VISION, LIGHT, AND COLOR
–MECHANISM OF SEEING AND TECHNIQUES FOR DISPLAYING–

Hiroyuki Shinoda

Department of Human and Computer Intelligence, College of Information Science and Engineering, Ritsumeikan University, Japan

Corresponding author: Hiroyuki Shinoda, hshinoda@is.ritsumei.ac.jp

Keywords: Lighting, Brightness Perception, Color Management, Elderly Vision, Color-Vision Deficiency

ABSTRACT

Having a good knowledge of physics of light and mechanism of visual perception is necessary, when one controls colors as one likes and creates comfortable and efficient environments. Here several topics are introduced on color perception and its applications, such as perceived brightness and its metric, elderly color vision and a color recovery lighting system, color vision deficiency and a color-barrier-free lighting, and color adaptation and a color management for displays.

INTRODUCTION

No visual experience is possible without light. Light conveys the information of the outside world into our eyes. In particular, color perception reflects spectral properties of lights and objects. Illumination affects our color perception in two ways [1][2]. In one way, the spectral composition of reflected light, the product of the spectral power of a light source and the spectral reflectance of a surface, directly determines color sensation (solid lines in Figure 1). In the other way, the state of the visual system is automatically adjusted by adaptation to illuminant and indirectly affects color perception (a dotted line in Figure 1).

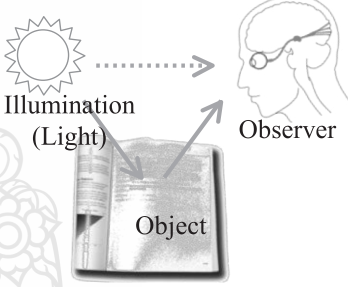

Figure 1. Three elements in color production

In Chapter 2, a new color management [3] is introduced, which achieves constant color appearance on self-luminous displays. Then observer's variability is considered in the following chapters. The concept and the derivation of suitable spectra for color-barrier-free lighting [4] are described in Chapter 3. A lighting system for cataractous elderly [5] is introduced in Chapter 4, which prevents desaturated color appearance. In Chapter 5, a brightness perception for lighting environments is discussed.

COLOR MANAGEMENT SYSTEM

The color management system (CMS) is to ensure color fidelity across different color devices. Since each device has its own color space, the goal of CMS is conversions of color representations from one to others. In many CMSs, the conversion is done through device-independent color spaces such as CIE XYZ or LAB (Figure 2). In other words, CMSs are designed to achieve colorimetrical equality. In metameric color match, however, equal colorimetric values assure equal appearance only to the standard observer but not to individual observers. Another and more serious problem of the CMS is the color adaptation to illuminants. Even though the spectral composition of a display is held constant, the color adaptation to an illuminant changes the appearance. To achieve the equal appearance, appropriate color conversion is necessary (Figure 3).

To solve the problem, we have developed a new CMS based on the color constancy on reflecting surfaces [3]. Color matching with color chips should assure equal appearance on the displays across different illuminants. The objective of the CMS is to derive a conversion matrix from one to another environment through a visual color match of display with the same set of color chips under each illuminant (Figure 4). Then the obtained conversion matrix m_{NA} is applied to (R_N, G_N, B_N) to get (R_A, G_A, B_A) which achieve the same appearance in condition A as in condition N (Eq. 1). Thus another advantage of the CMS is a procedure where no colorimetric measurement is requited.

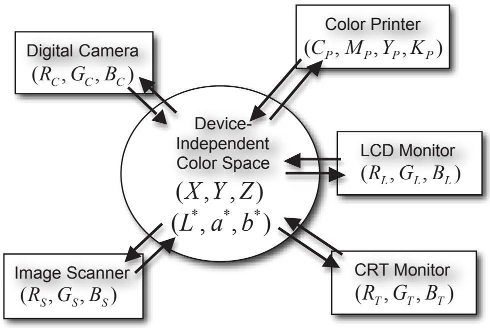

Figure 2. The CMS by way of device-independent color spaces

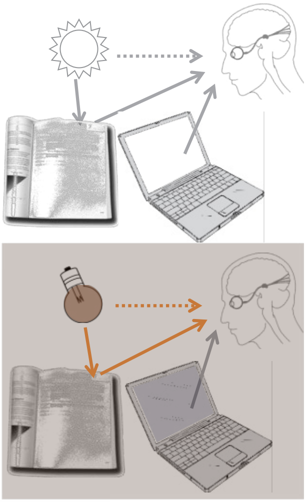

Figure 3. Color constancy on a reflecting surface and color constancy failure on a self-luminous display

$$\begin{pmatrix}R_A\\G_A\\B_A\end{pmatrix}=m_{NA}\begin{pmatrix}R_N\\G_N\\B_N\end{pmatrix}=\begin{pmatrix}a_0&a_1&a_2\\a_3&a_4&a_5\\a_6&a_7&a_8\end{pmatrix}\begin{pmatrix}R_N\\G_N\\B_N\end{pmatrix} \qquad (1)$$

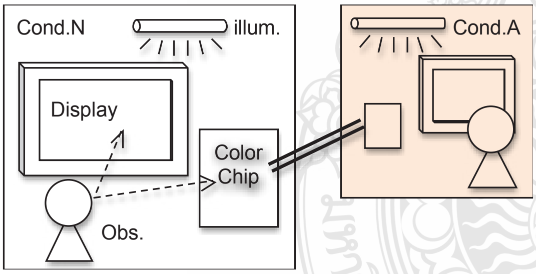

Figure 4. The idea of a new CMS

Here color matchings between mobile phone displays and color chips (5R 6/6, 5Y 6/6, 5G 6/6, 5B 6/6, 5P 6/6, N6) are shown as examples. Two observers carried out subjective matchings under illuminants D65 and A. Results are shown in Figure 5 of the (r, g) chromaticity calculated by Eq. (2). Values of RGB matched by two observers show large individual differences, suggesting the same colorimetric values does not assure the same color appearance. Notice that all the chromaticities shift toward reddish yellow direction when the illuminant changes from D65 to A. This indicates that (R, G, B) must be converted to those of reddish yellow so as to achieve the same extent of color constancy as on reflecting surfaces, Munsell color chips in this situation.

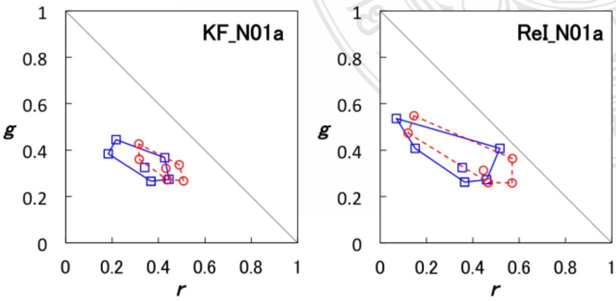

Figure 5. Subjective color matching between a mobile phone display and Munsell color chips.

$$r=\frac{R}{R+G+B},\quad g=\frac{G}{R+G+B} \qquad (2)$$

COLOR-BARRIER-FREE LIGHTING

Color sensation is initiated by the stimulation to the three types of photoreceptors (S, M, L cones). Therefore people with normal color vision are called normal trichromats. Color-vision-deficiency arises from the dysfunction of one of cone types or two. Dichromats are people who have only two types of cone. Anomalous trichromats posses all three types of cone but one of them has somewhat different spectral sensitivity from normal cones. Certain group of colors cannot be discriminated by color deficients. In a color space this set of colors composes a line called color confusion line. A set of the confusion lines for protan (absence of L cone) are drawn in the *xy* chromaticity diagram as an example (Figure 6).

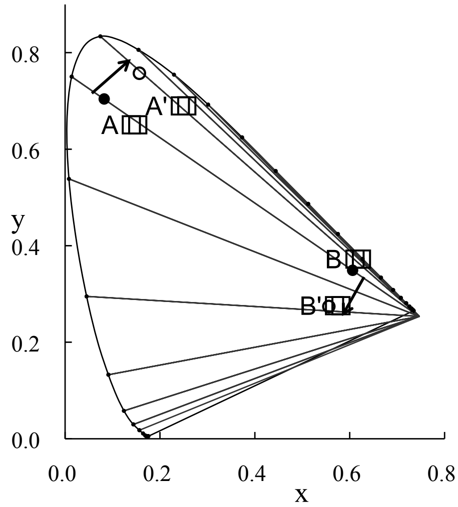

Figure 6. Color confusion lines for protan.

The idea of color-barrier-free lighting is to make confusing colors on objects discriminable to color deficient observers by modifying the spectrum of illuminant. For instance, although colors A (green) and B (red) in Figure 6 look very different to normal trichromats, they lie on the same confusion line and look the same to protan observers. If colors A and B are moved to A' and B' by the change of illuminant's spectrum, then they would be discriminable to protan observers.

To evaluate the performance of color-barrier-free illuminant, a measure, the color discriminability index i_{CD}, has been defined using Ishihara pseudoisochromatic plates. In the typical Ishihara plates two groups of colored dots form a figure, normally letters, and a background. Since the colors of the letter-dots and background-dots lie on a single confusion line, color deficient observers cannot segregate the letters from the background whereas normal trichromats can. The index i_{CD} is defined as the minimum color difference between figure and ground on the Ishihara plate under each illuminant. Color difference is calculated in the normalized LMS cone excitation space with remaining two variables of LMS.

First, the index i_{CD} was calculated for various virtual spectra [4]. The result showed that the spectrum of the largest i_{CD} should be composed of two monochromatic lights at 380nm and 660nm. Then, several psychophysical experiments were conducted with color deficient observers under various illuminants in the wide range of i_{CD}. All the results showed the good correlation between i_{CD} and the discriminability of color deficient observers, suggesting i_{CD} is practically effective as a measure for color-barrier-free lighting.

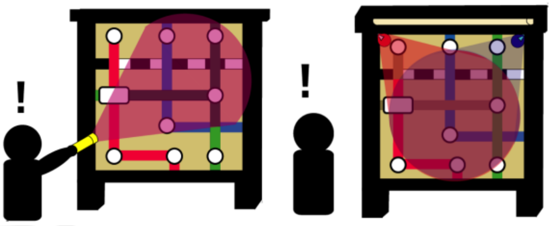

Figure 7. Color-barrier-free lighting

Note that the color-barrier-free lighting can make some confusing color pairs discernible but, at the same time, it may make some other new color pairs indiscernible. Therefore the color-barrier-free lighting should be used as an extra or a supplementary lighting together with the normal white illuminant (Figure 7). The illuminant for color-barrier-free lighting may be a good application target of newly developed types of solid state lighting such as LED and OLED because of the higher flexibility in spectral composition.

LIGHTING FOR CATARACTOUS ELDERLY

Cataract is one of the most typical age-related eye diseases. The hazy crystalline lens scatteres light which overlaps the color images on the retina and causes loss of colorfulness as shown in Figure 8.

In a new lighting system, two sets of illumination for an object and an environment are independently operated. To reduce color desaturation by the scattering light the intensity of the ambient illumination is reduced while that of illumination for an object is increased. The lighting system was implemented to a fitting room as Color-Recovery-System, CRS. The performance of the lighting system was evaluated by colorimetric measurements, psychophysical experiments (categorical and elementary color naming), and a questionnaire by customers [5].

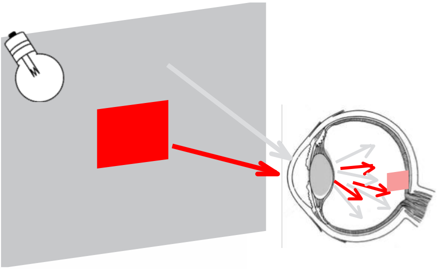

Figure 8. Color desaturation by light scattering from a hazy lens

Figure 9, as an example, shows chromaticities for Munsel color chips, 5R4/12, 5YR7/14, 5Y8/12, 5GY7/10, 2.5G5/10, 5BG6/8, 10B3/10, 2.5P5/10, measured with Minolta CS-100. Chromaticities measured through the goggle (circles) locate inside of those measured without the goggle (diamonds), showing the color desaturation in simulated elderly under the normal lighting. On the other hand, under the color-recovery lighting even through the goggle, chromaticities (triangles) returned toward the original locations (diamonds), showing increases in saturation.

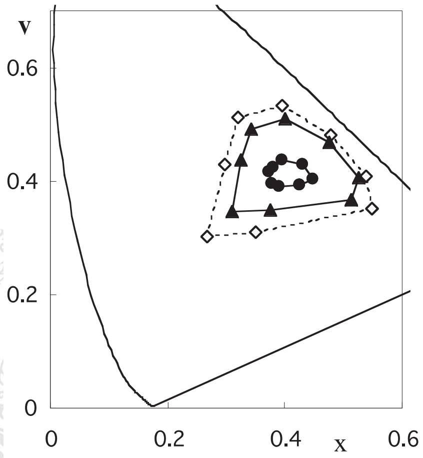

Figure 9. Colorimetric measurements

The color-recovery effect was confirmed by the questionnaire conducted on actual customers too. For instance, to the questions of how the clothes looked in the fitting room with CRS, the positive answer, such as "they looked clearer or more distinct than usual," increased with customer's age.

PERCEIVED BRIGHTNESS FOR LIGHTING ENVISONMENTS

In designing lighting environments, horizontal illuminance is generally used as a measure of brightness for a room. However illuminance and perceived brightness disagree in many circumstances. For evaluation of brightness for space, we have proposed a subjective measurement of a border luminance between object color mode and light-source color mode [6]. Then, as an approximation of the border luminance, a new metric for space brightness has been developed and named "Feu" which stands for "flame" and "fire" in French [7]. Using Eq. (3), Feu is calculated as a geometrical average of the luminance distribution $L(\square,\square)$ over the visual field of 100 deg. wide and 85 deg. tall.

$$Feu = 1.5 \times \left(\sqrt[N]{\square_{\square=-50^\circ}^{35^\circ} \square_{\square=-50^\circ}^{50^\circ} L(\square,\square)} \right)^{0.7} \tag{3}$$

Characterizing or evaluating a lighting environment in perceptual and physical dimensions of light increases the variety in lighting plan (Figure 10). Particularly its potency has been proved in energy-saving lighting using LED characterized by the 2nd quadrant of the diagram [8].

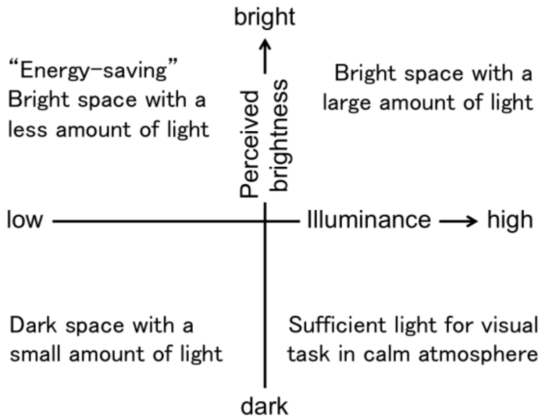

Figure 10. Characterization of environments with physical-perceptual dimensions of light

Thus a metric of perceived brightness has been used in many practical situations and rewarded with good results. However Feu is not perfect or completed yet but rather under development [9]. Insensitivity to color is one of the defects of Feu, which is calculated from luminance distribution. It has been reported that a room furnished with colored objects is perceived brighter than one with achromatic objects [10][11][12].

It has been recognized as another defect that Feu is incapable of assessing the brightness of a room with windows. To investigate the window effect, perceived brightness was evaluated by magnitude estimation on juxtaposed 1/8 scale models shown at the top of Figure 11 [13]. One of them, a reference, was a windowless room with a fixed illuminance, 100 lx in this example. The other was a test room to which an observer was asked to assign integer according to the perceived brightness by comparing with the reference room assigned 100.

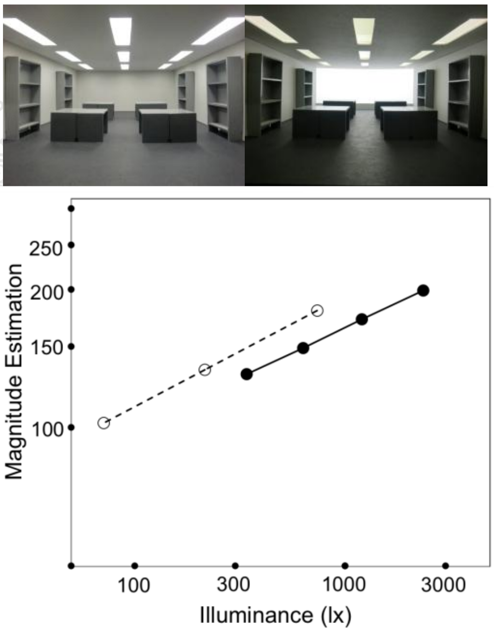

Figure 11. Experiment for window effect

The magnitude of perceived brightness increased with illuminance when the test was a windowless room whose illuminance was modulated by ceiling lamps (dashed lines with open symbols in Figure 11). When the test room had a window of several luminance levels which modulated the room illuminance, the brightness increased with illuminance but significantly below that for a windowless room (solid lines and symbols in Figure 11).

The chart indicates that the room appears darker with a bright window than a windowless room even though it provides an equal illuminance. This brightness reduction by window occurred when the intensity of ceiling lamps was relatively low. On the other hand, the brightness enhancement by window occurred with high intensity of ceiling lamps. Recently the energy-saving lighting is becoming popular where artificial light is reduced by a substitution of daylight. However, the window effects of brightness reduction/enhancement suggest that artificial light should be controlled in terms of perceived brightness not illuminance.

REFERENCES

1. Shinoda, H. and Fujieda, I.: Introduction to Color Science and Engineering, Morikita Pub. Co. Ltd., Tokyo, 2007
2. Shinoda, H.: Three elements for color production (1) –illumination and object–, Journal of the Color Science Association of Japan, 35-2, pp.113-117, 2011
3. Ishibashi, R., Shinoda, H., Yamaguchi, H., and Rattanakasamsuk, K.: Colorimetry-free color management system based on the color constancy, Journal of the Color Science Association of Japan, 33-suppl., pp.38-39, 2009
4. Nagai, T., Shinoda, H., Yamaguchi, H. and Rattanakasamsuk, K.: Estimation and verification of the optimum spectrum for color-barrier-free illumination, Journal of the Color Science Association of Japan, 33-suppl., pp.76-77, 2009
5. Shinoda, H. et al.: Lighting system to prevent color desaturation due to cataract crystalline lens, Technical Report of IEICE, HIP2005-15, pp.13-16, 2005
6. Yamaguchi, H. and Shinoda, H.: Space brightness evaluated using border luminance of color appearance mode, Journal of the Illuminating Engineering Institute of Japan, 91-5, pp.266-271, 2007
7. Iwai, W., and Iguchi, M.: New lighting evaluation techniques for comfortable lighting spaces using sensation-of-room-brightness index Feu, Matsushita Technical Journal, 53-2, pp.64-65, 2008
8. Mori, T., Iwai, W., Shinoda, H., Morimura, K., and Shibaike, M.: Luminous environment evaluation of the task and ambient lighting system using LED's, Proc. of 2005 Annual Conference of the Illuminating Engineering Institute of Japan, p.122, 2005
9. Shinoda, H. et al.: Evaluation of lighting environments with perceived space-brightness (1) –consept and method–, Proc. of 2nd CJK Lighting Symposium, Sapporo, pp.35-38, 2009
10. Ikeda, M., and Kaneko, F.: Effect of initial visual information on the recognized visual space of illumination –the case of lightness and saturation–, Journal of the Illuminating Engineering Institute of Japan, 80-5, pp.319-324, 1996
11. Yamaguchi, H., Tamoi, T., and Shinoda, H.: The effect of interior chromaticness on space brightness evaluated by border luminance of color appearance mode, Proc. of 3rd CJK Lighting Symposium, Seoul, pp.83-86, 2010
12. Takada, H., Yamaguchi, H., and Shinoda, H.: Effect of interior chromaticness of space brightness, i-Perception, 2-4, p.369, 2011
13. Maruyama, T., Yamaguchi, H., and Shinoda, H.: Space brightness evaluation for a daylit room, i-Perception, 2-4, p.371, 2011