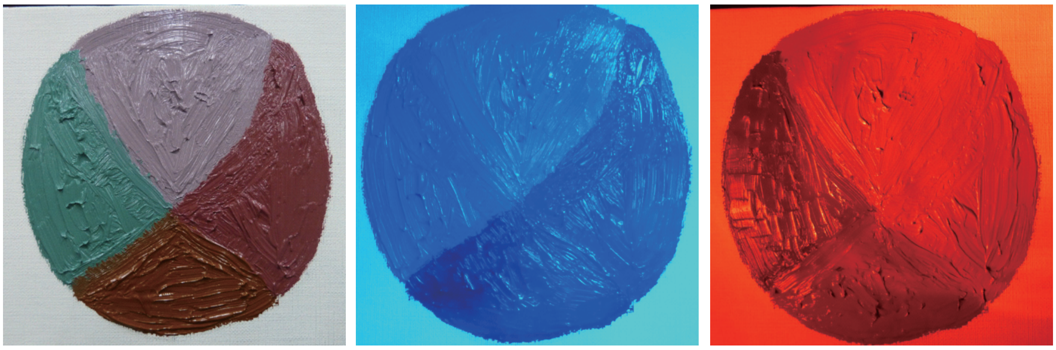
Metamerism-based Shading Illusion

Daisuke Miyazaki, Takafumi Saneshige, Masashi Baba,
Ryo Furukawa, Masahito Aoyama, Shinsaku Hiura
Hiroshima City University
http://www.ime.info.hiroshima-cu.ac.jp/



(a) (b) (c)

Figure 1. (a) Four kinds of mixed paints computed by the proposed method, (b) those illuminated by blue light, (c) those illuminated by red light.

Abstract

Metamerism is a phenomenon where two objects recognized as having different colors under one light are also recognized as having the same color under another light. This research proposes technology for actualizing artistic illusion that exploits metamerism. Specifically, the purpose of the research relates to automatic calculation of blending ratios of oil paints that cause metamerism to occur under specific light sources. It entails metamerism occurring between four types of object colors under two types of light sources. This enables us to create false shading where the observer recognizes the 2D oil painting as if it is a 3D object with plausible shading.

1 Introduction

The phenomenon where two objects recognized as having different colors under one light are also recognized as having the same color under another light is called metamerism. This research proposes technology for actualizing artistic illusion that exploits metamerism. Specifically, the purpose of the research relates to automatic calculation of paint blending ratios that cause metamerism to occur under specific light sources.

Metamerism, in which the colors of clothing and printed materials vary under fluorescent lighting and sunlight, is known as a source of annoyance among designers and photographers, and among those in the apparel, printing, and advertising industries. This paper rebels against such common sense, and fully brings out the value, disregarded in the past, of metamerism. In this paper, we show an artistic illusion, whose mixing ratio of oil paints are computed by our method, with four kinds of mixed paints (Fig. 1 (a)): The oil painting artwork is recognized as a sphere illuminated from upper-left direction under a certain colored light (Fig. 1 (b)), while it is recognized as if it is illuminated from upper-right direction under different colored light (Fig. 1 (c)).

1.1 Related work

Computer-aided art [1, 2, 3, 4, 5] has recently become the subject of research efforts to create new art that the human mind would find difficult to accomplish. Kawai [6] made an embossed plate so that the shading changes, when moving the illumination direction, as if the embossed figure is perceived as a three dimensional object. Amano [7] projected a shading pattern on to a planar paper so that the figure on the paper is perceived as a three dimensional object. The research of this paper considers metameric art like that produced by Valluzzi [8]. In addition, we make a shading illusion like that made by Kawai and Amano. We make 2D oil paintings without microscopic grooves like Kawai's approach, and we do not require a projector as is done in Amano's work.

Research into metamerism has existed for a long time, but little research has exploited metamerism for art. Bala et al. [9] used a CMYK printer to create watermarks using metamerism. They used two types of inks to represent black color: One is K ink and the other is CMY ink. These are observed as the same color under natural light, but as different colors when exposed to LEDs of specific wavelengths. Contrary to the research of Bala et al. [9], our research blended paints that generated the most metamerism, finding the optimum combination of paints from among many more colors.

Drew and Bala [10] took the two types of object colors prepared by Bala et al. [9], photographed them with an ordinary camera, and converted the colors by multiplying a 3×3 matrix for emphasizing metamerism. Finlayson et al. [11, 12] proposed a method for estimating many spectral distributions observed as the same color as given RGB values or XYZ values. Kobayashi et al. [13] detected cultivation colony using two images illuminated by two different LEDs. Nonoyama et al. [14] used a multispectral projector so that the appearance captured by a color camera and the appearance captured by a monochrome camera would be perceived as different forms. Our method is different from these methods since we actually reproduce the real paints using a multispectral database of oil paints, which can be observed by the human eye.

Miyazaki et al. [15] proposed a method for calculating the blending ratios of paint that generate the greatest metamerism in response to light sources designated by the user. They worked on metamerism occurring between three types of object colors under two types of light sources, but our research entails metamerism occurring between four types of object colors under two types of light sources. Moreover, they represented the art where the design of the canvas changes, while we generate illusive art where the false shading is perceived.

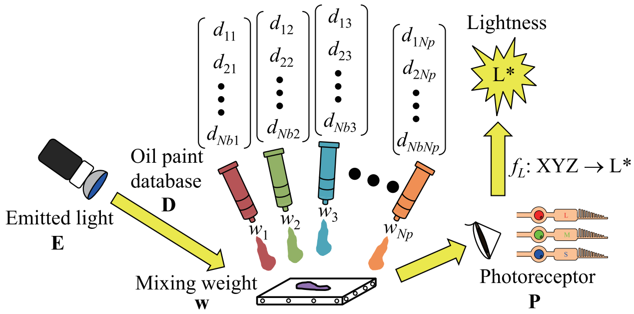


Figure 2. Mixing oil paints.

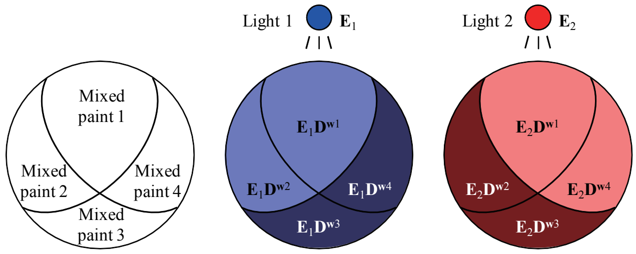


Figure 3. Metamerism of four sets of mixed paint illuminated by two different lights.

2 Shading illusion using oil paints

2.1 Theoretical background

Spectral distribution is represented as a continous function; however, we cannot measure the spectral distribution as a continous function but can measure it as a discretized value. In our research, we suppose that the spectral distribution is represented as N_b number of values, where the wavelength data of visible light from 400 to 800 nm are discretized with equal intervals. A typical method of expressing human perception of color concerns the XYZ color system defined by the International Commission on Illumination (CIE). The observed value $\mathbf{x} = (X, Y, Z)^\top$ of the scene can be represented as follows.

$$\mathbf{x} = \mathbf{PEs}\,. \tag{1}$$

Here, discrete data of the color matching functions are represented by the $3 \times N_b$ matrix $\mathbf{P}$, of which the first to third rows are color matching functions of X, Y, and Z.

$$\mathbf{P} = \begin{pmatrix} \bar{x}_1 & \cdots & \bar{x}_{N_b} \\ \bar{y}_1 & \cdots & \bar{y}_{N_b} \\ \bar{z}_1 & \cdots & \bar{z}_{N_b} \end{pmatrix}. \tag{2}$$

The spectral reflectance of the object surface is represented as the $N_b \times 1$ vector $\mathbf{s}$. $N_b \times N_b$ diagonal matrix $\mathbf{E}$ represents the spectral distributions of light source.

$$\mathbf{E} = \mathrm{diag}\left(E_1, E_2, \cdots, E_{N_b}\right). \tag{3}$$

The database of spectral reflectance for N_p types of paint necessary for mixing the paints is represented as the $N_b \times N_p$ matrix $\mathbf{D}$.

$$\mathbf{D} = \begin{pmatrix} d_{11} & d_{12} & \cdots & d_{1N_p} \\ d_{21} & d_{22} & \cdots & d_{2N_p} \\ \vdots & \vdots & \ddots & \vdots \\ d_{N_b1} & d_{N_b2} & \cdots & d_{N_bN_p} \end{pmatrix}. \tag{4}$$

Mixed paint is prepared by combining the N_p paints with N_p mixing proportions. The mix ratios are represented as the $N_p \times 1$ vector $\mathbf{w}$ (Fig. 2).

According to the exponential color mixing model proposed by Miyazaki et al. [15], the spectral reflectance of mixed paint can be calculated with the following equation.

$$\mathbf{s} = \mathbf{D}^{\mathbf{w}} \equiv \begin{pmatrix} d_{11}^{w_1} \times d_{12}^{w_2} \times \cdots \times d_{1N_p}^{w_{N_p}} \\ d_{21}^{w_1} \times d_{22}^{w_2} \times \cdots \times d_{2N_p}^{w_{N_p}} \\ \vdots \\ d_{N_b1}^{w_1} \times d_{N_b2}^{w_2} \times \cdots \times d_{N_bN_p}^{w_{N_p}} \end{pmatrix}. \tag{5}$$

Eq. (6)–(7) is one certain row extracted from Eq. (5).

$$\begin{aligned} s_i &= \exp\big(w_1 \log d_{i1} + w_2 \log d_{i2} + \\ &\quad w_3 \log d_{i3} + \cdots + w_{N_p} \log d_{iN_p}\big) \quad (6) \\ &= d_{i1}^{w_1} d_{i2}^{w_2} d_{i3}^{w_3} \cdots d_{iN_p}^{w_{N_p}}\,. \quad (7) \end{aligned}$$

Eq. (6) and Eq. (7) are the same; however, we use Eq. (7) in order to avoid calculating $\log 0$. Since $0 \log 0 = 0$ holds, we define $0^0 = 1$ in this model. This model is a linear sum model in logarithmic space as is shown in Eq. (6). This color mixing model calculates only the reflectance without shading. We do not calculate the shading since it is unnecessary for our purpose.

2.2 Cost function

This section describes the method for automatic calculation of oil paint blending ratios that cause metamerism to occur. Two different light sources are labeled as Light Source 1 and Light Source 2. Four different types of paint mixed from multiple oil paints are labeled Mixed Paint 1, Mixed Paint 2, Mixed Paint 3, and Mixed Paint 4. The purpose of this research is to reproduce the following phenomena: Under Light Source 1, Mixed Paint 1 and Mixed Paint 2 have the same brightness, which is brighter than Mixed Paint 3 and Mixed Paint 4, which have the same brightness; under Light Source 2, Mixed Paint 1 and Mixed Paint 4 have the same brightness, which is brighter than Mixed Paint 2 and Mixed Paint 3, which have the same brightness (Fig. 3).

As a result, the cost function $F(\cdot)$ to be minimized in order to fulfil our purpose (Fig. 3) is as follows, which is solved by simulated annealing based on the Nelder-Mead downhill simplex method [16].

$$\{\mathbf{w}_1, \mathbf{w}_2, \mathbf{w}_3, \mathbf{w}_4\} = \operatorname*{argmin}_{\mathbf{w}_1,\mathbf{w}_2,\mathbf{w}_3,\mathbf{w}_4} F(\mathbf{P}, \mathbf{E}_1, \mathbf{E}_2, \mathbf{D}, \mathbf{w}_1, \mathbf{w}_2, \mathbf{w}_3, \mathbf{w}_4)\,, \quad (8)$$

$$F(\mathbf{P}, \mathbf{E}_1, \mathbf{E}_2, \mathbf{D}, \mathbf{w}_1, \mathbf{w}_2, \mathbf{w}_3, \mathbf{w}_4) = C_1 + C_2 + C_3 + C_4 + C_5 + C_6\,, \quad (9)$$

where,

$$C_1 = \begin{cases} {c_1}^4 & ({c_1}^2 > T_1) \\ c_1 & ({c_1}^2 \leq T_1) \end{cases}, \quad C_2 = \begin{cases} {c_2}^4 & ({c_2}^2 > T_1) \\ c_2 & ({c_2}^2 \leq T_1) \end{cases},$$

$$C_3 = \begin{cases} {c_3}^4 & ({c_3}^2 > T_1) \\ c_3 & ({c_3}^2 \leq T_1) \end{cases}, \quad C_4 = \begin{cases} {c_4}^4 & ({c_4}^2 > T_1) \\ c_4 & ({c_4}^2 \leq T_1) \end{cases},$$

$$C_5 = \begin{cases} I_1 & (c_5 \geq 0) \\ I_2 & (T_2 < c_5 < 0) \\ I_3 {c_5}^{-1} & (\text{otherwise}) \end{cases},$$

$$C_6 = \begin{cases} I_1 & (c_6 \geq 0) \\ I_2 & (T_2 < c_6 < 0) \\ I_3 {c_6}^{-1} & (\text{otherwise}) \end{cases},$$

$$T_1 = 100\,, \quad T_2 = -1\,,$$
$$I_1 = 100000\,, \quad I_2 = 1000\,, \quad I_3 = I_2 T_2\,,$$
$$c_1 = (100|f_L(\mathbf{P}\mathbf{E}_1\mathbf{D}^{\mathbf{w}_1}) - f_L(\mathbf{P}\mathbf{E}_1\mathbf{D}^{\mathbf{w}_2})|)\,,$$
$$c_2 = (100|f_L(\mathbf{P}\mathbf{E}_1\mathbf{D}^{\mathbf{w}_3}) - f_L(\mathbf{P}\mathbf{E}_1\mathbf{D}^{\mathbf{w}_4})|)\,,$$
$$c_3 = (100|f_L(\mathbf{P}\mathbf{E}_2\mathbf{D}^{\mathbf{w}_1}) - f_L(\mathbf{P}\mathbf{E}_2\mathbf{D}^{\mathbf{w}_4})|)\,,$$
$$c_4 = (100|f_L(\mathbf{P}\mathbf{E}_2\mathbf{D}^{\mathbf{w}_2}) - f_L(\mathbf{P}\mathbf{E}_2\mathbf{D}^{\mathbf{w}_3})|)\,,$$
$$c_5 = (100 f_L(\mathbf{P}\mathbf{E}_1\mathbf{D}^{\mathbf{w}_3}))^2 + (100 f_L(\mathbf{P}\mathbf{E}_1\mathbf{D}^{\mathbf{w}_4}))^2 - (100 f_L(\mathbf{P}\mathbf{E}_1\mathbf{D}^{\mathbf{w}_1}))^2 - (100 f_L(\mathbf{P}\mathbf{E}_1\mathbf{D}^{\mathbf{w}_2}))^2\,,$$
$$c_6 = (100 f_L(\mathbf{P}\mathbf{E}_2\mathbf{D}^{\mathbf{w}_2}))^2 + (100 f_L(\mathbf{P}\mathbf{E}_2\mathbf{D}^{\mathbf{w}_3}))^2 - (100 f_L(\mathbf{P}\mathbf{E}_2\mathbf{D}^{\mathbf{w}_1}))^2 - (100 f_L(\mathbf{P}\mathbf{E}_2\mathbf{D}^{\mathbf{w}_4}))^2\,.$$

Fig. 4 indicates that C_1 is a monotonically increasing function with discontinuity. Since our method tries to minimize C_1 (Eq. (9)), c_1 is minimized (Fig. 4) as a result. The penalty drastically increases where c_1^2 is larger than the threshold T_1. Fig. 5 indicates that C_5 is a monotonically increasing function with discontinuity. Since our method tries to minimize C_5 (Eq. (9)), c_5 is minimized (Fig. 5) as a result. The penalty is extremely large where c_5 is larger than zero. The function $f_L(X, Y, Z)$ converts the (X, Y, Z) values to the lightness L* of the L*a*b* color space. Although the essence of metamerism is the difference of chromaticity, we evaluate the objective function by the lightness so that the resultant paints form an artistic illusion.

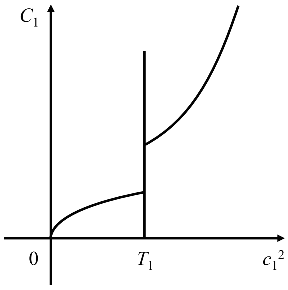


Figure 4. Schematic explanation of C_1.

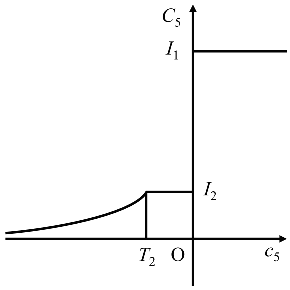


Figure 5. Schematic explanation of C_5.

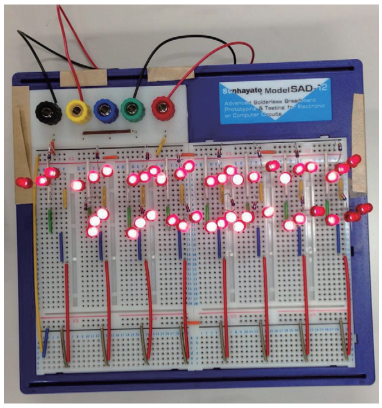


Figure 6. Electronic circuit of LEDs mounted on a solderless breadboard.

3 Experiments

A hyper-spectral camera HSC-1700 was used to photograph the spectral data from 400 nm to 800 nm. Radiance could be analyzed for a total of 81 bands (N_b = 81) from 400 nm to 800 nm in 5 nm intervals. Spectral distributions were analyzed for 20 types (N_p = 20) of different color oil paints, which were exposed to an artificial sunlight.

We use LEDs for illuminants. The multispectral data of LED is measured by the hyper-spectral camera with an ND filter attached. Since each oval LED is dark (*i.e.*, approximately 0.015–30 [cd]), we installed 45 LED lamps on a solderless breadboard (Fig. 6).

Calculations were made for each paint type and not on a pixel-unit basis. In this case, calculations were made for three types of mixed paints. The spectral distributions of the mixed paints 1–4 are shown in Fig. 7. Fig. 8 is the spectra of four mixed paints illuminated by two lights.

Based on the blending ratios determined, actual paints were mixed and visually confirmed to deliver the results envisioned in Fig. 3, and the results are shown in Fig. 1. Moreover, paint was not applied in layers, but after stirring, so that all paint colors were completely mixed and applied in such a way that the canvas was not visible.

4 Conclusion

This research confirmed the occurrence of metamerism between four object colors and two light

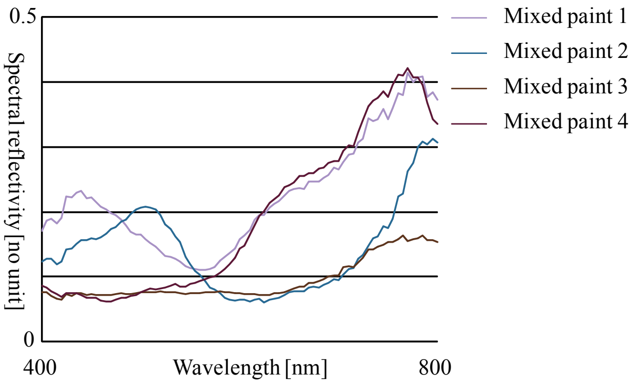


Figure 7. Spectral reflectance of four mixed paints.

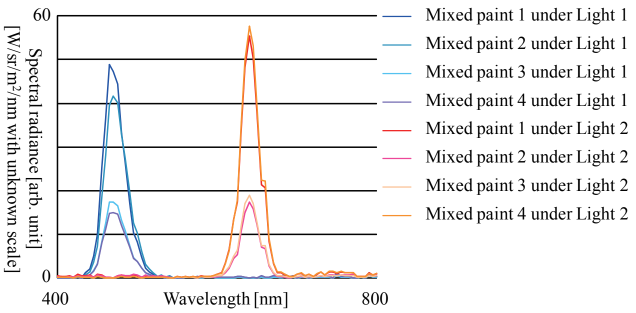


Figure 8. Spectra of four paints under two lights.

sources. The purpose was to generate metamerism under a light source designated by the user.

For the future, the automatic selection of optimum light source combinations is being considered, rather than the blending of paints only, to generate stronger metamerism [15, 10].

Miyazaki et al. [15] used three color paints while we used four color paints which presents a more difficult problem. A narrowband LED successfully produced an artistic illusion by considering the difference of the lightness. However, the produced artistic illusion is slightly insufficient to emphasize as metameric art since the method does not consider the difference of the chromaticity. We will concentrate on using two color paints for our next challenge in order to create a much more spectacular artwork.

Since the variation of LEDs is limited, one choice for the next step is to use interference filters since they can represent any kinds of narrowband filters. Moreover, we are also planning to use a programmable light source, which can represent arbitrary spectrum light.

Morovič et al. [17] argued that printers that use 11 colors of ink are useful for printing spectral distributions of various object colors. Tzeng and Berns [18] also conducted research on printers that use four or six colors of ink. A future task is to join with printer manufacturers to develop printers capable of printing spectral distributions of various object colors.

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