# An Efficient Designing Method of Spectral Distribution of Illuminant for the Enhancement of Color Discrimination

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## Abstract

*In this study, we propose a method for designing an illuminant for supporting color discrimination with maintaining the arbitrary illuminant color. It was applied to the problem of foreign substances detection in blueberry jam because it is especially difficult and essential for quality assurance. To obtain the optimal illuminant, a spectral dataset of metameric illuminants was constructed and a combination of the metameric illuminants with a given chromaticity was derived to maximize the color differences between the jam and foreign substances (leaf, branch, and stone). A color appearance model (CIECAM02) was used to evaluate difficulty of the substance discrimination. The designed illuminant was implemented using a synthesized spectral light source, which clearly showed that the color discrimination of jam and foreign substances was enhanced. The application field for this technique is not limited to foreign substance detection in blueberry jam because it could also be applied to quality control processes of other industrial products, medical imaging, and so on.*

## Introduction

Light reflected from an object's surface can reveal a variety of information about the object's physical and chemical properties. However, humans cannot discriminate characteristic variations in reflectance when spectra are transformed into tristimulus signals that are perceived as the same colors by human perception (metamerism). Metameric problems occur with a specific combination of observation targets and illumination, which suggests that specialized illumination to remove metamerism can also be designed. Several studies have investigated changes in perceived color with different light illumination sources [1][2]. Such unforeseen color changes are unacceptable from the perspective of color rendering. Ohta et al. described a method for designing an illuminant that renders objects in prescribed colors[3]. This indicates that a functional illuminant can also be designed to suit a specific purpose, such as color discrimination of a metameric color set. Most of the information in the spectral domain is lost, but colors contain diverse information. In many cases, humans subconsciously rely on color cue. In particular, examiners detect defective products based on indistinguishable color changes during visual inspection quality control. The development of specific illuminants to assist color discrimination will improve the accuracy of quality control.

In this study, we present a method for designing a spectral illuminant distribution for the enhancement of color discrimination to allow the discrimination of two colors from a predefined spectral color dataset with greater accuracy and ease. In our previous studies, a similar technique for designing a spectral transmittance function for the enhancement of CIEDE2000 color differences have been proposed[4] and have been applied to enhance the discrimination of made-up skin and skin above veins [5][6]. We improved this method by including the effects of the surrounding environment and adaptation using a color difference formula based on a color appearance model CIECAM02[7]. Furthermore, the optimization process was modified to obtain an optimal spectral distribution with arbitrary chromaticity coordinates. The proposed method was applied to the design of an illuminant to support the detection of foreign substances in blueberry jam. The illuminant was specialized for supporting foreign substance detection, allowing visual inspections to be performed with greater ease and accuracy. The second section describes the general context of this study, our proposed method for designing the spectral distribution, and the materials required for our experiment. The third section contains the computational results, a demonstration of a programmable illumination system, and the evaluation results of our psychophysical experiment. Finally, the conclusions of this study are presented in the fourth section.

## Materials and Methods

### Problem Setting

The problem addressed in this study deals with the design of a spectral distribution of an illuminant $I(\lambda)$ to enhance the color discrimination of two predefined targets. Thus, the target function of this problem is as follows:

$$maximize\ \overline{\Delta E} = \frac{1}{N}\sum_{i=1}^{N} f_{dE}(R_{1i}(\lambda), R_{2i}(\lambda), I(\lambda)) \tag{1}$$

where $\overline{\Delta E}$ is the average color difference of the predefined targets, $N$ is the sample number, $R_{1i}(\lambda)$ and $R_{2i}(\lambda)$ are the reflectance spectra of the two targets, and the function $f_{dE}$ gives the color difference between two input reflectance spectra under the illuminant $I(\lambda)$. The objective of this formula is to determine an optimal spectral distribution $I(\lambda)$ for maximizing the color differences of spectral datasets $R_{1i}(\lambda)$, $R_{2i}(\lambda)$ $(i = 1, 2, ..., N)$. A limitation for the optimization of $I(\lambda)$ is that the designed illuminant must be of an arbitrary color. A method for designing spectral distribution under this limitation is described in the following sections.

## Process for Designing the Spectral Distribution

### Color Difference Computation

A similar objective function was defined in an earlier study, where the CIEDE2000 color-difference formula was used for solving the problem described in Eq.1. However, this method was not developed with consideration for the effects of the surrounding environment and adaptation. In this study, CIECAM02-based color difference $\Delta E'$ proposed by Luo *et al.* [8] was used to obtain color differences that consider these effects. The color difference computation $f_{dE}$ used in Eq.1 is performed as described in the following paragraphs.

First, all reflectance spectra are transformed into $XYZ$ color signals. Here, a color computation function $f_{XYZ}$ is defined as Eq.2. $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ represent the $XYZ$ color matching functions. Subscripts $i$ and $k$ denote the sample number and index of the discrimination target, respectively.

$$\left\{ \begin{array}{l} \begin{bmatrix} X_{ki} \\ Y_{ki} \\ Z_{ki} \end{bmatrix} = f_{XYZ}(R_{ki}(\lambda), I(\lambda)) \\ \quad = \begin{bmatrix} \frac{100}{K} \int_{\lambda} R_{ki}(\lambda) I(\lambda) \bar{x}(\lambda) \\ \frac{100}{K} \int_{\lambda} R_{ki}(\lambda) I(\lambda) \bar{y}(\lambda) \\ \frac{100}{K} \int_{\lambda} R_{ki}(\lambda) I(\lambda) \bar{z}(\lambda), \end{bmatrix} \\ K = \int_{\lambda} I(\lambda) \bar{y}(\lambda), i \in \{1,2,...,N\}, k \in \{1,2\} \end{array} \right. \tag{2}$$

The $XYZ$ color signals of the background $X_b$, $Y_b$, $Z_b$ and the white reference $X_w$, $Y_w$, $Z_w$ are also computed using the color computation function above. Here, $R_b$ denote the spectral reflectance of the background. The relative luminance of the white reference $Y_w$ is always 100 because of the normalization in Eq.2. Furthermore, $X_w$ and $Z_w$ must also be constant in the optimization process because of the optimization limitation mentioned in the previous section. A procedure for keeping the color signals of the white reference $X_w$, $Y_w$, $Z_w$ constant is described in the next section.

$$\begin{bmatrix} X_b \\ Y_b \\ Z_b \end{bmatrix} = f_{XYZ}(R_b(\lambda), I(\lambda)) \tag{3}$$

$$\begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} = f_{XYZ}(1, I(\lambda)) \tag{4}$$

The $XYZ$ color signals of the discrimination targets can now be transformed into the responses of the color appearance model CIECAM02, and the color difference values $\Delta E'_i$ are computed according to the following equations:

$$\begin{aligned} \mathbf{C}_{ki} &= {}^{t}[J_{ki}, M_{ki}, h_{ki}] \\ &= f_{CAM02}({}^{t}[X_{ki}, Y_{ki}, Z_{ki}], Y_b, Y_w, L_A, srd), \\ &\quad i \in \{1,2,...,N\}, k \in \{1,2\}, \\ &\quad srd \in \{Average, Dim, Dark\} \end{aligned} \tag{5}$$

$$\begin{aligned} \Delta E'_i &= f_{dE\_CAM}(\mathbf{C}_{1i}, \mathbf{C}_{2i}, ver), \\ &\quad i \in \{1,2,...,N\}, ver \in \{LCD, SCD, UCS\} \end{aligned} \tag{6}$$

Here, the outputs $J$, $M$ and $h$ are the CIECAM02 lightness, colorfulness, and hue angle values, respectively. The transform function $f_{CAM02}$ is defined using the CIECAM02 color appearance model formulae [7]. $L_A$ and *srd* denote the luminance of the adaptation field and the viewing condition parameter. These parameters need to be determined based on the observation environment. The color differences $\Delta E'_i$ are defined as Euclidean distances by the modified CIECAM02, as proposed by Luo *et al.* [8]. The parameter *ver* indicates the selected version of the uniform color spaces, CAM02-LCD, CAM02 SCD, and CAM02 UCS.

### Generation of Metameric Illuminants

As mentioned above, the objective of the optimization is to determine the optimal spectral distribution $I(\lambda)$ that maintains an arbitrary color with the requisite color difference enhancement ability. Thus, the search of the optimal $I(\lambda)$ that satisfies Eq.1 (maximizes the color difference) should only be conducted for the metameric illuminant spectra. Therefore, we applied the metameric spectrum generation method proposed by Schmitt to limit the search range to the ensemble of metameric spectra [9]. Schmitt showed that the spectral ensemble generated by the linear sum of the predefined metameric spectra is a fairly efficient method for constructing the metameric ensemble because of the additive color mixture theory. This idea was applied in our method by limiting the search range to the inside of a polyhedral space constructed from the predefined metameric spectra. $I(\lambda)$ is described as follows:

$$I(\lambda) = \sum_{n=1}^{N_I} b_n S_n(\lambda) \tag{7}$$

where $N_I$ indicates the number of predefined metameric spectra, $S_n(\lambda)$ is a metameric spectrum, and $b_n$ is a weight of $S_n(\lambda)$. Thus, the optimal $I(\lambda)$ is determined via optimization of the weights $b_1, b_2, ..., b_{N_I}$. The predefined metameric spectra are automatically generated from the base spectra set $B_m(\lambda), m \in \{1,2,...,N_B\}$. An example of spectrum generation is shown as follows:

$$S(\lambda) = a_1 B_1(\lambda) + a_2 B_2(\lambda) + a_3 B_3(\lambda) \tag{8}$$

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} X_1 & X_2 & X_3 \\ Y_1 & Y_2 & Y_3 \\ Z_1 & Z_2 & Z_3 \end{bmatrix}^{-1} \begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} \tag{9}$$

where, $S(\lambda)$ is a generated spectrum, and $a_1$, $a_2$ and $a_3$ are weights of the three selected spectra, $B_1(\lambda)$, $B_2(\lambda)$ and $B_3(\lambda)$, respectively. The selected spectra have the color signals ${}^{t}[X_1, Y_1, Z_1]$, ${}^{t}[X_2, Y_2, Z_2]$ and ${}^{t}[X_3, Y_3, Z_3]$, respectively.The inverse matrix computation in Eq.9 derives the weights $a_1$, $a_2$ and $a_3$ that provide the illuminant color of $S(\lambda)$ ${}^{t}[X_w, Y_w, Z_w]$. As also mentioned in [9], all combinations of the base spectra set

$S_n(\lambda), n \in \{1,2,...,N_I\}$ are the apexes of polyhedral space, and their total number $N_I$ is less than ${}_{N_B}C_3$. The simplest $B_m(\lambda)$ is an element of spectral bands, i.e., monochromatic light. However, from an engineering viewpoint, the generation of a specific spectral distribution using a mixture of monochromatic lights is unrealistic. Thus, $B_m(\lambda)$ should be defined with consideration for its optical implementation.

### Spectral Dataset

The spectral dataset of color discrimination target $R_{ki}(\lambda)$ is required to design a spectral distribution for the illuminant. The spectral dataset needs to be composed of two groups and the color discrimination between them should be maximized. This section describes the construction of a spectral dataset used as the training data.

In the illuminant design experiment, we measured multispectral images of blueberry jam mixed with foreign substances (leaf, branch, and stone) and the spectral datasets were extracted from the images. Here, the thickness of jam covering the foreign substances varied from 1.75 to 7.0 mm in 1.75-mm steps to simulate the condition of being buried at various depths.

The multispectral images were measured using a Nuance spectral camera (Nuance, Multispectral Imaging System, CRi, VIS), excluding specular reflectance. The spectral range of the measurements varied from 420 to 720 nm in 5-nm steps. Various kinds of blueberry jams are made from a variety of blueberries. However, the color of blueberry jam is chiefly due to the same class of pigments, namely, anthocyanin-based pigments. Therefore, there might not be significant differences between the measured reflectance spectra of blueberry jam products. Thus, we tested only three types of commercial blueberry jams in the measurements. For each blueberry jam product, four sample measurements (containing stones, branches, and leaves) were conducted and the multispectral images were measured. Based on the spectral images, training datasets consisting of blueberry jams and foreign substances were automatically extracted. In total, 192 spectra (four blueberry jam types and substances, each with 48 spectra) were extracted from 12 samples.

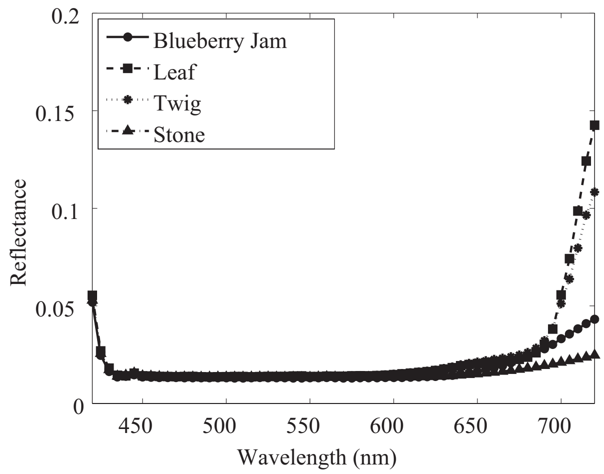

*Figure 1. Reflectance spectra of jam and the foreign substances, namely, stones, branches, and leaves.*

A spectral dataset extracted from the multispectral images was separated into two groups, $R_{1i}(\lambda)$ and $R_{2i}(\lambda)$. One group contained the spectral reflectance of blueberry jams, while the other group contained the spectral reflectance of the foreign substances. The average spectra of blueberry jam and foreign substances in the constructed dataset are shown in Fig.1. A spectrum attribution (red edge) was peculiar to the plant organs found in the leaf and the branch in the long-wavelength range from 680 nm to 720 nm, although each spectrum had a similar color. As a result, a difference in the spectral properties of the leaf and the branch and the spectra of the blueberry jam was found in the long-wavelength range. We also found a small difference of the spectral properties in the same range between the spectra of the stone and the spectra of the blueberry jam.

To test the spectral dataset obtained with the target function (Eq.1), the blueberry jam spectral group is applied to $R_{1i}$, while the foreign substances spectral group was applied to $R_{2i}$. The foreign substances spectral group included the spectra of three types of the items, so the target function was transformed as follows:

$$maximize\ \overline{\Delta E} = \frac{1}{MN} \sum_{j=1}^{M} \sum_{i=1}^{N} f_{dE}(R_{1i}(\lambda), R_{2i}^{j}(\lambda), I(\lambda)) \quad (10)$$

where $M$ indicates the number of types of foreign substances ($M = 3$).

## Optimization Process

We now describe the optimization conditions for the experiment in this section. First, CIECAM02 and its transformation based on UCS require some parameters. Parameters describing the viewing conditions used in the optimization are shown in Table 1.

**Table 1. Parameters of CIECAM02 and the transformation of CIECAM02 based on UCS, for designing the spectral distribution.**

| Parameters | Condition or Value |
|---|---|
| Viewing Condition | average |
| Adaptation Field Luminance ($L_A$) | 20% (30, 60, 90, 150, 210) |
| Luminance of Illuminant | 150, 300, 450, 750, 1050 $\mathrm{cd \cdot m^{-2}}$ |
| Relative luminance of backgound ($Y_b$) | 20% |
| Version of UCS based on CIECAM02 | CAM02-SCD |

We also defined the maximum spectral radiance as 0.037 $\mathrm{W \cdot sr^{-1} \cdot m^{-2} \cdot nm^{-1}}$, the spectral radiance of a programmable light source used in the psychophysical experiment. Under this limitation, five types of spectral distributions with different luminance (150, 300, 450, 750, and 1050 $\mathrm{cd \cdot m^{-2}}$) were designed to determine the relationship between the color difference, luminance, and the spectral distribution. Adaptation field luminance ($L_A$) was defined as 20% of the luminance for each of the designed illuminants $I(\lambda)$. The relative background luminance ($Y_b$) was defined as 20% of the white reference.

In this study, the base spectra set $B_m(\lambda), m \in \{1,2,...,N_B\}$ was defined based upon the spline function in Eq.11[10]. $Bs_l(\lambda)$

indicates the basis function, where $\omega$ is a parameter describing the width of the function and $\lambda_k$ is the center of the function. The base spectra $B_m(\lambda)$ were generated by the fusion of three adjacent basis functions (Eq.12). This was to fix $B_m(\lambda)$ close to the spectral-radiance characteristics of the equalized light source (ELS-Vis, Nikon).

$$
Bs_l(\lambda) = \begin{cases} \{\omega^3 + 3\omega^2(\omega - |\lambda - \lambda_l|) \\ \quad + 3\omega(\omega - |\lambda - \lambda_l|)^2 \\ \quad - 3(\omega - |\lambda - \lambda_k|)^3\}/6\omega^3 \\ \qquad\qquad for\ |\lambda - \lambda_l| \le \omega, \\ (2\omega - |\lambda - \lambda_l|)^3/6\omega^3 \\ \qquad\qquad for\ \ \omega \le |\lambda - \lambda_l| \le 2\omega, \\ 0 \qquad\qquad for\ \ 2\omega \le |\lambda - \lambda_l| \end{cases} \tag{11}
$$

$$
B_m(\lambda) = Bs_{3m-3}(\lambda) + Bs_{3m-2}(\lambda) + Bs_{3m-1}(\lambda) \tag{12}
$$

The number of generated ensembles of metameric functions $N_I$ was 270 and we optimized their weights $b_n$ in Eq.7 to enhance color discrimination between blueberry jams and foreign substances. The computational effort required for optimization by full search was unrealistic because the number of variables $N_I$ was very large. Thus, we used a hill-climbing method as the reality-based optimization method. The hill-climbing method is a search method, so it is possible that an optimum solution will not be obtained, although the computational effort is decreased. However, a localized solution near the optimal solution can be obtained by computing numerous search solutions by varying the initial values and selecting the best solution. Thus, the value with the highest average color difference was selected from a set of spectra for the designed spectral illuminant distribution. In this study, the set of spectra was composed of 50 different spectra, each with a different initial value.

## Optimization Results

The optimization results for the described conditions are shown in Fig. 2. The top figure shows the spectral-radiance distributions of the designed illuminants and the lower figure shows the spectra of equal-energy white illuminants that had the same luminance as the designed illuminants. The color difference values $\overline{\Delta E'}$ of these illuminants are shown in Table 2. All of the designed illuminants had high energy in the wavelength range from 650 nm to 700 nm. This energy probably works to enhance the color difference of spectra shown in Fig.1 because the spectral differences between the jam and the substances only exist within this wavelength range. The peak at 500 nm might work if the illuminant color control is a white illuminant. Radiant energy at 500 nm did not affect the $X$ signal because the $\bar{x}$ color matching function was mostly zero. Therefore, spectral differences enhanced by the long-wavelength energy can strongly affect the X signals with the designed illuminants. In contrast, the equal-energy white illuminant contains spectral energies other than 500 nm, "noise energies," that weaken the perceived signal differences. For this reason, noise energies increase with the luminance of the designed illuminant, which results in the decreased enhancement of color differences. However, the color difference enhancement of a designed illuminant with a luminance of 150 $\mathrm{cd \cdot m^{-2}}$ was lower than the enhancement of an illuminant with 300 $\mathrm{cd \cdot m^{-2}}$, although the noise energies were the lowest. This illuminant may be too dark to discriminate internal foreign substances. The enhancement of color differences in low LER conditions was greater than that in high LER conditions because long-wavelength energy influences enhancement. Therefore, the color difference enhancement and the LER improvement required a trade-off. In our experiment, the lower LER limit was achieved by limitation of the luminance and the maximum spectral-radiance. However, the LER should be included in the objective function and a multi-objective optimization should be performed if the design requires a high LER. Probably the designed illuminant can also work for other kinds of blueberry jam product because the spectral differences in Fig.1 are caused by the absorption property of anthocyanin pigment. Actually, the spectral absorption of anthocyanin pigment decreases sharply from 600 nm to near-infrared wavelength range[11].

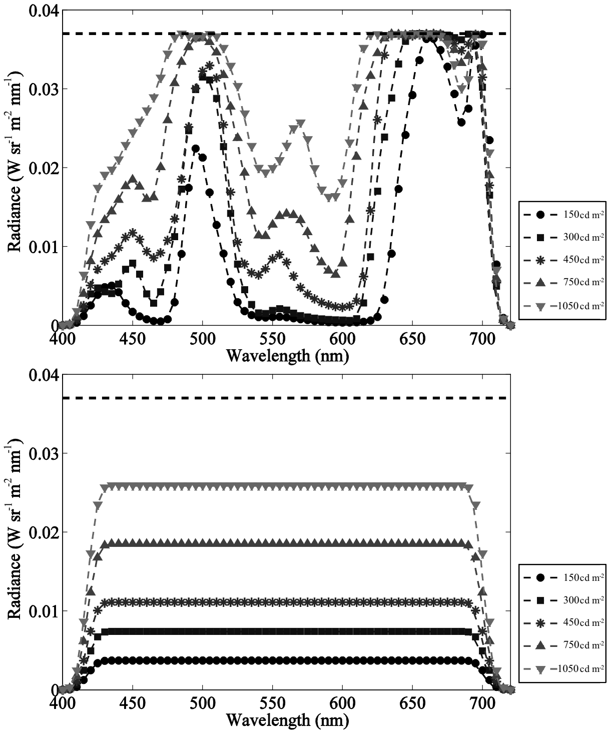

***Figure 2.*** *Designed illuminants and equal-energy white illuminants. The upper figure shows the spectral-radiance distributions of the designed illuminants, while the lower figure shows the spectra of equal-energy white illuminants with the same luminance as the designed illuminants.*

**Table 2. Average color differences $\overline{\Delta E'}$ and luminance of the designed illuminants.**

| | Color difference $\overline{\Delta E'}$ | |
|---|---|---|
| Luminance $\mathrm{cd \cdot m^{-2}}$ | Equal-energy | Designed |
| 150 | 1.561 | 2.884 |
| 300 | 1.638 | 2.826 |
| 450 | 1.685 | 2.548 |
| 750 | 1.747 | 2.253 |
| 1050 | 1.789 | 2.035 |

## *Illumination with a Synthesized Spectral Light Source*

The designed illuminants were roughly produced and emitted using a synthesized spectral light (ELS-VIS, Nikon) to confirm the effects of different color enhancements. The illumination target was blueberry jam placed in a glass Petri dish mixed with some stones. The designed illuminant with a luminance of 10% and an equal-energy white illuminant with the same luminance were produced using ELS-VIS. The illuminated target was photographed with a standard Nikon D70 RGB digital camera. During this measurement, it was necessary to perform a color calibration for each illumination condition, because of the spectral sensitivity difference at the long wavelength range. RGB images of blueberry jam photographed under these two illuminants are shown in Fig.3. The transparency of the blueberry jam was greatly increased under the designed illuminant, and the foreign substances (stones) were easily discriminable. In addition, the gray scale of a color patch (X-rite ColorChecker Mini) did not change when switching between the designed illuminant and an equal-energy illuminant. This indicated that the designed illuminant chromaticity was maintained around the white point by the predefined illuminant. Thus, the eye stress experienced by visual examination staff would be decreased if the designed illuminant was used for foreign substance detection. This is because the color discrimination is obtained with lower luminance than commercial illumination sources and a color adaptation mechanism would not be induced with the designed white illuminant.

## *Evaluation with a psychophysical experiment*

Color discrimination enhancements obtained with the designed illuminants were evaluated in a psychophysical experiment. A paired comparison method was used for this evaluation. Blueberry jam containing foreign substances was illuminated by five different types of designed illuminant and an equal-energy white illuminant, as shown in Fig.2. The light-condensing accessory of the optical fiber meant that the luminance value at the center of the illumination area was increased by approximately 1.7 times compared with the theoretical design. The measurement was performed in a darkroom environment. The number of subjects was 10 (seven males and three females) and their average age was 23.0. The evaluation results are shown in Fig. 4. All of the designed illuminants were found to provide better discrimination than the equal-energy white illuminant, and the variation in scale value (y-axis) was with the CIECAM02-based color difference (Fig. 5). It was apparent that using a $\overline{\Delta E'}$ based on CIECAM02 represented the perceptual color difference well.

## Conclusions

In this study, we proposed a method for designing a spectral distribution of illuminant which can enhance the color discrimination of predefined target. The illuminant was designed to maximize the color difference of two spectral dataset (= discrimination target) described in Eq.1. The color difference computation was performed on the uniform color space based on CIECAM02 for considering the effect of surrounding and adaptation. (Eq.5, Eq.6) Furthermore, the designing method based on generation of metameric ensembles proposed by Schmitt can obtain an optimal illuminant with optional illuminant color. This method was applied to design an illuminant for supporting foreign sustance detection in the blueberry jam manufacturing process. Spectral datasets of blueberry jam and foreign substances mixed to jam were measured by the multispectral imaging system Nuance (Fig.1). In total, five optimal illuminants which have different luminance were designed (Fig.2). As shown in Fig.2, all designed

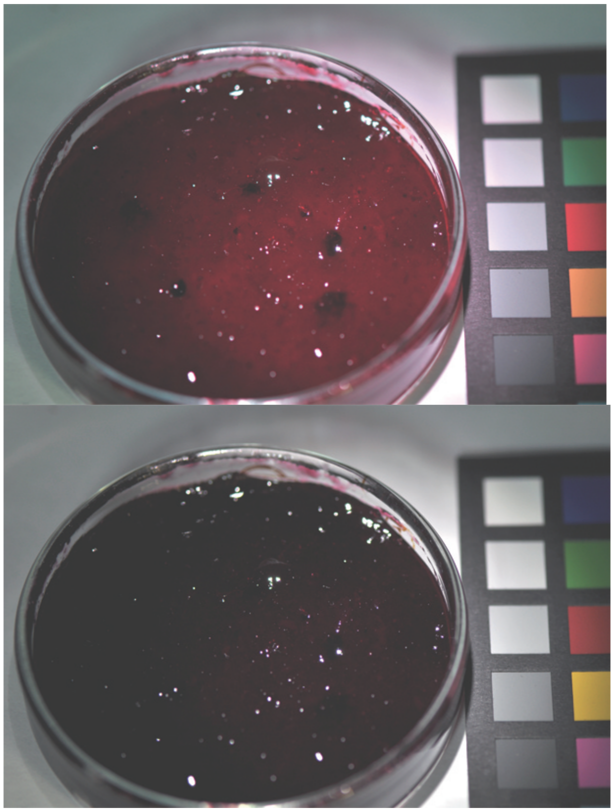

***Figure 3.*** *RGB images of jam with stones under the designed illuminant and an equal-white illuminant. Images were captured with a standard Nikon D70 RGB digital camera. The illuminants were produced using an equalized light source (ELS-VIS, Nikon).*

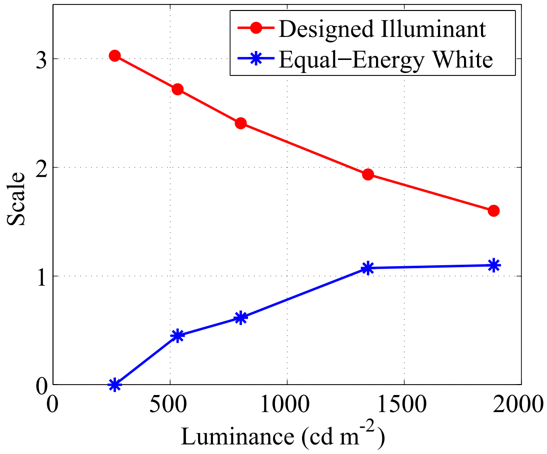

***Figure 4.*** *Psychophysical scale for easiness of target discrimination evaluated by a paired comparison experiment*

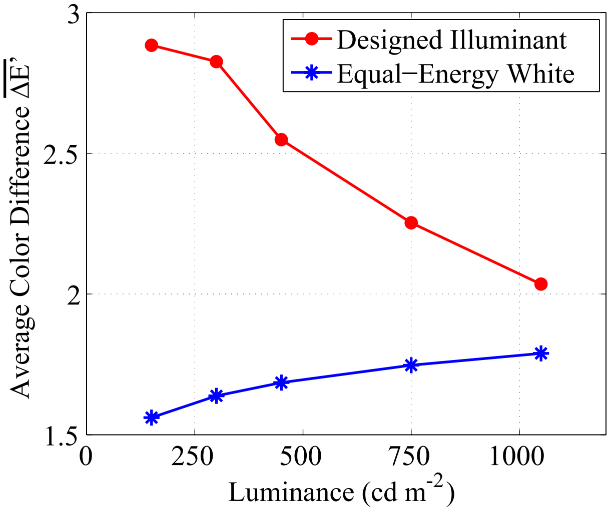

***Figure 5.*** *Relationship between average color difference and luminance.*

illuminants have high energy on the wavelength range of 650 nm to 700nm for enhancing the spectral difference shown in Fig.1. The designed illuminant achieved by the Equalized Light Source (ELS-VIS, Nikon) clearly showed that the color discrimination of jam and mixed foreign sustances are obviously enhanced Fig.3. The application field of this technique is not limited to the foreign sustance detection for blueberry jam: quality control of iudustrial products, medical imaging and so on.

In this study, we proposed a method for designing a spectral illuminant distribution to enhance the color discrimination of a predefined target. The illuminant was designed to maximize the color difference between the two spectral datasets (=discrimination target) described in Eq.1. The color difference computation was performed in a uniform color space based on CIECAM02, but with consideration for the effects of the surrounding environment and adaptation (Eq.5, Eq.6). Furthermore, the design method was also based on the generation of metameric ensembles as proposed by Schmitt [9], allowing the selection of an optimal illuminant with a preferred illuminant color. This method was applied to the design of an illuminant to support foreign substance detection in the blueberry jam manufacturing process. Spectral datasets of blueberry jam and foreign substances mixed with jam were measured using the multispectral imaging system Nuance (Fig.1). In total, five optimal illuminants with different luminances were designed (Fig.2). As shown in Fig. 2, all the designed illuminants produced high energy in the wavelength range from 650 nm to 700 nm when enhancing the spectral difference shown in Fig.1. The designed illuminant was implemented using an equalized light source (ELS-VIS, Nikon), which clearly showed that the color discrimination of jam and foreign substances was enhanced, as shown in Fig.3. The application field for this technique is not limited to foreign substance detection in blueberry jam because it could also be applied to quality control processes of other industrial products, medical imaging, and so on.

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