Vol.2016-CG-165 No.13
Vol.2016-DCC-14 No.13
Vol.2016-CVIM-204 No.13
2016/11/9

メタメリズム生起のための光源色・物体色の同時最適化

宮崎 大輔[1,a)]　中根 郁実[†1]　古川 亮[1]　日浦 慎作[1]

概要：メタメリズムとはある光源下では 2 つの物体が異なる色として知覚されるが別の光源下では同じ色として知覚される現象である．本研究では，メタメリズムを利用したトリックアートの作成手法を提案する．複数の塗料を組み合わせることで，目的とするスペクトル反射率に近い塗料を作成することができる．また，複数の光源を組み合わせることで，目的とするスペクトル分布に近い光源を作成することができる．そのため，複数の塗料と複数の光源を組み合わせることで，目的とするアート作品を作成することができる．本論文では，複数の塗料のスペクトル反射率と複数の光源のスペクトル分布のデータベースを用いて最適な組み合わせを求めることでトリックアートを作成した実験結果を示す．

1. Introduction

The phenomenon by which two objects are recognized as having different colors under one light source but as the same color under another light source is called metamerism. Metamerism, which can cause the colors of clothing and printed materials to vary under fluorescent lighting and sunlight, is known as a source of annoyance among designers and photographers, as well as those in the apparel, printing, and advertising industries. This paper rebels against such common sense and fully brings out the value of metamerism, which was disregarded in the past. The proposed method involves a multi-spectrum database of many types of light-emitting diode (LED). Two sets of light source have been designed as mixtures of these LEDs, and in addition, two sets of paints have been designed as mixtures of these oil paints. The proposed method simultaneously estimates both the mixing ratio of LEDs and the mixing ratio of oil paints so that those two paints look identical under one of those two lights but different under the other.

[1] 広島市立大学
Hiroshima City University, Hiroshima 731–3194, Japan
[†1] 現在，富士通ミッションクリティカルシステムズ
Presently with Fujitsu Mission Critical Systems Limited, Kanagawa 221–0013, Japan
[a)] miyazaki@hiroshima-cu.ac.jp

2. Related work

Computer-aided art software has made it possible for users to create artwork that would have been very difficult to create manually [1], [2], [3], [4], [5], [6], [7], [8]. This paper proposes a new computer-aided art system. Our system can be used to create metameric art such as that presented by Valluzzi [9]. Unlike Valluzzi [9], whose purpose was not to express intended figures, the objective of this paper is to design an illumination and a paint that can achieve metamerism so as to represent premeditated shapes.

Bala et al. [10] also made watermarks using metamerism; because CMYK printers can express black-colored prints either with key (K) ink or cyan, magenta, and yellow (CMY) inks, they printed one of their black colors using K ink and another black color using CMY ink. These colors appear the same under natural light but different when illuminated by LEDs of certain wavelengths. They selected an LED with a peak wavelength at which the spectral energies of two inks are sufficiently far apart to be distinguished visually. Drew and Bala [11] improved their method to exaggerate the color difference [10]. Unlike Bala et al. [10], [11], we have designed not only a paint but also an illumination that creates metamerism by combining different types of

LEDs as well as combining different types of paints.

Finlayson et al. [12], [13] proposed a calculation method for a spectral distribution that achieves metamerism; their method produces various sets of spectral distributions that appear to have the same color as a given RGB or XYZ value. Although, in theory, an infinite number of spectral distributions appear to be the same color, Finlayson et al. confined the scope of their paper to those that could be expressed as linear sums of the spectral distributions of the Macbeth (X-rite) color checker. In our paper, we use LED spectral distributions as well as oil paint spectral distributions as our database instead of Macbeth color checker distributions, since we aim to design the illuminants and the paints existingin the real world.

Miyazaki et al. [14], [15], [16] proposed a method for calculating the blending ratios of paint that generate the metamerism in response to light sources suggested by the user. The paints have wide-band spectral distributions, whereas the LEDs have narrow-band spectral distributions, which can better represent custom-built spectral distributions by using different LED combinations. Kobayashi et al. [17] proposed a method for detecting cultivation colonies using images obtained by illuminating the medium with LEDs of different wavelengths. Unlike Miyazaki et al. [14], [15], [16], who used paints for metameric art, Kobayashi [17] and Bala [10] have shown that LEDs are useful for enhancing color differences; their methods use only one LED for illuminating a single scene. Rencently, Miyazaki et al. [18] proposed a method that calculates the LED blending ratios that generate the most metamerism possible given the oil paints used. In this paper, we estimates the belnding ratios of both LEDs and oil paints that generate the most metamerism possible. We then create pieces of artwork that take advantage of the metamerism occurring between the two designed paint colors under the two designed illuminant colors.

3. Perception of reflected light

The XYZ color system [19], [20] is a representative method for expressing human perceptions of colors and was defined by the Commission Internationale de l'Eclairage. It can express the colors perceived by the human brain stimulated by photoreceptor cells. X, Y, and Z correspond to red, green, and blue, respectively. In general, the lower limit wavelength of visible light is approximately 380–420 nm, and the upper limit is approximately 680–800 nm [21], [22], [23], [24]. In this paper, we consider light with wavelengths varying from 380 to 780 nm because our measurement device can only measure spectral distributions within this range. Expressing the color-matching functions of X, Y, and Z for a wavelength λ as $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$, respectively, the observed X, Y, and Z values are expressed as follows (Fig. 1):

$$X = \int_{380}^{780} L(\lambda)B(\lambda)\bar{x}(\lambda)d\lambda\,, \tag{1}$$

$$Y = \int_{380}^{780} L(\lambda)B(\lambda)\bar{y}(\lambda)d\lambda\,, \tag{2}$$

$$Z = \int_{380}^{780} L(\lambda)B(\lambda)\bar{z}(\lambda)d\lambda\,. \tag{3}$$

Here, $L(\lambda)$ is the spectral distribution of the light source and $B(\lambda)$ is the spectral reflectance of the object surface. The above equations express the spectral distributions as continuous functions, but the observed spectral distributions are discrete. In this paper, wavelengths ranging from 380 to 780 nm are discretized with constant intervals of $(780-380)/N_b$, where N_b is the number of the bands used to discretize the spectral range. Expressing the observed values as $\mathbf{x} = (X, Y, Z)^\top$, Eqs. (1)–(3) can be expressed as follows:

$$\mathbf{x} = \mathbf{PLb}\,. \tag{4}$$

We express the discretized data of the color-matching functions as the $3 \times N_b$ matrix $\mathbf{P}$, and place the X, Y, and Z color-matching functions in each row:

$$\mathbf{P} = \begin{pmatrix} \bar{x}_1 & \bar{x}_2 & \cdots & \bar{x}_{N_b} \\ \bar{y}_1 & \bar{y}_2 & \cdots & \bar{y}_{N_b} \\ \bar{z}_1 & \bar{z}_2 & \cdots & \bar{z}_{N_b} \end{pmatrix}. \tag{5}$$

We express the observed spectral distribution as $N_b \times 1$ vector $\mathbf{b}$. The spectrum of the illumination source $\mathbf{l} = (l_1, l_2, \cdots, l_{N_b})^\top$ is expressed by an $N_b \times N_b$ diagonal matrix, $\mathbf{L}$:

$$\begin{aligned} \mathbf{L} &= \mathrm{diag}\,(\mathbf{l}) \\ &= \begin{pmatrix} l_1 & 0 & \dots & 0 \\ 0 & l_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & l_{N_b} \end{pmatrix}. \end{aligned} \tag{6}$$

In this paper, "diag" represents a function that aligns each element of the vector onto the diagonal elements of a matrix to form a diagonal matrix.

4. Light-Mixing Model

Our purpose is to create artwork by mixing LEDs. In this section, we explain the mathematical model used to calculate the mixed illumination.

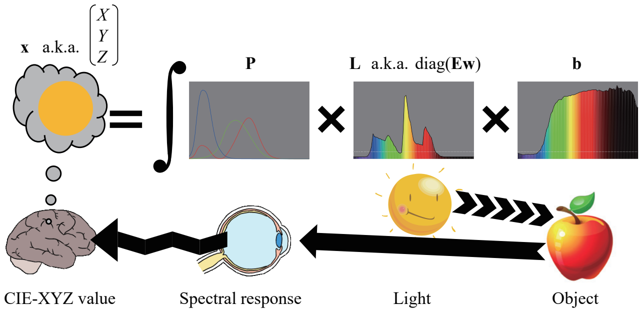

図 1 Mechanism of perception of visible light

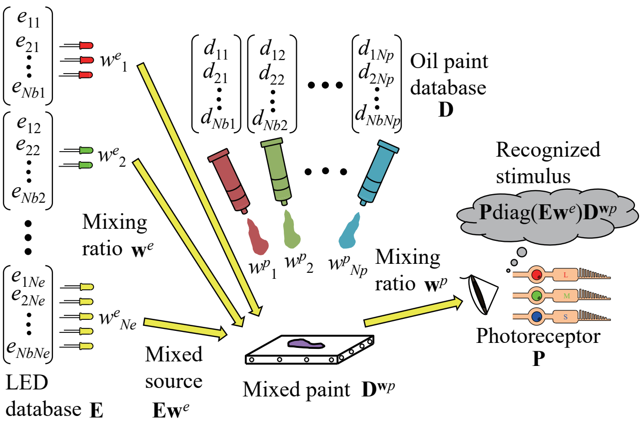

図 2 Perception of mixed paint illuminated by mixed source

We express the spectral reflectance of N_e types of LEDs as an $N_b \times N_e$ matrix, $\mathbf{E}$:

$$\mathbf{E} = \begin{pmatrix} e_{11} & e_{12} & \cdots & e_{1N_e} \\ e_{21} & e_{22} & \cdots & e_{2N_e} \\ \vdots & \vdots & \ddots & \vdots \\ e_{N_b1} & e_{N_b2} & \cdots & e_{N_bN_e} \end{pmatrix}. \tag{7}$$

We make mixed-light illumination by combining N_e LEDs with N_e mixing ratios. We express the mixing ratios using an $N_e \times 1$ vector $\mathbf{w}^e$ (Fig. 2).

The mixed light can be calculated by a linear summation model [12], [13], [25]:

$$\mathbf{L} = \mathrm{diag}(\mathbf{E}\mathbf{w}^e). \tag{8}$$

Each element of the vector $\mathbf{l} = \mathbf{E}\mathbf{w}^e$ is described as follows.

$$\begin{aligned} l_1 &= w_1^e e_{11} + w_2^e e_{12} + \cdots + w_{N_e}^e e_{1N_e}, \\ l_2 &= w_1^e e_{21} + w_2^e e_{22} + \cdots + w_{N_e}^e e_{2N_e}, \\ &\vdots \\ l_{N_b} &= w_1^e e_{N_b1} + w_2^e e_{N_b2} + \cdots + w_{N_e}^e e_{N_bN_e}. \end{aligned}$$

This model is well known as an additive color mixture model [25].

5. Paint-Mixing Model

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 $\mathbf{D}$.

$$\mathbf{D} = \begin{pmatrix} d_{11} & d_{12} & \cdots & d_{1N_p} \\ d_{21} & d_{22} & \cdots & d_{2N_p} \\ \vdots & \vdots & \ddots & \vdots \\ d_{N_b1} & d_{N_b2} & \cdots & d_{N_bN_p} \end{pmatrix}. \tag{9}$$

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 $\mathbf{w}^p$ (Fig. 2).

$$\mathbf{w}^p = \begin{pmatrix} w_1^p \\ w_2^p \\ \vdots \\ w_{N_p}^p \end{pmatrix} \tag{10}$$

In the field of optics, the subtractive color mixture model [25] shown below is used to calculate the spectral reflectance of mixed paint.

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

The effectiveness of this model to oil paints is empirically proved also by Miyazaki et al. [15].

One of the row of Eq. (11) is shown in Eq. (12)–(13).

$$\begin{aligned} s_i &= \exp\bigl(w_1^p \log d_{i1} + w_2^p \log d_{i2} + \\ &\quad w_3^p \log d_{i3} + \cdots + w_{N_p}^p \log d_{iN_p}\bigr) \qquad (12) \\ &= d_{i1}^{w_1^p} d_{i2}^{w_2^p} d_{i3}^{w_3^p} \cdots d_{iN_p}^{w_{N_p}^p}. \qquad (13) \end{aligned}$$

Eq. (12) and Eq. (13) are same, however, we use Eq. (13) in order to avoid calculating $\log 0$. As is shown in Eq. (12), this model is a linear system in logarithmic space. Since $0 \log 0 = 0$ holds, we define $0^0 = 1$ in this model.

6. Proposed method

In this section, we explain the proposed method for automatically calculating the mixing ratios for LEDs and paints to generate metamerism. Two paints are referred to as mixed paint 1 and mixed paint 2. We also represent two types of mixed illumination as mixed source 1 and mixed source 2. We calculate the mixing ratios such that mixed paints 1 and 2 have the same color and brightness

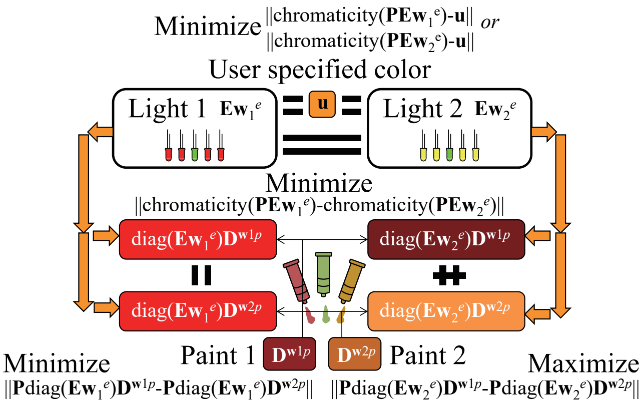

図 3 Metamerism generated when two paints are illuminated by two different lights

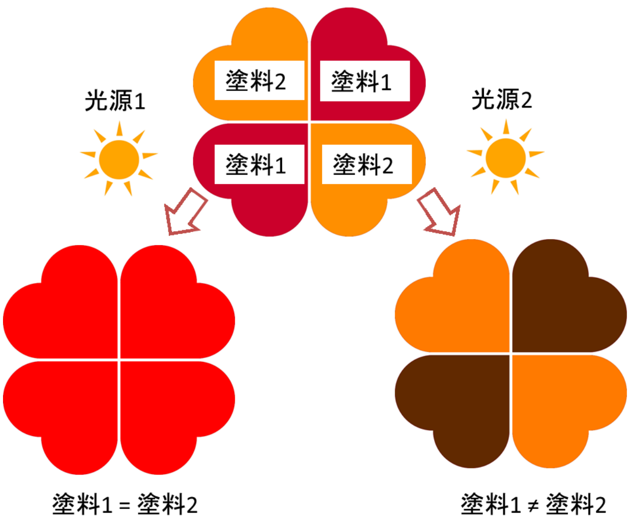

図 4 Purpose of our experiment

under mixed source 1, but appear to have different colors or brightnesses under mixed source 2. Our algorithms constrain both the color of mixed source 1 and the color of mixed source 2 to be the same. This is because we want the two illuminants to be perceived as having the same color by human eyes but to be different in the spectral domain. Our aim is to create a trick artwork whereby two paints look different under a certain colored light but the same under another kind of same colored light. If the users decide to illuminate their artwork using an illuminant of a specific color, our algorithm can constrain the illuminant color to be as similar as possible to the user-specified color. A flowchart of our method is shown in Fig. ??. We first measure the spectral distributions of the paints and the LEDs (Section 7.1). Next, we calculate the mixing ratios for the paints and the LEDs (Section 6). Finally, we illuminate the designed paints using the designed source (Section 7.2).

The chromaticity of mixed source 1 is represented as $(x_1, y_1)^\top = f(\mathbf{PEw}_1)$ and the chromaticity of mixed source 2 is represented as $(x_2, y_2)^\top = f(\mathbf{PEw}_2)$. Function $f : (X, Y, Z) \to (x, y)$ converts XYZ to xy chromaticity [19], [20]:

$$f\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \dfrac{X}{X+Y+Z} \\ \dfrac{Y}{X+Y+Z} \end{pmatrix} . \tag{14}$$

We use xy-chromaticity in this article, and we do not use the a*b* chromaticity of L*a*b* color space due to the reason explained by Miyazaki et al.[18].

Specifying the colors of illuminants is convenient for artists who wish to design their own metameric artwork. Suppose that the user has specified a certain chromaticity $\mathbf{u} = (x_u, y_u)^\top$. If we minimize the difference between the chromaticity of the user-specified value and the mixed sources ($(x_1, y_1)^\top$ and $(x_2, y_2)^\top$), the user can obtain mixed sources with the user-specified color.

The cost function $F(\cdot)$ that must be minimized to realize the intended appearance is as follows:

$$\{\mathbf{w}_1^e, \mathbf{w}_2^e, \mathbf{w}_1^p, \mathbf{w}_2^p\} = \mathop{\mathrm{argmin}}_{\mathbf{w}_1^e, \mathbf{w}_2^e, \mathbf{w}_1^p, \mathbf{w}_2^p} F(\mathbf{w}_1^e, \mathbf{w}_2^e, \mathbf{w}_1^p, \mathbf{w}_2^p; \mathbf{P}, \mathbf{E}, \mathbf{D}, \mathbf{u}) , \tag{15}$$

$$\begin{aligned} &F(\mathbf{w}_1^e, \mathbf{w}_2^e, \mathbf{w}_1^p, \mathbf{w}_2^p; \mathbf{P}, \mathbf{E}, \mathbf{D}, \mathbf{u}) = \\ &a_1 \|\mathbf{P}\mathrm{diag}(\mathbf{Ew}_1^e)\mathbf{D}^{\mathbf{w}_1^p} - \mathbf{P}\mathrm{diag}(\mathbf{Ew}_1^e)\mathbf{D}^{\mathbf{w}_2^p}\|^2 \\ &-a_2 \|\mathbf{P}\mathrm{diag}(\mathbf{Ew}_2^e)\mathbf{D}^{\mathbf{w}_1^p} - \mathbf{P}\mathrm{diag}(\mathbf{Ew}_2^e)\mathbf{D}^{\mathbf{w}_2^p}\|^{0.5} \\ &+a_3 \|f(\mathbf{PEw}_1^e) - f(\mathbf{PEw}_2^e)\|^2 \\ &+a_4 \max\{\|f(\mathbf{PEw}_1^e) - \mathbf{u}\|^2, \|f(\mathbf{PEw}_2^e) - \mathbf{u}\|^2\} \end{aligned} \tag{16}$$

where

$$\sum_{n=1}^{N_e} w_{1,n}^e = 1, \sum_{n=1}^{N_e} w_{2,n}^e = 1,$$
$$\sum_{n=1}^{N_p} w_{1,n}^p = 1, \sum_{n=1}^{N_p} w_{2,n}^p = 1, \tag{17}$$

$$\sum_{n=1}^{N_e} w_{1,n}^e N_l = N_l, \sum_{n=1}^{N_e} w_{2,n}^e N_l = N_l . \tag{18}$$

Also, for $n = 1, \ldots, N_e$,

$$w_{1,n}^e \geq 0, w_{2,n}^e \geq 0 \tag{19}$$

$$w_{1,n}^e N_l = \lfloor w_{1,n}^e N_l \rfloor, w_{2,n}^e N_l = \lfloor w_{2,n}^e N_l \rfloor \tag{20}$$

And, for $n = 1, \ldots, N_p$,

$$w_{1,n}^p \geq 0, w_{2,n}^p \geq 0 \tag{21}$$

図 5　Spectrometer

図 6　29 types of oil paints

図 7　Artificial sunlight

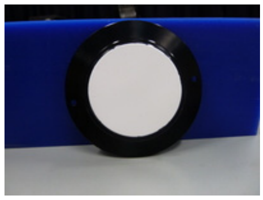

図 8　Diffuse white reflectance standard

a_1, a_2, a_3, and a_4 in Eq. (16) are non-negative constants.

Because Eq. (15) is a complicated function with multiple constraints, we employ a simulated annealing method [26] based on the Nelder–Mead downhill simplex method [26] to solve it stably.

Here, we explain Eqs. (18) and (20). Mixed-light sources are created by placing certain LED bulbs on a solderless breadboard, with the bulbs being selected based on the mixing ratios calculated in the preceding sections. We represent the number of LED bulbs stuck on a solderless breadboard as N_l. Since the sum of the mixing ratio is 1, we constrain the mixing ratio w_n to be an integer multiple of $1/N_l$. The details of this procedure are given in Miyazaki et al. [18].

7. Experiment

7.1 Experimental setup

Using a spectrometer CS-2000 (Fig. 5), we recorded the optical spectrum data of wavelengths in the range 380-780 nm. This spectrometer can measure the brightness of a total of 81 bands ($N_b = 81$) between 380 nm and 780nm at intervals of 5nm. We then measured the spectral distributions of 29 types of oil paints ($N_p = 29$) (Fig. 6) illuminated by artificial sunlight. The artificial sunlight used was Probright V (Fig. 7), which has a color temperature of 6500 K and Ra98 color-rendering characteristics. After obtaining the spectral distributions of the 29 oil paints, we divided them by the spectral distribution of a diffuse white reflectance standard (Fig. 8) illuminated by artificial sunlight.

We measured 53 types ($N_e = 53$) of LED bulbs. Spectrometer can measure the correct radiant energy. We used such spectral distributions to form the database $\mathbf{E}$.

Fig. 9 shows a picture of LEDs implemented on a solderless breadboard. We implemented 45 LED bulbs ($N_l = 45$) on a solderless breadboard.

7.2 Experimental results

We conducted experiments to achieve metamerism using 53 LED colors and 29 oil paints. Table 1 and Table 2 show the mixing ratios calculated using the proposed method. In this experiment, we set the coefficients in Eq. (16) to $\mathbf{u} = (0.5, 0.5)$, $a_1 = 5000$, $a_2 = 1$, $a_3 = 0.5$, $a_4 = 3$. Mixed sources 1 and 2 are perceived to be of the same color by the human eye. Figure 13 shows the spectral reflectance of mixed paint 1 and mixed paint 2. Figure 15 shows the spectral distributions of mixed paint 1 and mixed paint 2 when illuminated by mixed source 1. Figure 17 shows the spectral distributions of mixed paint 1 and mixed paint 2 when illuminated by mixed source 2. The two oil paints (Fig. 12) appear the same (Fig. 14) under the illumination in Fig. 10 (left), but they appear differently (Fig. 16) under the illumination in Fig. 10 (right), which is the intended result.

Actually mixed sources are shown in Fig. 19 and Fig. 20.

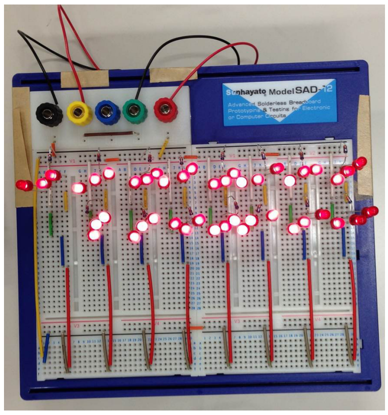

図 9　LEDs stuck on a solderless breadboard

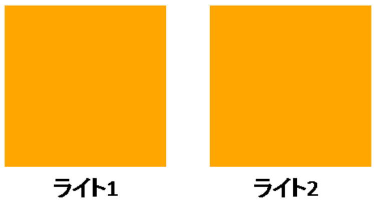

図 10　Mixed source 1 and mixed source 2

Vol.2016-CG-165 No.13
Vol.2016-DCC-14 No.13
Vol.2016-CVIM-204 No.13
2016/11/9

表 1　Number of LED bulbs for mixed source 1 and mixed source 2

NO.	LED	Mixed source 1	Mixed source 2
3	GL3HD402E0S	0	1
7	GL5PR8	11	0
8	GL5UR2K1	27	0
15	L-513ET	1	0
16	L-513GT	1	0
22	NSPG500S	1	0
35	OSG5DA5111A	1	2
36	OSG5DADSA4D	0	2
37	OSG58DA131U	2	1
52	TLYH20TP	1	39

表 2　Mixing ratios of mixed paint 1 and mixed paint 2

NO.	Oil paint	Mixed paint 1	Mixed paint 2
5	Transparent red	0.95	0.00
8	Light magenta	0.00	0.02
10	Cadmium yellow	0.00	0.97
16	Cobalt green	0.04	0.00

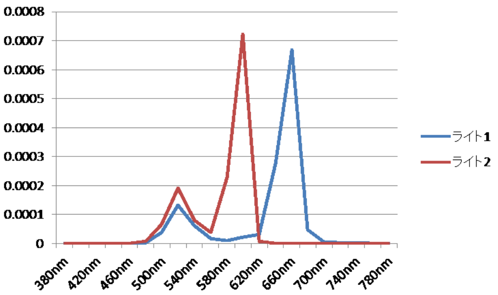

図 11　Spectral distribution of mixed source 1 and mixed source 2

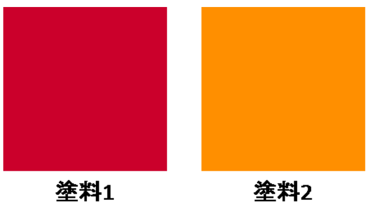

図 12　Mixed paint 1 and mixed paint 2

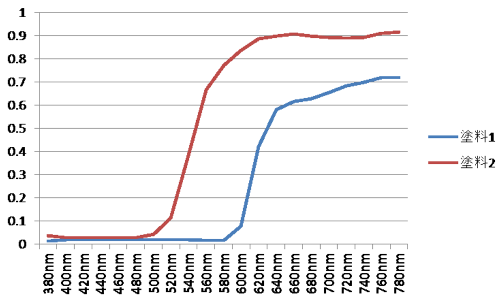

図 13　Spectral reflectance of mixed paint 1 and mixed paint 2

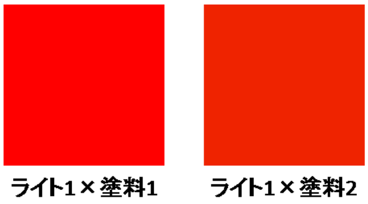

図 14　Appearance under mixed source 1

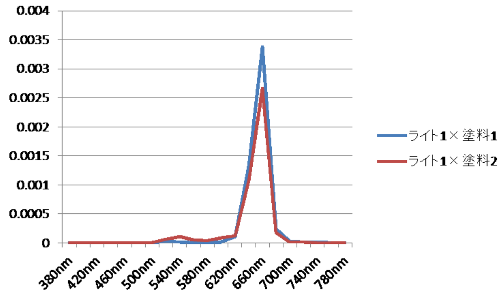

図 15　Spectral distribution of Fig. 14

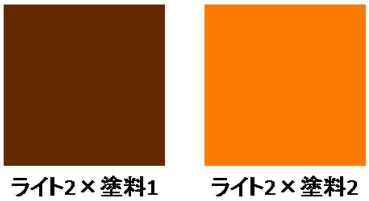

図 16　Appearance under mixed source 2

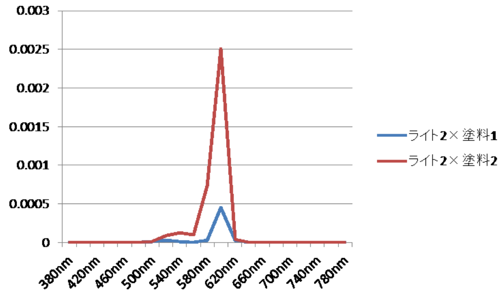

図 17　Spectral distribution of Fig. 16

図 18　User-specified color

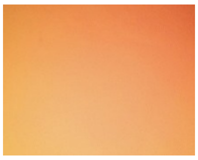

図 19　Actual mixed source 1

図 20　Actual mixed source 2

図 21　Actually painted artwork

図 22　Fig. 21 illuminated by mixed source 1

Actually painted artwork is shown in Fig. 21, and the resultant appearances are shown in Fig. 22 and Fig. 23.

8. Conclusion

We have actualized metamerism with two light sources and two object colors. Our method designs illumination and paints that will actualize metamerism. We have developed a method to estimate the number of LED bulbs and the number of oil paints under the given database of spectral distributions. We have performed some experiments and confirmed the efficacy of our method.

Miyazaki et al.[14], [15], [16] previously enhanced metamerism by combining paints. On the other hand, Miyazaki et al.[18] describes the enhancement of metamerism by combining LED light sources. By mixing not only the light sources but also the paints, the proposed method can improve the metamerism art compared with existing methods [14], [15], [16], [18].

図 23　Fig. 21 illuminated by mixed source 2

We are planning to provide the database of LED spectral distribtions and oil paints spectral reflectances obtained in this article online at `http://www.cg.info.hiroshima-cu.ac.jp/~miyazaki/`, so that those who may not have measurement devices for spectral distributions can make metameric artwork using generic LEDs and generic oil paints.

謝辞　This research was supported in part by MEXT KAKENHI Grant Number 15H05925, and in part by JSPS KAKENHI Grant Number 24700176.

参考文献

[1] J. Mitani, "A design method for 3D origami based on rotational sweep," *Computer-Aided Design and Applications*, vol. 6, no. 1, pp. 69–79, 2009.

[2] R. D. Hersch and S. Chosson, "Band moiré images," *SIGGRAPH 2004 Papers*, pp. 239–247, 2004.

[3] N. J. Mitra and M. Pauly, "Shadow art," *ACM Trans. Graph.*, vol. 28, no. 5, article 156, 7 pages, 2009.

[4] Y. Yue, K. Iwasaki, B. Chen, Y. Dobashi, and T. Nishita, "Pixel art with refracted light by rearrangeable sticks," *Computer Graphics Forum*, vol. 31, no. 2, pp. 575–582, 2012.

[5] M. Papas, T. Houit, D. Nowrouzezahrai, M. Gross, and W. Jarosz, "The magic lens: refractive steganography," *ACM Trans. Graph.*, vol. 31, no. 6, article 186, 10 pages, 2012.

[6] M. Nonoyama, F. Sakaue, and J. Sato, "Multiplex image projection using multi-band projectors," in *Proceddings of the IEEE International Conference on Computer Vision (ICCV) Workshops*, 2013.

[7] N. Kawai, "Bump mapping onto real objects," *ACM SIGGRAPH 2005 Sketches*, article no. 12, 2005.

[8] T. Amano, "Shading illusion: A novel way for 3-D representation on the paper media," in *Proceedings of Procams 2012 Workshop on CVPR2012*, W11_01, pp. 1–6, 2012.

[9] R. Valluzzi, "LEDs illuminat metamerism in abstract

Vol.2016-CG-165 No.13
Vol.2016-DCC-14 No.13
Vol.2016-CVIM-204 No.13
2016/11/9

art - no 2,"
http://www.youtube.com/watch?v=fyJHlinM730, 2012.

[10] R. Bala, K. M. Braun, and R. P. Loce, "Watermark encoding and detection using narrowband illumination," in *Proceedings of Seventeenth Color Imaging Conference*, pp. 139–142, 2009.

[11] M. S. Drew and R. Bala, "Sensor transforms to improve metamerism-based watermarking," in *Proceedings of 18th Color Imaging Conference*, pp. 22–26, 2010.

[12] A. Alsam and G. Finlayson, "Metamer sets without spectral calibration," *J. Opt. Soc. Am. A*, vol. 24, no. 9, pp. 2505–2512, 2007.

[13] G. D. Finlayson and P. Morovic, "Metamer sets," *J. Opt. Soc. Am. A*, vol. 22, no. 5, pp. 810–189, 2005.

[14] D. Miyazaki, K. Nakamura, M. Baba, R. Furukawa, M. Aoyama, S. Hiura, and N. Asada, "A first introduction to metamerism art," *SIGGRAPH ASIA Posters*, 2012.

[15] D. Miyazaki, K. Takahashi, M. Baba, H. Aoki, R. Furukawa, M. Aoyama, and S. Hiura, "Mixing paints for generating metamerism art under 2 lights and 3 object colors," in *IEEE International Conference on Computer Vision Workshops*, pp. 874–882, 2013.

[16] D. Miyazaki, T. Saneshige, M. Baba, R. Furukawa, M. Aoyama, and S. Hiura, "Metamerism-based shading illusion," in *The 14th IAPR Conference on Machine Vision Applications*, pp. 255–258, 2015.

[17] K. Kobayashi, T. Yamada, A. Hiraishi, S. Nakauchi, "Real-time optical monitoring of microbial growth using optimal combination of light-emitting diodes," *Optical Engineering*, vol. 51, no. 12, pp. 123201-1–123201-8, 2012.

[18] D. Miyazaki, M. Nakamura, M. Baba, R. Furukawa, and S. Hiura, "Optimization of LED illumination for generating metamerism," *Journal of Imaging Science and Technology*, 2016.

[19] CIE, *Commission internationale de l'Eclairage proceedings, 1931*, Cambridge: Cambridge University Press, 1932.

[20] T. Smith and J. Guild, "The C.I.E. colorimetric standards and their use," *Transactions of the Optical Society*, vol. 33, no. 3, pp. 73–134, 1931–32.

[21] G. Laufer, *Introduction to Optics and Lasers in Engineering*, Cambridge University Press, p. 11, 1996.

[22] H. Bradt, *Astronomy Methods: A Physical Approach to Astronomical Observations*, Cambridge University Press, p. 26, 2004.

[23] L. Ohannesian and A. Streeter, *Handbook of Pharmaceutical Analysis*, CRC Press, p. 187, 2001.

[24] V. K. Ahluwalia and M. Goyal, *A Textbook of Organic Chemistry*, Narosa, p. 110, 2000.

[25] L. Simonot and M. Hébert, "Between additive and subtractive color mixings: intermediate mixing models," *J. Opt. Soc. Am. A*, vol. 31, no. 1, pp. 58–66, 2014.

[26] W. H. Press et al., "Numerical recipes in C: the art of scientific computing," *Cambridge: Cambride University Press*, 994 p., 1997.