Estimating Spectral Sensitivity of Human Observer for Multiplex Image Projection

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Abstract: In this paper, we propose an efficient method for estimating the spectral sensitivity of human retina. The proposed method is used for the multiplex image projection by using multi-band projectors. The multiplex image projection can represent different images to different observers by using the differences of spectral sensitivities of these observers. Although precise spectral sensitivity is required for the multiplex image projection, the ordinary estimation methods require a lot of time for estimation. Thus, we in this paper propose an efficient method for estimating the spectral sensitivity of human eye. The experimental results show the efficiency of the proposed method.

1 INTRODUCTION

Recently, multi-band imaging is widely studied in the field of computer vision, image processing and many other applications (Miyake et al., 1999; Tominaga, 1999; Monno et al., 2012; Miao and Qi, 2006; Parmar and Reeves, 2010; Park et al., 2007; Ng and Allebach, 2006). In particular, multi-band cameras are used for obtaining precise spectral information of natural scene. From the multi-band images taken by the multi-band cameras, we can obtain valuable color information which can not be obtained from ordinary RGB color cameras.

On the other hand, multi-band displaying is also studied in recent years (INFITEC, 2002; Nonoyama et al., 2013; Miyazaki et al., 2013). Nonoyama et al.(Nonoyama et al., 2013) showed that it is possible to represent different images to different observers simultaneously by controlling the spectral distribution of displayed images precisely by using a multi-band projector. It is called multiplex image projection. The difference of observation is occurred by the difference of the spectral sensitivity of observers. The method can be applied to various applications, such as 3D displaying system without using special glasses.

In order to represent different images accurately in the multiplex image projection, it is necessary to obtain precise spectral sensitivities of the observers. If the observer is a camera or digital imaging devices, we can obtain their spectral sensitivity directly from their observations. However, it is very difficult to obtain the spectral sensitivity of human retina, since we cannot obtain the observed signals in human retina numerically. Thus, the efficient method for estimating the spectral sensitivity of human visual system is required for multiplex image projection.

Traditionally, the spectral sensitivity of human visual system has been measured by using several methods, such as brightness matching, flicker photometry, etc. The CIE published the standard spectral sensitivity of human visual system. However, the ordinary measurement method needs a lot of time to obtain precise spectral sensitivity, since many observations are required to obtain the precise spectral sensitivity.

In this paper, we propose a new parametrization of the spectral sensitivity of human visual systems. Furthermore, an efficient method for measuring the spectral sensitivity based on this new parametrization is proposed. In the proposed method, the measurement time of human spectral sensitivity is much smaller than that of the ordinary measurement method.

2 METAMERISM

We first consider the relationship among light spectrum, observed signals and spectral sensitivity of observers. In general, ordinary sensors, such as human retina and CCD, cannot receive light spectrum directly. They encode the light spectrum to a limited number of signals by using their receivers. The

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receivers have characteristic spectral sensitivity, and thus, received signals depend on their spectral sensitivity and input light spectrum. Each receiver in the sensors has different spectral sensitivity, and thus, the encoded signals are different from each other. The combination of the signals determines observed colors. For example, a human retina has 3 different receivers, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$, and each receiver encodes the spectrum of light $E(\lambda)$ into X, Y and Z as follows:

$$X = K\int_{400}^{700} E(\lambda)\bar{x}(\lambda)d\lambda \quad (1)$$

$$Y = K\int_{400}^{700} E(\lambda)\bar{y}(\lambda)d\lambda \quad (2)$$

$$Z = K\int_{400}^{700} E(\lambda)\bar{z}(\lambda)d\lambda \quad (3)$$

where K is a constant for normalization. Note that, human retina can encode only from about 400nm to 700 nm, and thus, the range of integral is limited as shown in the above equations.

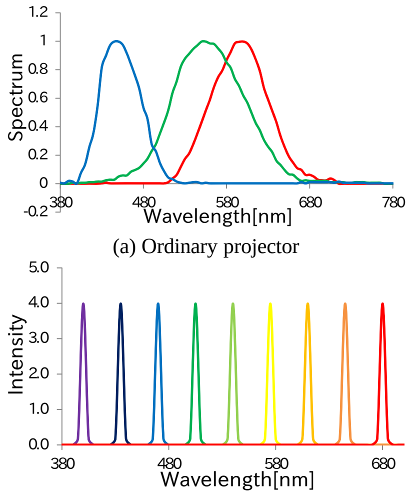
As described in the above equations, DoF (degree of freedom) of received signals is much smaller than that of the input light spectrum. Therefore, the same set of signals X, Y and Z can be observed, even if the input light spectrum is different. In this case, we cannot distinguish these lights, and we recognize that the input lights have the same color. This property is called as *metamerism* and such colors are called as *metameric colors*. The metamerism is important property in this paper. It is used for multiplex image projection and measurement of human retina sensitivity.

3 MULTIPLEX IMAGE PROJECTION

We next consider multiplex image projection proposed by Nonoyama et al.(Nonoyama et al., 2013). Equations from (1) to (3) represents that there are a lot of metameric colors for each color, and thus, we can choose many different light spectrum to represent a specific color. In addition, the received signal depends not only on input light spectrum, but also on the spectral sensitivity of the observer. As a result, a pair of metameric colors for a certain observer may not be metameric for other observers. Thus, we can change the observed color for a particular observer without changing the observed color of other observers by using the metamerism.

If we can control whole light spectrum in image representation, we can represent arbitrary colors one by one. For example, we can emit a special light which is recognized as red by an observer, while it is recognized as blue by the other observer. Thus, we can represent different images to different observers.

However, the existing ordinary displaying devices, such as displays and projectors, cannot control the spectrum of light freely. This is because these devices represent colors by combining few specific colors, i.e. red, green and blue. In multiplex image projection, they do not have sufficient ability for exploiting metamerism. Therefore, we construct a multi-band projector in order to achieve multiplex image projection. The multi-band projector can project much more color channels to represent colors, and thus, its DoF of light spectrum is much higher than that of the ordinary projectors.



(a) Ordinary projector

(b) Multi-band projector

Figure 1: Light spectrum of ordinary and multi-band projectors.

Figure 1 shows the example of light spectrum of an ordinary projector and a multi-band projector. Each projector represents colors by the combination of each band lights. In Fig.1, the ordinary projector can emit three wide-band lights, while the multi-band projector can emit nine narrow-band lights. Therefore, the DoF of light spectrum emitted from the multi-band projector is much higher than that of the ordinary projector.

4 MULTIPLEX IMAGE ENCODING/DECODING

By using the multi-band projector, we encode multiple images into a single multi-band image. In this section, we first explain decoding of multi-band images, and then explain encoding of multiple images.

4.1 Image Decoding

We first explain image decoding from a particular light spectrum. In fact, we do not need any processes for the image decoding, since the image decoding can be realized just by observing images by sensors, which have different spectral sensitivities. Now let us consider the projection and observation from an N-band projector. Let $E_i(\lambda)$ and b_i $(i = 1, 2, \cdots, N)$ be the light spectrum and the radiance of i-th band respectively. Suppose the projected light is observed by M different receivers, whose spectral sensitivities are $x_j(\lambda)$ $(j = 1, \cdots, M)$. Then, the observed signal X_j of the j-th receiver can be described as follows:

$$X_j = \sum_{i=1}^{N} \int b_i E_i(\lambda) x_i(\lambda) d\lambda. \tag{4}$$

Let C_{ji} be an observed signal when $b_i = 1$ in Eq.(4) as follows:

$$C_{ji} = \int E_i(\lambda) x_i(\lambda) d\lambda. \tag{5}$$

Then, Eq.(4) is rewritten by using C_{ji} as follows:

$$X_j = \sum_{i=1}^{N} C_{ji} b_i \tag{6}$$

From these equations, the relationship between the radiance b_i of each band and the received signal X_j of each sensor can be described as follows:

$$\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_M \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1N} \\ C_{21} & C_{22} & \cdots & C_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ C_{M1} & C_{M2} & \cdots & C_{MN} \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_N \end{bmatrix} \tag{7}$$

We call the matrix in the right side of the above equation a spectral sensitivity matrix. The equation (7) indicates that we can control observed signals X_j by changing the projecting radiance b_i of the N-band projector.

4.2 Multiplex Image Encoding

We next consider the encoding of multiple images into a single multi-band image. In order to achieve multiplex image encoding, we solve Eq.(7) and obtain projection intensities b_i from objective (observed) signals X_j and the spectral sensitivity matrix C_{ji} by using least means square method. The equation (7) has one or more than one solutions, if $N \geq M$. However, the solution b_i includes negative values in general. In ordinary case, general projectors cannot project negative intensities, and thus, we should avoid this problem. For this objective, we use virtual negative intensities, where the values lower than a virtual zero level x are regarded as negative intensities as shown in Fig.2.

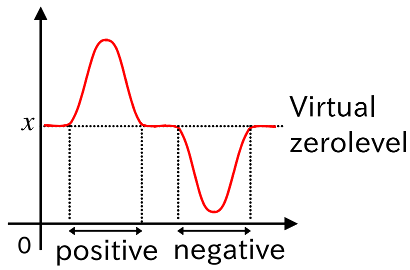


Figure 2: Virtual negative intensities.

After this zero level correction, the radiance of the projection image is computed as follows:

$$\{\hat{b}_1, \cdots, \hat{b}_N\} = \underset{\{b_1, \cdots, b_N\}}{\text{argmin}} \; ||X_j - \sum_{i=1}^{N} C_{ji} b_i|| \quad \text{subject to} \;\; 0 \leq b_j \leq I_{max} \tag{8}$$

where I_{max} is maximum value of radians, such as 255 for an 8 bit image.

5 SPECTRAL SENSITIVITY ESTIMATION

The multiplex image projection can be applied to not only cameras vs humans, but also a human vs the other human. Furthermore, it may be applied to the left eye vs the right eye if there are sufficient difference among their spectral sensitivities. In order to realize them, we should measure precise spectral sensitivities of these receivers. However, ordinary estimation method requires a lot of time, e.g. 1 or 2 hours, to estimate the sensitivity and thus, it is not easy to estimate the spectral sensitivity of many people precisely. In order to estimate the spectral sensitivity in short time, we propose a parametric representation of the spectral sensitivity. Furthermore, we propose a new estimation method of spectral sensitivities by using the new representation method. By using the proposed method, the time required for the estimation becomes much smaller than that of the ordinary method, and thus, we can estimate the spectral sensitivity of many people easily.

5.1 Measurement of Spectral Sensitivity

We first explain a general measurement of a spectral sensitivities of human retina. As described in the previous sections, a spectral sensitivity of the human retina is determined by three types of cone cell. Therefore, we should estimate characteristics sensitivities of them to estimate the spectral sensitivity.

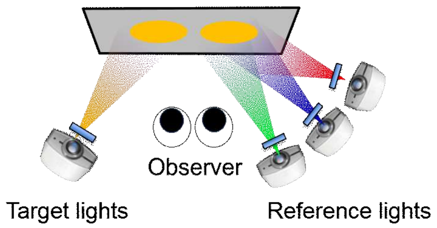


Figure 3: Human spectral sensitivity measurement: radiance of the reference lights are controlled, so that they become a metameric color of the target light.

However, it is not easy to represent the characteristic numerically because the sense of human cannot be extracted directly. Thus, the metamerism described at **2** is used for measuring the spectral sensitivities.

As described in **2**, a human cannot classify the difference of light spectrum when received values X, Y and Z are the same. By using this property, we can estimate relative relationship among spectral sensitivities.

For this objective, several reference lights and a target light is observed simultaneously as shown in Fig.3. The number of reference light is 3 in general. The spectrum of the target light and the reference lights are known. In this measurement system, a human observer observes the target light and combined reference light. Then, the radiance of each reference light is controlled, so that the reference light is observed as a metameric color of the target light. When the reference light becomes a metameric color of the target light, the relationship among the target light E_T, the reference lights E_{Ri} and the spectral sensitivity f_j of the target human observer can be described as follows:

$$\int_{400}^{700} E_T(\lambda) f_j(\lambda) d\lambda = \sum_{i=1}^{N} b_i \int_{400}^{700} E_{Ri}(\lambda) f_j(\lambda) d\lambda \tag{9}$$

where E_T and E_{Ri} denote light spectrum of the target light and the i-th reference light. N denotes a number of reference lights, and f_j indicates j-th spectral sensitivity of the target human observer. In ordinary case, human observer has three types of cone cell, and thus, $j = \{1,2,3\}$. b_i denotes controlled radiance of i-th light.

When the target person observes a pair of metameric colors, we have three equation on f_j from Eq.(9). Thus, we can estimate the spectral sensitivity f_j from several number of metameric color observations.

Note that we need large number of equations when a precise spectral sensitivity is required. For example, if the spectral sensitivity is sampled for every 10 nm, 31 variables are required for representing the whole spectral f_j. Thus, 31 pairs of metameric colors are required for estimating the sensitivity. In addition, it is not easy to control radiance for obtaining metameric colors. Therefore, long measuring time is required for estimating accurate spectral sensitivity, and thus more efficient sensitivity estimation method is required.

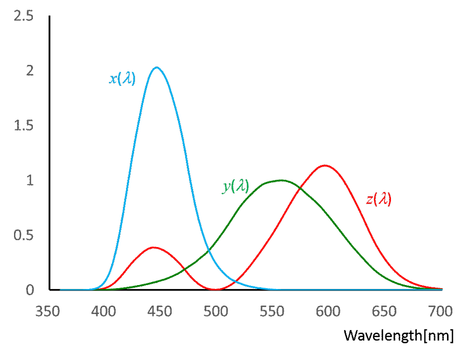


Figure 4: Spectral sensitivity defined by CIE (1964).

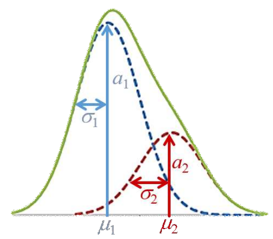


Figure 5: Representation by using Gaussian Mixture Model(GMM).

5.2 Spectral Sensitivity Representation by using GMM

In order to realize efficient estimation of human spectral sensitivity, we propose a new representation of the spectral sensitivity. Fig.4 shows representative spectral sensitivity defined by CIE(1964). As we can see in Fig.4, the spectral sensitivity of human observer is similar to the Gaussian function. Thus, we in this paper utilize Gaussian Mixture Model (GMM)(Reynolds, 1992) for representing the spectral sensitivity of human retina. The GMM can represent general functions by the combination of Gauss function as shown in Fig.5. Especially, the spectral sensitivity can be represented by small number of Gaussian functions, since the shapes of spectral sensitivities are similar to the Gaussian function.

By using the GMM, a spectral sensitivities $f_j(\lambda)$ can be described as follows:

$$f_j(\lambda) = \sum_{k=1}^{K} \frac{a_{kj}}{\sqrt{2\pi\sigma_{kj}^2}} e^{-\frac{(\lambda-\mu_{kj})^2}{2\sigma_{kj}^2}} \tag{10}$$

where K is a number of Gaussian functions, a_{kj} is scale parameter of k-th Gaussian function for j-th sensitivity, μ_{kj} and σ_{kj} are a center and standard deviation the function. By using the GMM, the spectral sensitivity can be represented by $3K$ parameters. Empirically, the number of Gaussian K can be small for representing the spectral sensitivities, and thus, the spectral sensitivity can be estimated stably and efficiently.

5.3 Sensitivity Estimation by using GMM

We next consider the estimation of spectral sensitivity by using the GMM. Let $f(a_{kj},\mu_{kj},\sigma_{kj})$ be a spectral sensitivity with parameters $a_{kj},\mu_{kj},\sigma_{kj}$. Then, Eq.(9) can be rewritten as follows:

$$\int_{400}^{700} E_T(\lambda) f_j(a_{kj},\mu_{kj},\sigma_{kj}) d\lambda = \sum_{i=1}^{N} b_i \int_{400}^{700} E_{Ri}(\lambda) f_j(a_{kj},\mu_{kj},\sigma_{kj}) d\lambda \quad (11)$$

From this equation, an evaluation function E_{GMM} can be defined as follows:

$$E_{GMM} = \sum_{l=1}^{L} \Big| \int_{400}^{700} E_l(\lambda) f_j(a_{kj},\mu_{kj},\sigma_{kj}) d\lambda - \sum_{i=1}^{N} b_{li} \int_{400}^{700} E_{Ri}(\lambda) f_j(a_{kj},\mu_{kj},\sigma_{kj}) d\lambda \Big|^2 \quad (12)$$

where L is a number of observed metameric colors. Then, by minimizing the cost function E_{GMM}, we can estimate the parameters for representing target spectral sensitivities. The DoF of spectral sensitivity is $3 \times 3K$ when $j = \{1,2,3\}$, and thus, we can estimate the spectral sensitivities, if $9K \leq 3L$. For example, if the number of Gaussian K is 2, the spectral sensitivities can be estimated from 6 or more than 6 pairs of metameric colors.

As described in this section, we can estimate the spectral sensitivity from much smaller number of observations by using GMM. Therefore, estimation time can be much smaller than that of the ordinary estimation method.

5.4 Spectral Sensitivity Representation by using Linear Bases

We next consider another representation of spectral sensitivities under general statistical assumptions. In the previous sections, we described that the spectrum sensitivities of humans are different from each other. Although this assumption is valid, the differences are not so large, and thus, we can represent the sensitivities by combining the small number of linear bases.

In this paper, we compute the linear bases by using PCA (Principal Component Analysis). Let $\mathbf{f}_i$ denote a spectral sensitivity of i-th person. The covariance matrix Σ of spectral sensitivities derived from K inputs is computed as follows:

$$\Sigma = \frac{1}{K}\sum_{i=1}^{K} (\mathbf{f}_i - \overline{\mathbf{f}})(\mathbf{f}_i - \overline{\mathbf{f}})^\top \quad (13)$$

where $\overline{\mathbf{f}} = 1/K \sum_{i=1}^{K} \mathbf{f}_i$ and it is an average of the sensitivities. The covariance matrix is decomposed into an orthogonal linear bases $\mathbf{Q}$ and a diagonal matrix Λ by using the eigenvalue decomposition as follows:

$$\sigma = \mathbf{Q}\Lambda\mathbf{Q}^\top \quad (14)$$

where, $\Lambda = \mathrm{diag}(\lambda_1,\cdots,\lambda_K)$ is from K eigenvalues $\lambda_1 \geq \cdots \geq \lambda_K$, and $\mathbf{Q} = [\mathbf{q}_1,\cdots,\mathbf{q}_K]$ is a set of eigenvectors $\mathbf{q}_i$.

By using the eigenvectors $\mathbf{q}_i$, the sensitivity $\mathbf{f}$ can be represented linearly as follows:

$$\mathbf{f} = \sum_{i=1}^{J} c_i \mathbf{q}_i + \overline{\mathbf{f}} \quad (15)$$

where $J(\leq K)$ is the number of bases and c_i is the coefficient of the i-th base $\mathbf{q}_i$. This equation indicates that the spectral sensitivity $\mathbf{f}$ can be represented by J coefficients.

The coefficients can be estimated from several number of observations like the previous estimation methods. By using the linear representation, Eq.(9) can be rewritten as follows:

$$\int_{400}^{700} E_T(\lambda) f_j(\mathbf{c},\lambda) d\lambda = \sum_{i=1}^{N} b_i \int_{400}^{700} E_{Ri}(\lambda) f_j(\mathbf{c},\lambda) d\lambda \quad (16)$$

where $f(\mathbf{c})$ indicates the spectral sensitivity from a set of coefficients $\mathbf{c}$. Thus, an evaluation function E_{lin} for linear estimation can be described as follows:

$$E_{lin} = \sum_{l=1}^{L} \Big| \int_{400}^{700} E_T(\lambda) f_j(\mathbf{c},\lambda) d\lambda - \sum_{i=1}^{N} b_i \int_{400}^{700} E_{Ri}(\lambda) f_j(\mathbf{c},\lambda) d\lambda \Big| \quad (17)$$

By minimizing E_{lin}, a set of coefficients $\mathbf{c}$ which represents the spectral sensitivity $\mathbf{f}$ can be estimated.

The linear representation of the spectral sensitivity is efficient when we have a data set of spectral sensitivities. By using the linear method, we can estimate the spectral sensitivity with a small computational cost.

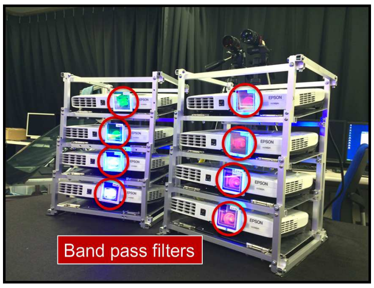


Figure 6: Multi-band projector: This projector is constructed by 8 projectors and 8 different band-pass filters. Each filter is equipped in front of each projector.

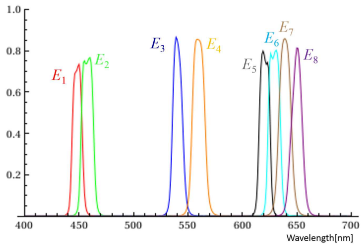
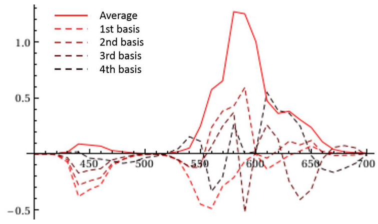
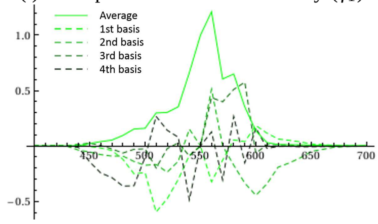


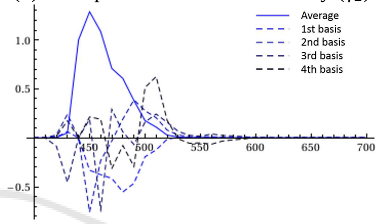
Figure 7: Spectral characteristics of the multi-band projector. Each line indicates spectral distribution of each band.



(i) Principal bases for 1st sensitivity (f_1)



(ii) Principal bases for 2nd sensitivity (f_2)



(iii) Principal bases for 3rd sensitivity (f_3)

Figure 8: The average and the principal bases of three spectral sensitivities, f_1, f_2 and f_3.

6 EXPERIMENTAL RESULTS

6.1 Environment

In this section, we show experimental results by using our proposed method. At first, we show experimental environment for these experiments. In the series of experiments, we used 8-band multi-band projector as shown in Fig.6. This projector was constructed by 8-projectors and each projector equipped a different band-pass filter. The light spectrum of each projector with band-pass filter is shown in Fig.7 The projectors are calibrated in advance by using homography estimation, and thus, they can project arbitrary images onto the same area on the screen simultaneously. In general, a characteristic of projected intensities are not nonlinear because projected images include gamma correction. Therefore, these gamma parameters were calibrated beforehand, and thus, linear image projection was achieved

6.2 Sensitivity Estimation Result

We first show estimation result of a human retina's spectral sensitivity. In this experiment, the spectral sensitivity of the human's retina was estimated by (a) general measurement method described in **5.1**, (b) proposed method using GMM and (c) proposed method using PCA.

In general method (a), 3 narrow band lights were used for reference lights. As the target light, 31 lights were used, and metameric colors for each target light were observed by controlling the radiance of reference lights. From these observations, 3 spectral sensitivities were derived.

In the proposed method (b) and (c), 8 fixed lights were used. One of the 8 lights was used as the target light and the other 7 lights were used as reference lights. The target light was changed in order and 8 sets of metameric colors were observed, and the 3 spectral sensitivities f_1, f_2, f_3 were estimated from the metameric colors.

At first, the spectral sensitivities of 8 persons were estimated by the general method (a), and their average and principal bases were computed by using the PCA. The estimated bases and the average are shown in Fig 8. Then, three principal bases and the average were used for method (c), Thus, 3 parameters were estimated in the method (c).

Figure 9 shows the spectral sensitivity of a person estimated from these three methods. In this figure, the solid lines indicate results from (a) general method, the dashed lines indicate results from (b) GMM, and the dash-dot lines indicate results from (c) PCA. Table 1 shows the time required for these estimations and

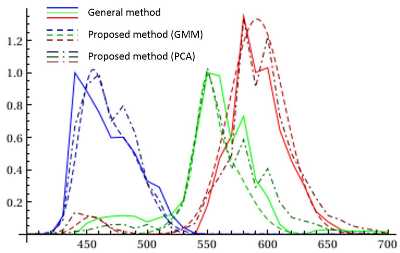


Figure 9: Estimated spectral sensitivity of the target human. The solid lines show results from the general method, the dashed lines show results from the GMM and dash-dot lines show results from the PCA.

Table 1: Estimation time for the proposed method and the ordinary method.

	ordinary	GMM	PCA
# of observations	60	18	18
time required	5 hours	40 min	40 min

the number of metameric colors for each estimation method. Note, minimum number of metameric colors required for method (b) and method (c) is different, since the number of parameters for these estimations is different. We however used the same number of the metameric colors for stable estimation in this experiment. Thus, the number of metameric colors and measurement time for (b) and (c) is the same in the Tab. 1.

As shown in Figure 9, the results from the proposed methods are very similar to the results from the ordinary method. These results indicate that the GMM and the linear bases from PCA can represent the sensitivity of human retina efficiently, and the proposed methods can work well, even if the number of metameric colors is small. In addition, Table 1 shows that the estimation time of the proposed methods is much smaller than that of the ordinary method. These results show that the proposed methods can estimate spectral sensitivity of human retina more efficiently than the ordinary measurement method.

Figure 10 shows the spectral sensitivity of another person estimated from the proposed methods and the ordinary method. These results shows that the proposed method can estimate spectral sensitivity for arbitrary human observers. Furthermore, we can observe the difference between the estimated result in Fig.9 and Fig.10. The fact indicates that the proposed method can estimate slight sensitivity difference between two different human observers. Furthermore, the results shows that there is explicit deference in the spectral sensitivity of two different human observers. Therefore, we can use the proposed method for realizing multiplex image projection for human vs human.

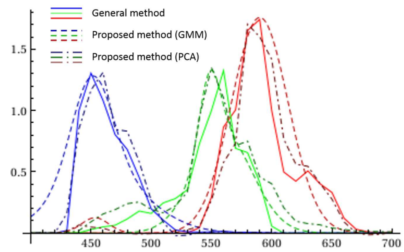


Figure 10: Spectral sensitivity estimated by our proposed methods and the ordinary method.

6.3 Multiplex Image Projection Result

We next show the results of multiplex image projection using the estimated spectral sensitivities. In this experiment, multi-band images were synthesized for a camera and a target human. The multi-band images were synthesized from a known camera spectral sensitivity and estimated sensitivity of the human retina. The spectral sensitivity of the human retina was estimated by the proposed method and the ordinary method. Result from the ordinary method was used as ground-truth.

For comparison, multi-band images were synthesized from our two proposed estimation results, ground-truth and CIE (1964) color function. In this case, three signals, X, Y and Z, were exchanged to RGB and displayed as an RGB image. These images were projected onto the screen and observed by the target human and the target camera.

Figure 11 shows objective images and observed results. Note that the observed results of human retina cannot be represented directly, and thus, these results show images observed by the ground-truth spectral sensitivity. From these results, we confirm that the appearances of these observation results are similar to the objective images. In particular the observation results in (d) is very close to the objective images in (a). This is because the multi-band images were synthesized from ground-truth spectral sensitivity in (d). The results indicate that multiplex image projection works well, if the spectral sensitivities of the observers are known. The observation results in (b) and (c) were derived from the proposed methods. In these results, observed images are slightly different from the objective images in (a). The difference occurred from the difference between the estimated spectral sensitivity and the ground truth spectral sensitivity as shown in Fig.9. The results indicate that multiplex image projection is very sensitive to the difference of spectral sensitivity. However, multi-band images can be roughly synthesized from our estimated results as shown in (b) and (c).

The observation results in (e) were derived from

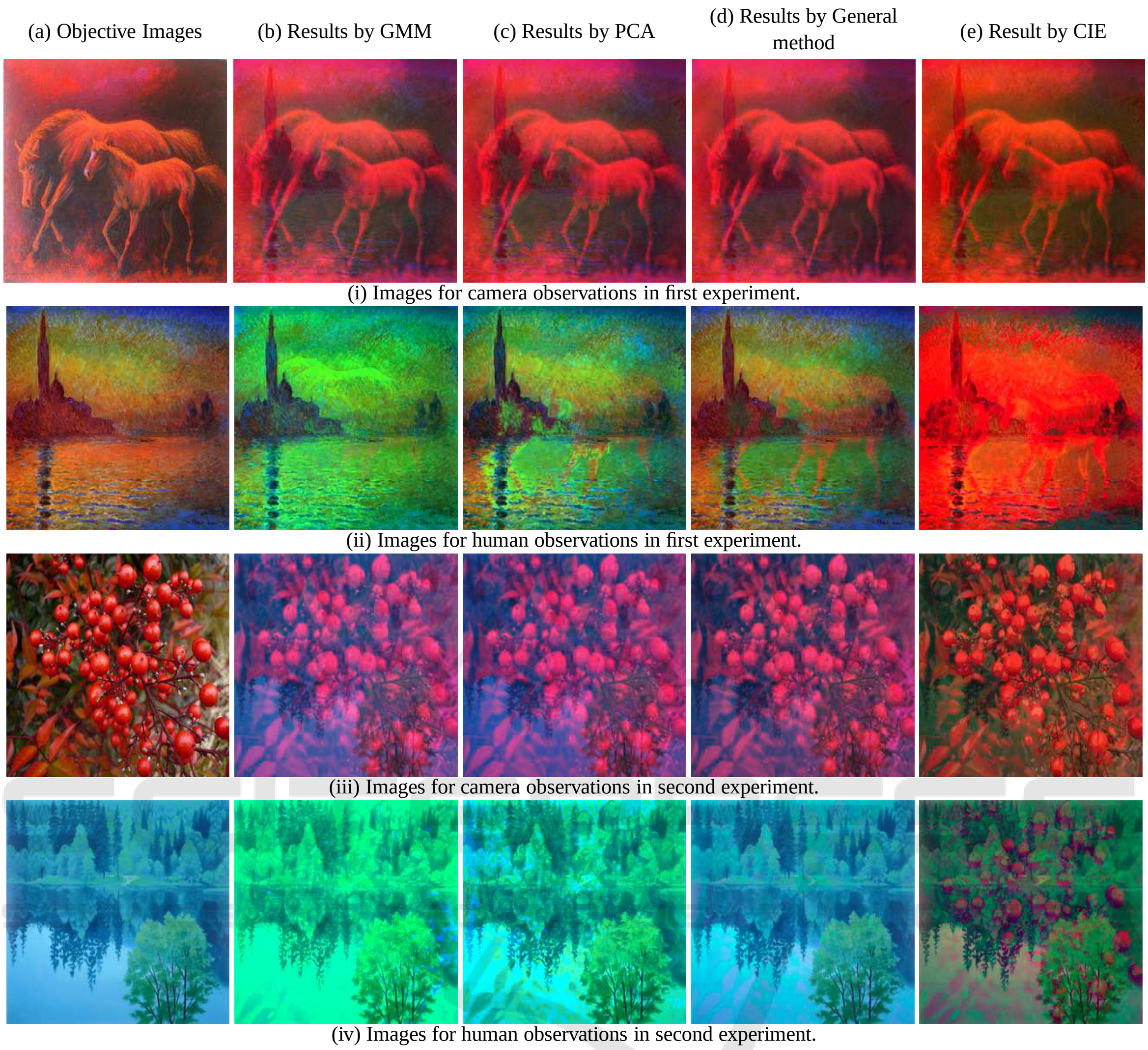


Figure 11: Objective images and observed results. First and second rows shows experimental results from first experiment and third and fourth rows shows results from second experiment. The column (a) shows objective images for a camera and a human. The columns (b) and (c) show observed results of a multi-band image generated from the spectral sensitivity estimated by the proposed method. The column (d) shows those from the ordinary method. The column (e) shows those from the CIE standard function.

the CIE color function. In this result, human observations are very different from the objective images. This is because the CIE color function is very different from the spectral sensitivity of the target person, and thus, multi-band images could not be synthesized properly. This means that the spectral sensitivity of human retina is different one by one, and thus, we should estimate individual spectral sensitivity for realizing proper multiplex image projection. Although the proposed method cannot measure the spectral sensitivity completely, the measurement time is much shorter than the ordinary measurement method, and thus, our method is very efficient for realizing multiplex image projection.

6.4 Multiplex Image Projection for Human vs Human

Finally, we show multiplex image projection results for human vs human. In this experiment, the CIE standard function is used for the sensitivity of a human and the estimated sensitivity is used for the other human. The synthesized multi-band image is virtually observed by the CIE color function and the estimated spectral sensitivity respectively. Figure 12 shows images observed by the CIE color function and the target human. As shown in these results, the two humans observed different images, since their spectral sensitivities were different from each other. The results

(i) for target human (ii) for CIE

(a) Objective images.

(i) target human (ii) CIE

(b) Observed images.

Figure 12: Multiplex image projection for human vs human. (a) shows objective images for two humans, and (b) shows images observed by these two humans.

indicates that we can present different images to different human observers, if they have different spectral sensitivities.

7 CONCLUSIONS

In this paper, we proposed a new method for estimating the spectral sensitivity of human observers. In the proposed method, we represent the spectral sensitivity function by using GMM and linear combining of principal bases. As a result, the number of parameters for representing the spectral sensitivity was extremely decreased. Therefore, estimation time of spectral sensitivity is also decreased from 5 hours to 40 minutes. The experimental results show our proposed method is useful for realizing multiplex image projection by using a multi-band projector. We will consider more efficient and accurate estimation method in future work.

REFERENCES

INFITEC (2002). Infitec-excellence in 3d. http://www.infitec.net/.

Miao, L. and Qi, H. (2006). The design and evaluation of a generic method for generating mosaicked multispectral filter arrays. *IEEE Trans. on Image Processing*, 15(9):2780–2791.

Miyake, Y., Yokoyama, Y., Tsumura, N., Haneishi, H., Miyata, K., and Hayashi, J. (1999). Color imaging: Device-independent color. In *Color Hardcopy and Graphic Arts IV (Proc. SPIE)*, volume 3648, pages 218–225.

Miyazaki, D., Takahashi, K., Baba, M., Aoki, H., Furukawa, R., Aoyama, M., and Hiura, S. (2013). Mixing paints for generating metamerism art under 2 lights and 3 object colors. In *The IEEE International Conference on Computer Vision (ICCV) Workshops*.

Monno, Y., Kitao, T., Tanaka, M., and Okutomi, M. (2012). Optimal spectral sensitivity functions for a single-camera one-shot multispectral imaging system. In *Proc. IEEE International Conference on Image Processing (ICIP2012)*, pages 2137–2140.

Ng, D. and Allebach, J. P. (2006). A subspace matching color filter design methodology for a multispectral imaging system. *IEEE Trans. on Image Processing*, 15(9):2631–2643.

Nonoyama, M., Sakaue, F., and Sato, J. (2013). Multiplex image projection using multi-band projectors. In *The IEEE International Conference on Computer Vision (ICCV) Workshops*.

Park, J., Lee, M., Grossberg, M. D., and Nayar, S. K. (2007). Multispectral imaging using multiplexed illumination. In *Proc. of IEEE Int. Conf. on Computer Vision (ICCV)*, pages 1–8.

Parmar, M. and Reeves, S. J. (2010). Selection of optimal spectral sensitivity functions for color filter arrays. *IEEE Trans. on Image Processing*, 19(12):3190–3203.

Reynolds, D. (1992). *A Gaussian Mixture modeling Approach to Text-independent Speaker Identification*. PhD thesis, Georgia Institute of Technology.

Tominaga, S. (1999). Spectral imaging by a multichannel camera. *J. Electron. Imaging*, 8(4):332–341.