g) “Autumn leaves” (Illuminant D65 and indirect sunlight)

(h) “Sea” (Illuminant D65 and indirect sunlight)

(i) “Tulip” (Illuminant D65 and indirect sunlight)

(j) Usage guide

Figure 4 Experimental values and Prediction values

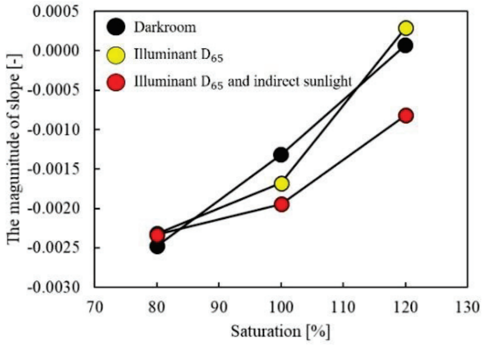
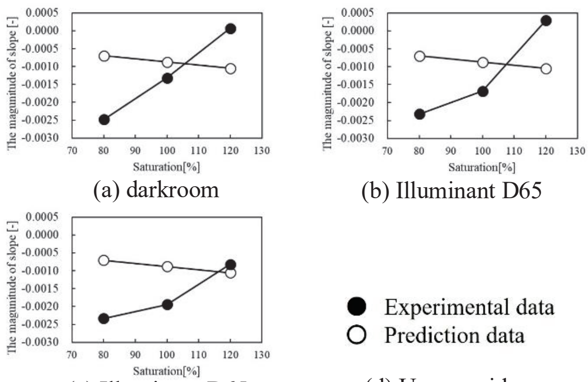


Figure 5 The magunitude of slope of lightness change of each environment



(a) darkroom

(b) Illuminant D65

(c) Illuminant D65 and indirect sunlight

(d) Usage guide

Figure 6 Changes in the slope of lightness changes in each environment

images other than the image being analyzed. For example, when predicting the image of “Autumn leaves,” the correction value was derived from the “Sea” and “Tulip” images.) Because the magnitude of the B/L ratio depends on the image, the scales were matched by normalizing the calculated ratio to the predicted value of the image being corrected. Figure 6 shows the slope of the predicted values at the same saturation before and after the correction, and Tables 2 and 3 show the correlation coefficients between the slopes before and after the correction. The correlation between the slopes of the lightness changes in the experimental and predicted values improved from negative to positive, and the positive correlation was close to 1.0. This correction confirms that the decreasing lightness change with increasing saturation, which is observed experimentally, was reflected in the predicted value.

5 CONCLUSIONS

This study proposed an accurate modeling equation for the data obtained from subjective evaluation experiments under various ambient lighting conditions. We measured the luminance of the adaptive background and substituted the lightness parameter into the model equation. We confirmed that the prediction accurately matched the experimental results. However, when the lightness change was monitored under different saturation conditions, it was found to depend on the saturation level.

Therefore, we multiplied the predicted value by the ratio of

Table. 2 Correlation coefficients before correction

Before correction	Dark room	Illuminant D_{65}	Illuminant D_{65} and indirect sunlight	Average
Autumn leaves	-1.000	-0.982	-0.979	-0.987
Sea	-0.997	-0.986	-0.984	-0.989
Tulip	-0.997	-0.991	-1.000	-0.996
Average	-0.998	-0.986	-0.987	

Table. 3 Correlation coefficients after correction

After correction	Dark room	Illuminant D_{65}	Illuminant D_{65} and indirect sunlight	Average
Autumn leaves	0.995	0.995	0.994	0.995
Sea	0.636	0.703	0.714	0.684
Tulip	0.799	0.659	0.771	0.743
Average	0.810	0.786	0.826	

the experimental and predicted values. At a given saturation level, the correlation coefficient between the slopes of the experimental and predicted lightness improved from negative to positive (close to 1.0).

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