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Abstract. *A concept of image quality metamerism as an expansion of conventional metamerism defined in color science is introduced, and it is applied to segment similar color areas in a cultural property. The image quality metamerism can unify different image quality attributes based on an index showing the degree of image quality metamerism proposed. As a basic research step, the index is consisted of color and texture information and examined to investigate a cultural property. The property investigated is a pair of folding screen paintings that depict the thriving city of Kyoto designated as a nationally important cultural property in Japan. Gold-colored areas painted by using high granularity colorants compared with other color areas are evaluated based on the image quality metamerism index locally, then the index is visualized as a map showing the possibility of the image quality metamer to the reference pixel set in the same image. This visualization means a segmentation of areas where color is similar but texture is different. The experimental result showed that the proposed method was effective to show areas of gold color areas in the property.* © *2013 SPIE and IS&T [DOI: 10.1117/1.JEI.22.1.013029]*

1 Introduction

Museums possess a wide variety of artworks, historical materials and cultural properties. For example, there are over 220,000 items in the National Museum of Japanese History, and they are investigated to obtain historical and cultural information. Though scientific or chemical analysis techniques are used in the investigations, methods based on color imaging science and technology are getting one of important investigation techniques to preserve further degradations of the materials during the investigations.[1–3] In this paper, we introduce a concept of image quality metamerism that is an expansion of the metamerism defined in color science; two stimuli are observed as the same color under an illuminant, even those spectra that are different each other. Based on the concept of the image quality metamerism, an index showing degree of the image quality metamerism is defined to unify different attributes affecting the image quality, and it is applied to segment areas; similar color but different texture.

Recently digital imaging technology has promised to enhance activities in museums, and images with high quality that could provide benefits to the activities such as exhibitions, websites, databases, history research, education, and so on. Therefore, evaluation of image quality is important for improving images recording the cultural properties. Not only the improvement of image quality, but also the feature extraction from the images is an important technique for the activities because the images of the cultural properties have a lot of information including invisible ones.

In this research, a pair of folding screen paintings is focused on in the investigation based on the image quality metamerism. One of the purposes in the investigation is to find areas where more detailed investigation has to be required compared with other areas for cultural properties and historical materials. Our global research goal is to develop a method to find such areas based on imaging techniques for giving suggestions to researchers in the field of cultural properties and historical materials. To achieve the global goal, we have developed new image quality metamerism index and applied to the folding screen. Colors painted on the screen paintings are faded and observed as the same color, even those are painted by different colorants originally. Some parts in the folding screens are painted by using high granularity colorants such as gold color compared with other colorants. This difference in the granularity could tell us additional information to segment colored areas. Because the gold-colored areas have specific meanings to a history or culture from the property, the texture information is focused on together with the color information based on the concept of the image quality metamerism.

2 Related Work

It is well known that the total quality of images consists of image quality attributes such as graininess, sharpness, tone reproduction and color reproduction. Quantitative evaluation of image quality is required to improve and compare images acquired by different imaging systems. Although research has been done on the evaluation of image quality, it is

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still a challenging task. Dainty and Shaw investigated quality of images and discussed image quality assessment in the point of view of the information theory.[4] Image quality is determined by a variety of image quality attributes. Stultz and Zweig showed the relationship between sharpness and granularity for black and white samples.[5] Bartleson also showed the relationship between sharpness and graininess by using color prints and derived that total image quality is determined by a lower attribute.[6] Barten investigated perceived image quality from the effect of picture size and definition.[7] In the evaluation of image quality, structure information is applied based on the degree of degradation compared with reference image.[8–10]

In our previous research, it was assumed that imaging systems consisted of three devices: acquisition, recording, and display, and the imaging system was formulated as a linear model for evaluating and improving the total image quality with respect to the sharpness and graininess obtained by subjective experiments.[11,12] On the basis of the linear model, the subjective quality of degraded images was summarized into image quality maps showing relations between the sharpness and graininess. The image quality maps told us that the same total image quality was obtained from different combinations of the sharpness and graininess. Hasegawa et al. proposed a method for surface reconstruction of artist paintings to reproduce the appearance of a painting including color, surface texture, and glossiness.[13] Vangorp et al. showed an exploratory psychophysical experiment to study various influences on material discrimination in a realistic setting, and the resulting data set was analyzed using a wide range of statistical techniques.[14] Seetzen et al. showed a high dynamic range display systems. They described the design of both systems as well as the software issues that arise, and also discussed the advantages and disadvantages of the two designs and potential applications for both systems.[15] Matusik et al. proposed a complete system that uses appropriate inks and foils to print documents with a variety of material properties, and showed that the effectiveness of the proposed method with printed samples of a number of measured spatially varying bidirectional reflectance distribution functions (BRDFs).[16] Akao et al. characterized sheets of white paper using three BRDF model parameters estimated from the BRDF in the specular reflection plane.[17]

The metamerism is a phenomenon in which colors are matched under one illuminant but are different under other illuminants.[18] Research has been carried out relating to the metamerism.[19–23] Because color is also an important attribute in the application of the image quality, the metamerism defined in color science was applied to analyze historical materials to detect areas that have possibly been repainted in the past.[24,25] Many studies have addressed the estimation of spectral reflectance for a variety of materials.[26,27] Historical properties tend to be very fragile, and thus they need to be preserved from further degradation for research purposes. Because measurement methods of the spectral reflectance need a long measurement time, an estimation technique is introduced to obtain the spectral reflectance by using an estimation matrix including higher order terms of RGB signals determined by using the color chart.[28,29] Bochko et al. also proposed analysis methods used for developing imaging systems estimating the spectral reflectance. The system incorporated the estimation technique for the spectral reflectance.[30]

3 Acquisition of Cultural Property

The cultural property focused on in this research is a pair of folding screen paintings named "Scenes In and Around Kyoto" (Rekihaku "A" version, National Museum of Japanese History) designated as a nationally important cultural property in Japan. It is the oldest extant version of a genre of folding screen paintings that depict the thriving city of Kyoto in the four seasons. Clues in the scenes indicate that the painting was probably executed in 1525 based on the historical research results in the point of view in the buildings and people painted. In total, 1426 people and many residences, temples, and houses are painted, and it is an important historical material telling us about city scenes and people's life in Kyoto at that time.[31]

Due to the size that each screen measures (138×343 cm) and to ensure uniform lighting without distortions in the acquisition process, a large scaled flatbed type scanner has been selected (Scamera Museum II, Newly Corporation, Japan) that has RGB line sensor of 600 dpi resolution and 8 bits per pixel gray level. This scanner can change the angle of the line sensor head from 0 to 20 deg to acquire fine texture on the surface of scanning objects. The sensor head angle for the folding screen was set to 15 deg based on the test scans. Figure 1 shows the scanned images of the pair of the folding screen paintings.[32]

4 Image Quality Metamerism

Definition of the metamerism in color science can be expanded to provide a general form that is two responses obtained through the human visual system are matched but their objective stimuli are different. Furthermore, the

(a) (b)

Fig. 1 The scanned images of the paired folding screen paintings named as "Scenes In and Around Kyoto" (Rekihaku "A" version, National Museum of Japanese History) designated as national important cultural property of Japan. (a) Right panel and (b) left panel.

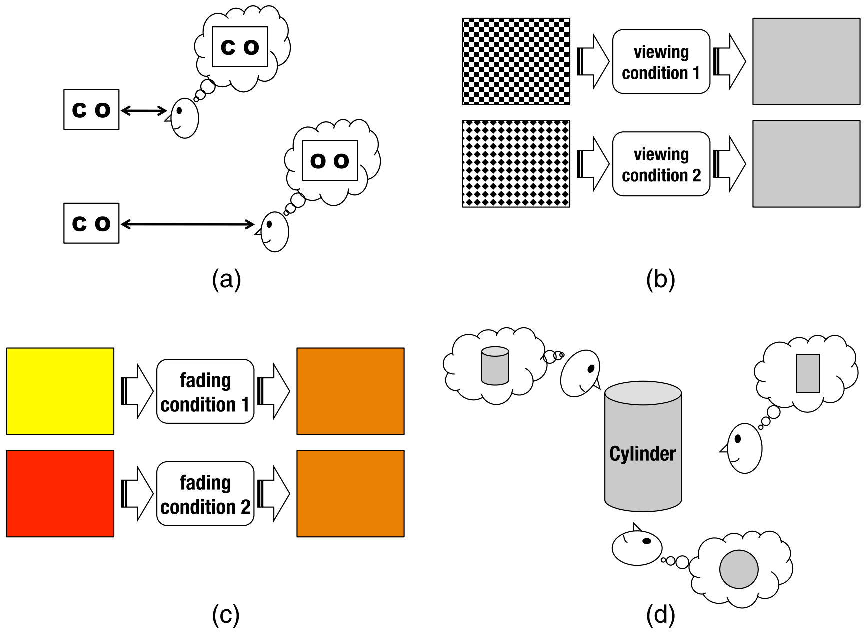


Fig. 2 Examples of different types of metamerism with respect to attribute in the image quality. (a) Sharpness metamerism; (b) graininess metamerism; (c) temporal metamerism; and (d) shape metamerism.

definition can be expanded to objective response space that two objective responses are matched even though two signals caused by the responses are not matched. In this general definition of the image quality metamerism, the responses are not limited to the visual response or the same image quality attributes. In our previous research, the total image quality was obtained from different combinations of the sharpness and graininess. In that case, the sharpness and graininess can be referred to as metamerism attributes.

In the conventional color metamerism, the response is perceived color and the stimulus is spectral reflectance. Because color is also affected by gloss property of object surface that is a function of incident and reflection angles, different objects can be observed as the same under a certain angle condition but different under another. This can be referred to as a glossiness metamerism. Figure 2 shows examples of different types of metamerism corresponding to each of image quality attributes. Figure 2(a) shows sharpness metamerism; that is two letters, C and O, can be recognized as different letters at near distance but those may be observed as the same letter at far distance. In the same way, graininess metamerism is also described as shown in Fig. 2(b). Two textures having different granularity may be observed as the same under different viewing conditions such as viewing distance. Colors will fade as time goes by. As a result, originally different colors may be matched after a certain time as shown in Fig. 2(c). This phenomenon can be referred to as temporal metamerism. Shape of objects is also depending on viewing conditions as shown in Fig. 2(d). This dependency of shape recognition is described in term of the metamerism. If each metamer caused by different image quality attributes can be combined, the framework of unified image quality could be established.

In the case of image quality, if two images have the same image quality but the images are different objectively, the images are the image quality metamer each other. Figure 3 shows a schematic diagram showing the image quality metamerism. An image can be represented as a vector in a signal space and it can be projected onto a response space. This response space is not limited to the human visual system. The projected vector is a fundamental attribute vector and the rest is a vector for image quality metameric black. The image quality metamerism can be used not only to compare different images but also to evaluate in one image locally to extract local image quality metamer as a feature extraction for classification. The benefit of the image quality metamerism is that different attributes affecting the total image quality could be unified to build an index for evaluating the total quality of images obtained by the different imaging systems and observed under different viewing conditions. This is our global goal, and as a basic step to achieve it only the color and texture information are unified in terms of the image quality metamerism in this paper.

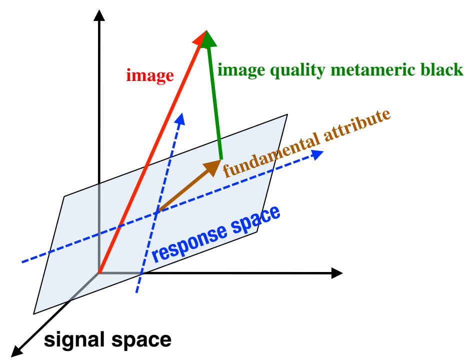


Fig. 3 Scematic diagram showing the image quality metamer.

5 Index for Image Quality Metamerism

In addition to color information, texture of the material surface is employed in the framework of the image quality metamerism in this research because it is difficult to segment adjoining similar color areas based on the color information only for faded colors in authentic cultural property. The texture information on the surface gives us additional and effective information to segment gold-colored areas from brownish-colored areas because the gold-colored areas are painted by using higher granularity colorant compared with brownish-colored areas. Therefore in this research, the index to evaluate the image quality metamerism is calculated from the spectra, color, and texture attributes. The color and spectra are evaluated by using the color difference $\Delta E(x, y)$ in CIELAB and the correlation coefficient $C(x, y)$ in the spectral domain. Both are calculated pixel by pixel between the test and reference pixel from Eqs. (1) and (2), respectively. Although more advanced color difference formulas are investigated nowadays,[33,34] we have started the simplest formula to confirm the concept of the image quality metamerism.

$$\Delta E(x,y) = \sqrt{[L^*(x_r,y_r) - L^*(x,y)]^2 + [a^*(x_r,y_r) - a^*(x,y)]^2 + [b^*(x_r,y_r) - b^*(x,y)]^2}, \quad (1)$$

$$C(x,y) = \frac{\sum_{j=1}^{N_\lambda} [f(x_r,y_r,\lambda_j) - \bar{f}_r(x_r,y_r)][f(x,y,\lambda_j) - \bar{f}(x,y)]}{\sqrt{\sum_{j=1}^{N_\lambda} [f(x_r,y_r,\lambda_j) - \bar{f}_r(x_r,y_r)]^2}\sqrt{\sum_{j=1}^{N_\lambda} [f(x,y,\lambda_j) - \bar{f}(x,y)]^2}}. \quad (2)$$

In the equations, $f(x, y, \lambda)$ is estimated spectral reflectance, N_λ is the number of the spectral dimension where $N_\lambda = 401$, (x, y) and (x_r, y_r) are pixel position to be tested and reference pixel position, respectively. In this research, the reference pixel is placed arbitrary in the image in advance. The purpose of the metamer detection is to segment gold-colored areas from brownish-colored area as an initial investigation of cultural property, the reference pixel is, therefore, placed in a brown-colored area for the folding screens. $L^*(x, y)$, $a^*(x, y)$, and $b^*(x, y)$ correspond to CIELAB coordinates for CIE D65 standard illuminant. From the definition of the metamerism, if $C(x, y)$ is 1.0, the test pixel at the position (x, y) is referred to as the same and not a metamer to the reference pixel at (x_r, y_r) in the same image. $G(x, y)$ shows the difference in the granularity between the test and reference pixel calculated by Eq. (3). In Eq. (3), $f(x, y)$ shows 8 bits digital image, and $\bar{f}$ shows mean value in the $D \times D$ pixels area. $G(x, y)$ calculated by Eq. (3) is averaged for R, G, and B color channel. It is assumed that graininess observed though the human visual system in brown and gold-colored areas would be matched if viewing distance is long enough. In this research, fine texture information on the surface of the folding screens that could not be recognized by the human visual system is used in the segmentation of the gold-colored area. To obtain such fine texture information, a granularity parameter is calculated from a small local area. Because the degree of granularity is dependent on size of the local area, changes of the local granularity are used in the granularity parameter. Based on this assumption, the difference of the local standard deviation is calculated from $D \times D$ pixels area around the reference and the test pixel, where D is 3, 5, 7, and 9 pixels as follows:

$$G(x,y) = \sum_{D=3,5,7,9} \left\{ \sqrt{\frac{1}{D^2-1}\sum_{j=1}^{D}\sum_{i=1}^{D}[f(x_{ri},y_{rj}) - \bar{f}_r]^2} - \sqrt{\frac{1}{D^2-1}\sum_{j=1}^{D}\sum_{i=1}^{D}[f(x_i,y_j) - \bar{f}]^2} \right\}, \quad (3)$$

where $\Delta E(x, y)$, $C(x, y)$, and $G(x, y)$ are calculated as the first parameters, which have their own ranges of value. The image quality metamerism index $M(x, y)$ is calculated from the second parameters $p\Delta E(x, y)$, $pC(x, y)$, and $pG(x, y)$ having the same range of 0 to 1, and showing how each attribute influence the image quality metamerism. The second parameters are calculated from Eqs. (4) to (6), and finally the index $M(x, y)$ is calculated from Eq. (7) as a joint probability of the second parameters, which shows where the area has high potential as the image quality metamer. In Eqs. (4) to (6), $\sigma_{\Delta E}$, σ_C, and σ_G are control parameters to determine sensitivity in the image quality metamerism, and a methodology to determine the control parameters is described in the next section.

$$p\Delta E(x,y) = \exp\left[-\frac{\Delta E(x,y)^2}{2\sigma_{\Delta E}^2}\right], \quad (4)$$

$$pC(x,y) = 1 - \exp\left\{-\frac{[C(x,y)-1]^2}{2\sigma_C^2}\right\}, \quad (5)$$

$$pG(x,y) = 1 - \exp\left[-\frac{G(x,y)^2}{2\sigma_G^2}\right], \quad (6)$$

$$M(x,y) = p\Delta E(x,y)pC(x,y)pG(x,y). \quad (7)$$

6 Detection of Image Quality Metamer

The control parameters $\sigma_{\Delta E}$ and σ_C in Eqs. (4) and (5) are determined by using metamerism test charts as shown in Fig. 4. On the other hand, the control parameter σ_G in Eq. (6) is determined adaptively from local standard deviation calculated in $D \times D$ pixels around the reference pixel, where D is 3, 5, 7, and 9 pixels. Figure 4 is an image taken by a digital camera (DP2 Merrill, SIGMA Corporation, Japan) under a tungsten illuminant, and the spectral reflectance is estimated for each pixel in the image. In Fig. 4, there are two sets of metamerism test patches that are namely V1 and V2 for violet color set, and B1 to B4 for blue color set. The Macbeth color checker in Fig. 4 is used to estimate the spectral reflectance and to check a performance of the proposed method. Figure 5 shows measured spectral reflectance for all of metamerism test patches. In this research, spectral reflectance is measured by using a spectroradiometer

Fig. 4 Metamerism test charts used to determine the control parameters $\sigma_{\Delta E}$ and σ_C.

(Specbos 1201, JETI Technische Instrumente GmbH, Germany) in 1 nm steps from 380 to 780 nm. Table 1 shows correlation coefficients between the spectral reflectance of the metamerism test patches, which are used to determine the control parameter σ_C.

The parameter $p\Delta E(x, y)$ is used to pick metamer candidate pixels up in the folding screen image. Because the purpose of the initial investigation is to find questionable areas, it requires detailed investigation, so the control parameter $\sigma_{\Delta E}$ is adjusted to cover widely enough the metamerism patches. The role of the parameter $pC(x, y)$ is to reject pixels from the metamer candidates that have the same or very similar spectral reflectance to the reference pixel. The similarity is adjusted by the control parameter σ_C determined by using the metamerism patches with consideration of the

Table 1 Correlation coefficients between metamerism color patches in Fig. 4.

(a) Violet patches

Violet	V1	V2
V1	1.000	0.892
V2	—	1.000

(b) Blue patches

Blue	B1	B2	B3	B4
B1	1.000	0.970	0.974	0.917
B2	—	1.000	0.995	0.958
B3	—	—	1.000	0.957
B4	—	—	—	1.000

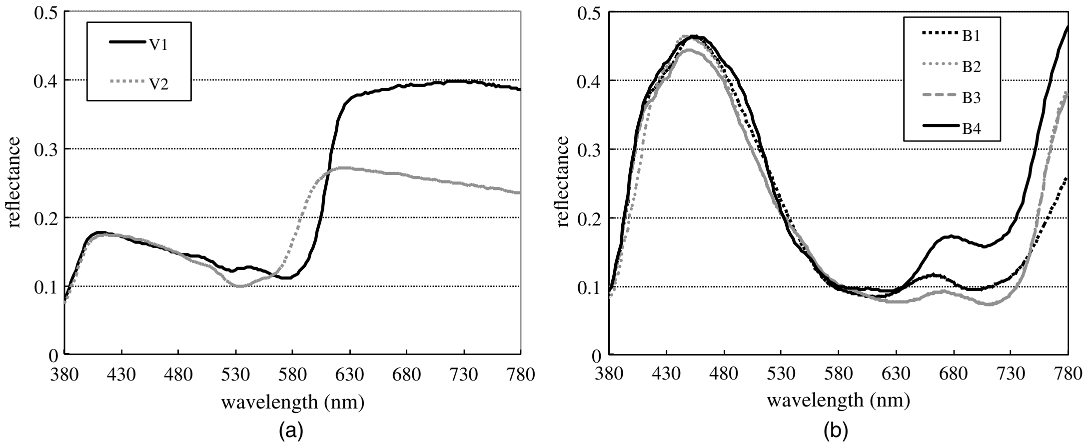


Fig. 5 Measured spectral reflectance of the metamerism patches in Fig. 4. (a) Violet patches and (b) blue patches.

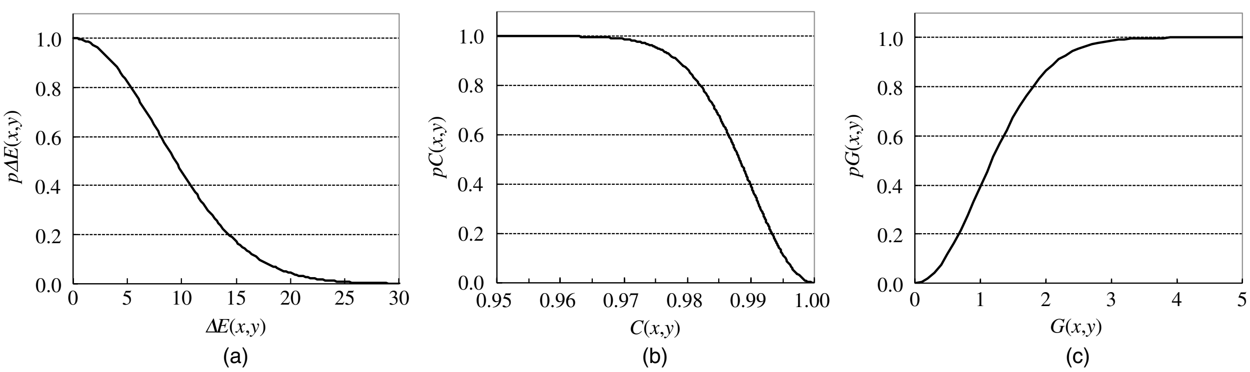


Fig. 6 Relationships between the first and second parameters to be used for the index. (a) For color attribute; (b) for spectra attribute; and (c) for granularity attribute. σ_G is determined adaptively in the detection.

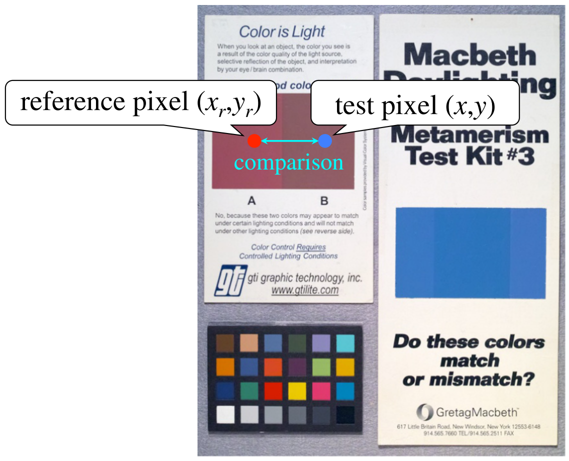


Fig. 7 A reference pixel is placed arbitrary in the image. Test pixel in the same image is scanned from top-left to bottom-right direction.

correlation coefficients in Table 1. Figure 6 shows resultant relationships between the first and second parameters, where the control parameters are $\sigma_{\Delta E} = 8.0$ in Fig. 6(a) and $\sigma_C = 0.01$ in 6(b). Because the control parameter σ_G is determined adaptively in the metamer detection, Fig. 6(c) illustrates the relationship for the granularity attribute where $\sigma_G = 1.0$ as an example.

As a performance test of the proposed method, ability to detect color metamer is confirmed by using the metamerism test charts shown in Fig. 4. The reference pixel is placed in each of metamerism patches as shown in Fig. 7. The test pixel in the same image is scanned from top-left to bottom-right direction in pixel by pixel process. Figure 8 shows results of the color metamer detection represented as a grayscale map, where $pG(x, y) = 1.0$ in Eq. (7). All of the grayscale maps in this paper are applied a gamma transformation by $\gamma = 1/2.2$ for improving visualization result, and the target pixel is indicated as a red square dot. In the grayscale maps, brighter area shows higher possibility of the metamerism to the reference pixel. In Fig. 8(a), the reference pixel is placed in V1 patch, therefore V2 patch

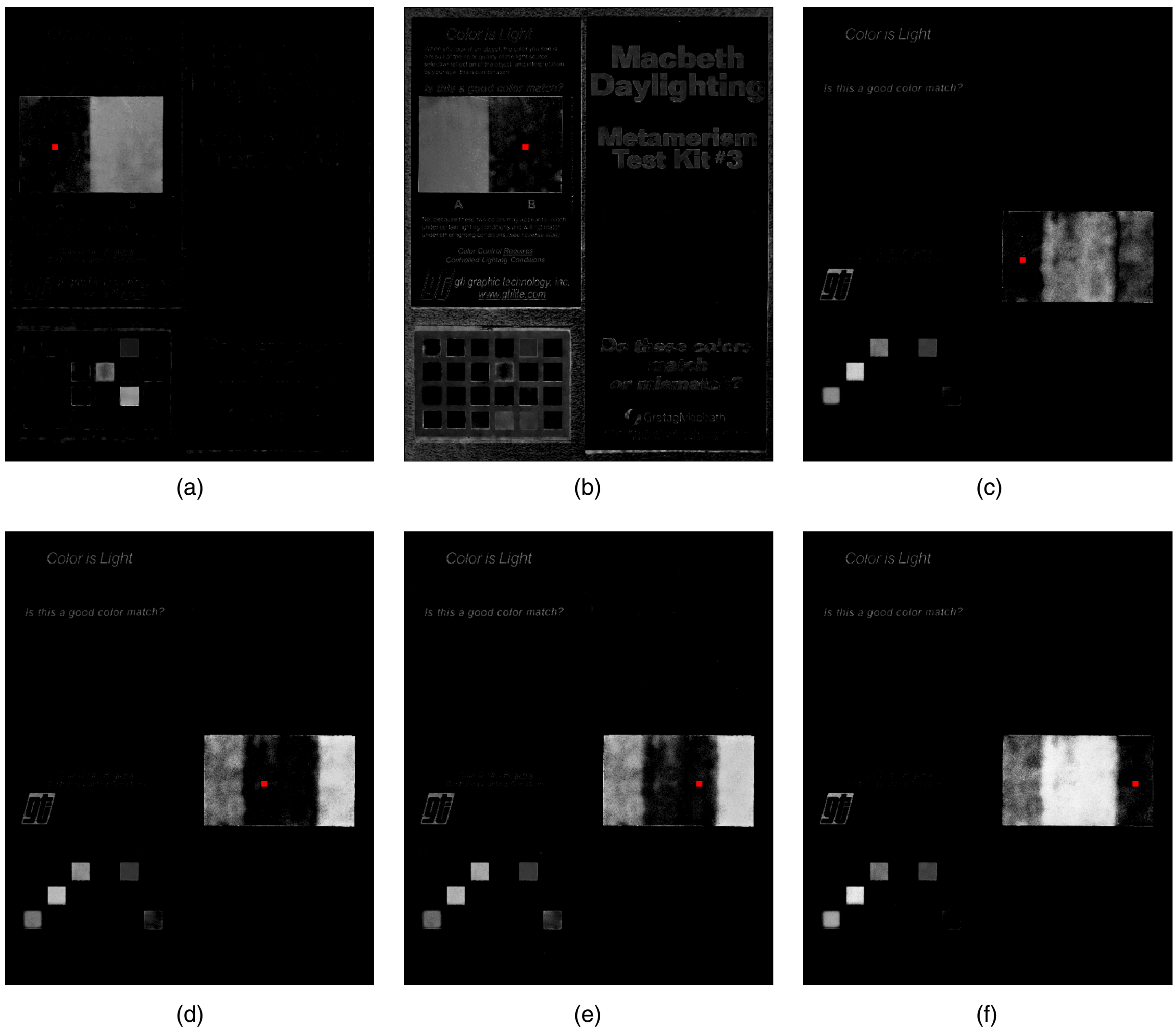


Fig. 8 Result of performance test on color metamerism, where $\sigma_{\Delta E} = 8.0$, $\sigma_C = 0.01$. The reference pixel is set in each of the metamerism patches. (a) V1; (b) V2; (c) B1; (d) B2; (e) B3; and (f) B4.

is indicated as higher possibility of the color metamer to V1 patch. In other patches, the results show appropriate performance to detect the color metamerism areas. To illustrate effect of control parameters, σ_C is changed to $\sigma_C = 0.001$ as shown in Fig. 9. The color metamers are detected more strictly compared with $\sigma_C = 0.01$.

Figure 10(a) shows color charts scanned with the folding screens, which consisted of the Macbeth color checker used to estimate the spectral reflectance of the folding screens and hand-made colorants chart created by a researcher. Figure 10(b) shows a result of the metamer detection.

The result of the detection for the folding screens is summarized in Fig. 11. The gold color is mainly used for cloud parts in the folding screen as shown in Fig. 11(a), and it is faded to seem brownish in color. As a result, borders between the gold and brownish colors are not clear. Figure 11(b) shows resultant grayscale map for $M(x, y)$ representing the degree of the image quality metamer to the reference pixel (x_r, y_r) marked by a red squared dot set in the brownish color area. The cloud part of the folding screens is indicated as higher metamerism possibility. Figure 11(c) shows $M(x, y)$ map without consideration of the granularity parameter that includes too many metamer pixels meaning false detections. This result is corresponding to expected detection based on the observation of the real folding screens. However, it is also necessary to improve the definition for each attribute and to include other image quality attributes that are not used in this paper.

Figure 11(d)–11(f) shows grayscale maps for $p\Delta E(x, y)$, $pC(x, y)$, and $pG(x, y)$ corresponding to the possibility of metamer in the sense of the color difference, spectral reflectance, and granularity to the reference pixel position. Those figures show the difficulty in distinguishing the difference between the gold and brownish colored parts by using only each of the image quality attributes, which supports the effectiveness for the feature extraction with respect to the image quality metamerism. Figure 12 shows another example of the metamer detection for the folding screen. As in Fig. 11(b), the cloud part painted in gold color is indicated as higher metamerism region in Fig. 12(b).

The detection results have been evaluated as reasonable and proper by an expert of the folding screen. The result shown in Fig. 11(b) could be obtained by visual observations; however, it is hard for the result shown in Fig. 12(b). Therefore, the method proposed in this paper can be helpful to investigate areas painted by the same or not same colorants in the folding screen. The expert also emphasized that this method can indicate the difference of colorants used but it does not indicate that the colorant is gold. To conclude it, chemical or scientific investigation is required.

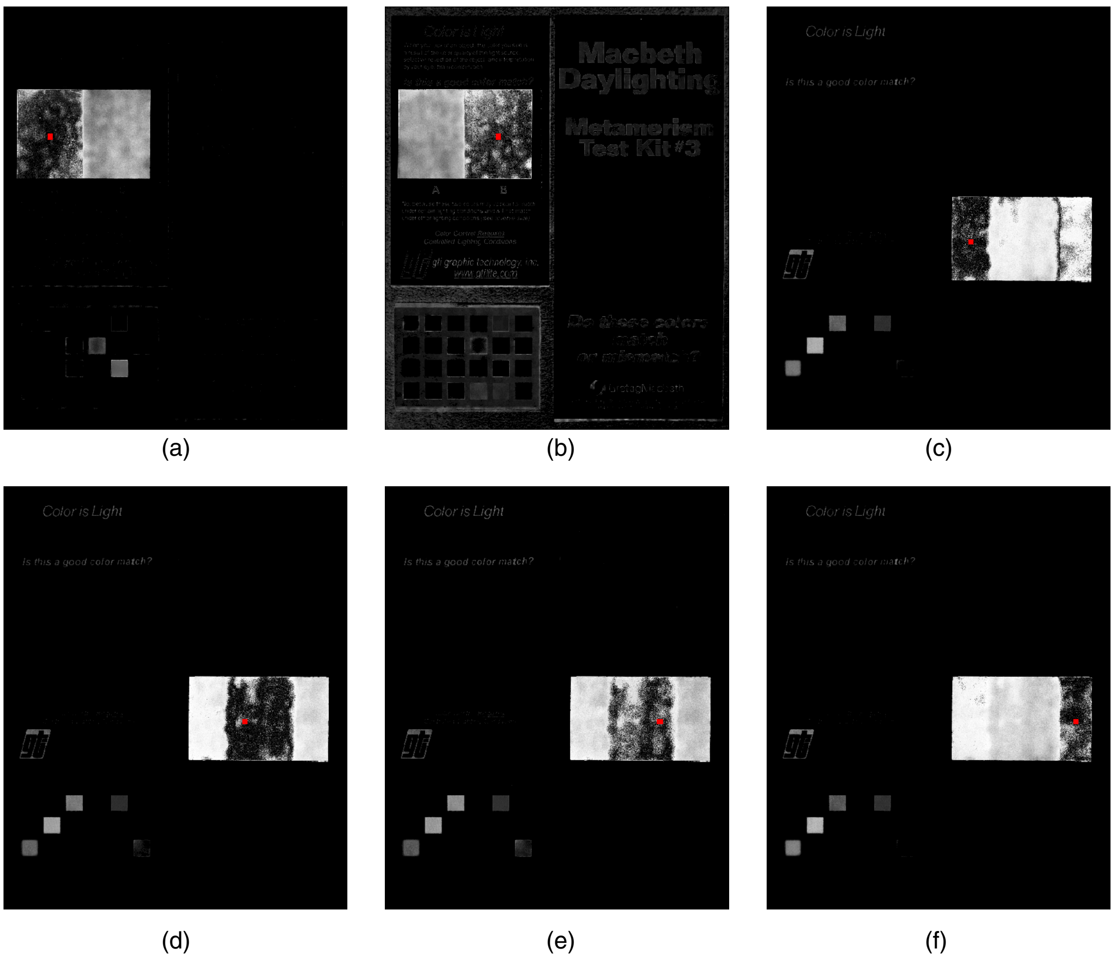


Fig. 9 Result of performance test on color metamerism, where $\sigma_{\Delta E} = 8.0$ and $\sigma_C = 0.001$. The reference pixel is set in each of the metamerism patches. (a) V1; (b) V2; (c) B1; (d) B2; (e) B3; and (f) B4.

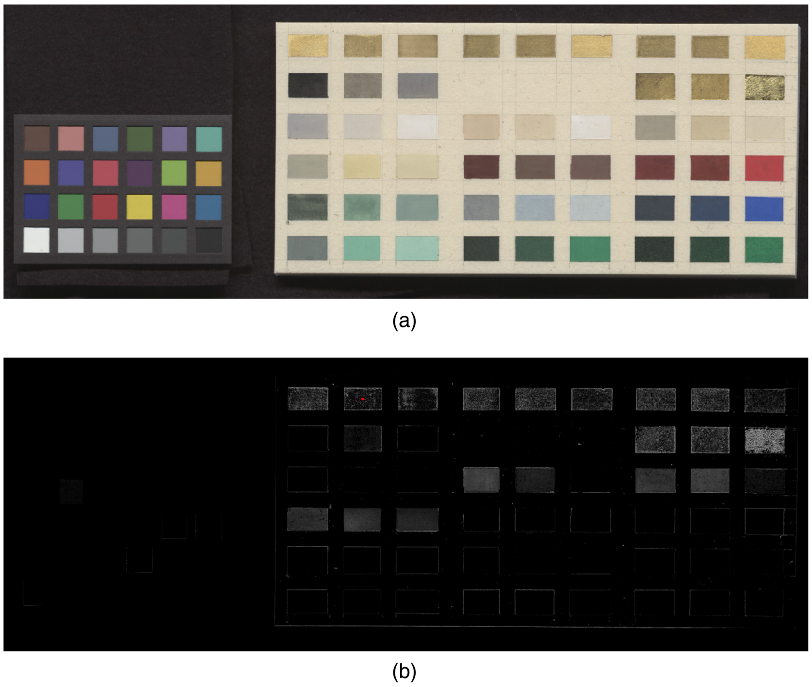


Fig. 10 Color charts scanned with the folding screens, and its $M(x, y)$ map. (a) Scanned chart image, (b) $M(x, y)$ map.

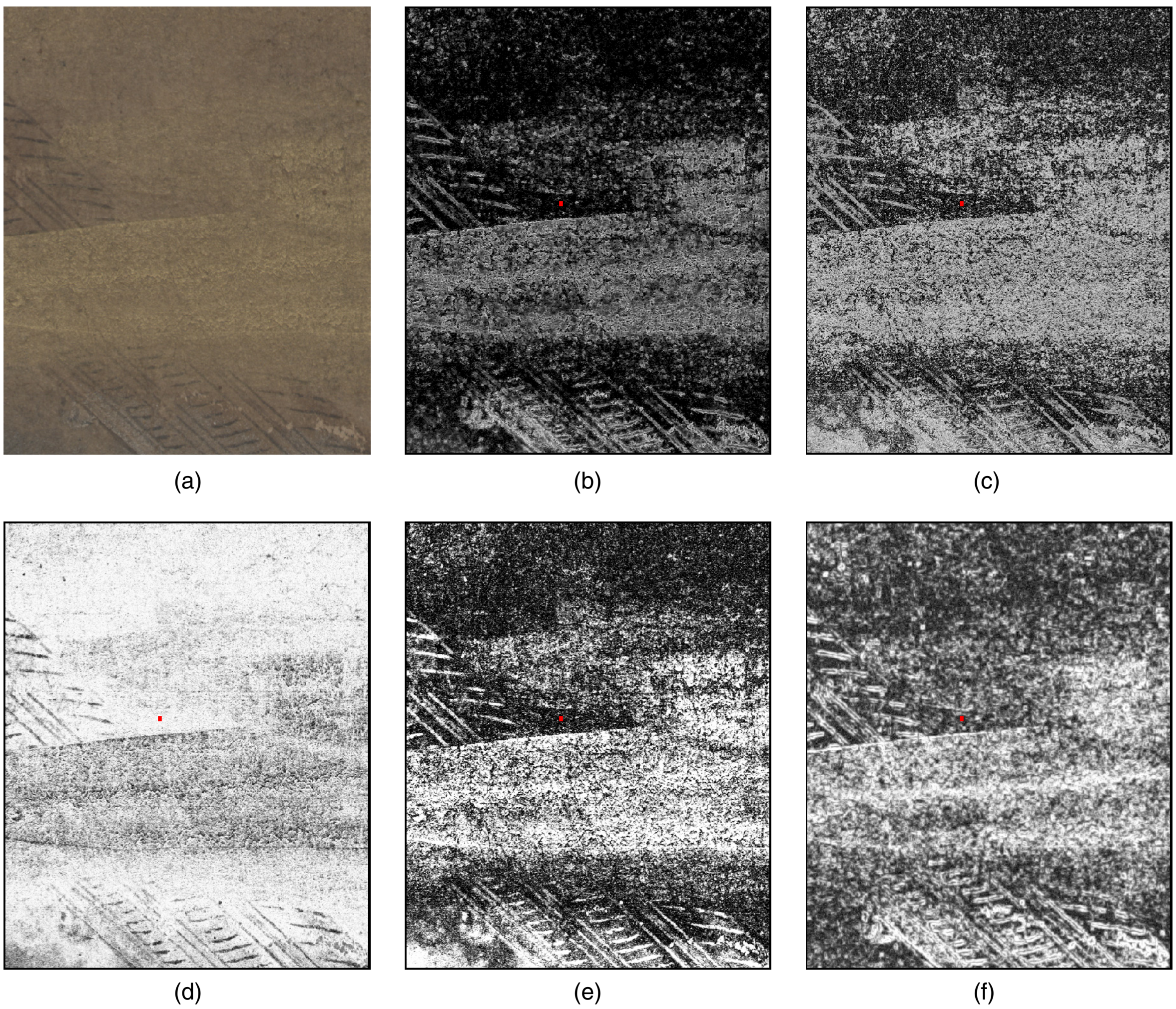
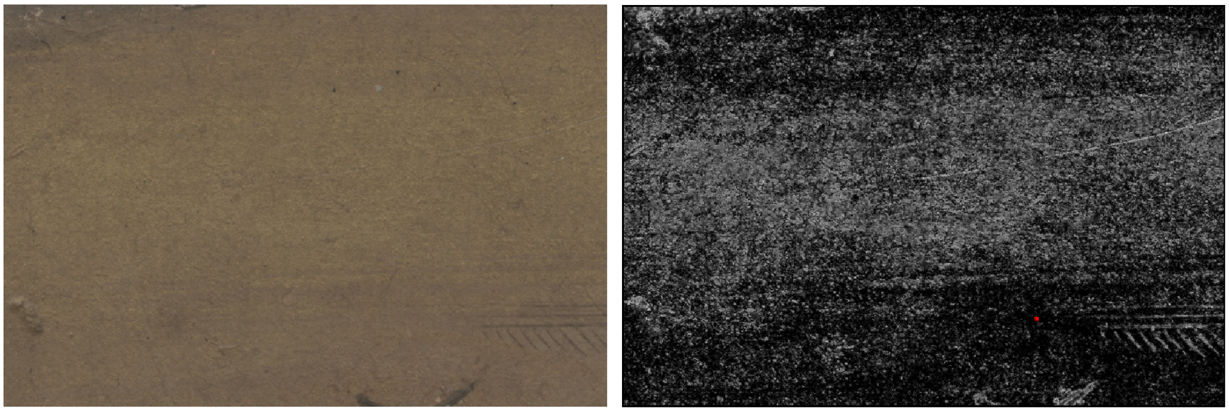


Fig. 11 The scanned image, grayscale maps for $M(x, y)$, $p\Delta E(x, y)$, $pC(x, y)$, and $pG(x, y)$ to the reference pixel in the folding screens. (a) scanned image; (b) $M(x, y)$ map; (c) $M(x, y)$ map without granularity; (d) $p\Delta E(x, y)$ map; (e) $pC(x, y)$ map; and (f) $pG(x, y)$ map.



(a) (b)

Fig. 12 Another example of the metamer detection for the folding screen. (a) Scanned image of the folding screen and (b) $M(x,y)$ map.

7 Conclusion

One of the difficulties in the evaluation of image quality is how to determine an index that can evaluate the total image quality. In this research, an index is proposed based on the expanded definition of the metamerism to unify different attributes affecting the total image quality, and it is applied to segment similar colored areas in a cultural property. The metamerism is originally a phenomenon defined in color science, however, the definition can be expanded not only for the color but also image quality. There is a word, "paramers," meaning different stimuli that produce approximately the same colors under specified viewing conditions.[35,36] Our target in the detection is metamers that are perfectly matched under distinct viewing conditions. However, in the investigation of cultural properties, it is more effective to show the degree of metamerism than to separate whether it is a metamer or not. Therefore, our work can be addressed as one of the proposals of the degree of metamerism. If the index to evaluate the image quality metamerism can be calculated locally in the image as shown in this paper, local image quality metamers can be detected, and it could be applied to develop an image quality-based image segmentation method. The measures used in this paper to evaluate color and spectral attributes are commonly used in the field of color science, however, the original measure to evaluate local granularity is defined and applied to investigate the cultural property. Only the granularity is included to the color metamerism in this paper, however, the concept can be expanded to other image quality attributes such as glossiness, sharpness, and viewing conditions. In the investigation of cultural properties and historical materials, generally speaking, color information is the most important. Therefore, color and spectrum have a priority than the texture in this paper. This priority can be switched corresponding to other research purposes in the investigations. For example, if a researcher knows the texture distribution of similar colors, metamer candidates can be detected based on the texture at first, then color and spectrum are evaluated to detect image quality metamers more accurately.

The proposed method is effective for an initial stage of investigations for the cultural properties as a nondestructive investigation technique. The experimental results showed that the accuracy of the detection of the image quality metamer was required to improve more for actual use in the investigations, but it could offer more convenience as the first investigation in the investigation workflow for the cultural properties. After the initial investigation by the proposed method, more detailed investigation or measurement methods could be applied in questionable areas intensively. It is hard to conclude whether the detection by the proposed technique is correct or not because techniques with scientific analyses are necessary to conclude the correctness of the detection results. Therefore, further experiments are required and examined as a future work.

It is necessary to evaluate the image quality based on the subjective evaluation experiment, however, it is hard to use the authentic cultural property in the subjective experiment for preservation reasons. In this paper, the assumption is employed that graininess would be matched in far distances but would be different objectively on the surface of the object. This difference could not be observed by the human visual system but could be detected by the objective measure such as that proposed in this paper.

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References

1. J. Y. Hardeberg et al., "Spectral imaging in multimedia," in *Proc. CIM'98, Colour Imaging in Multimedia*, Derby, UK, pp. 75–89 (1998).
2. F. König and W. Praefcke, "Practice of multispectral image acquisition," *Proc. SPIE* **3409**, 34–41 (1998).
3. N. Tsumura et al., "Limitation of color samples for spectral estimation from sensor responses in fine art painting," *Opt. Rev.* **6**(1), 57–61 (1999).
4. K. F. Stultz and H. J. Zweig, "Relation between graininess and granularity for black and white samples with nonuniform granularity spectra," *J. Opt. Soc. America* **49**(7), 693–702 (1959).
5. J. C. Dainty and R. Shaw, *Image Science*, Chapter 3–10, Academic Press, New York (1974).
6. C. J. Bartleson, "The combined influence of sharpness and graininess on the quality of colour prints," *J. Photogr. Sci.* **30**(2), 33–38 (1982).
7. P. G. J. Barten, "The effect of picture size and definition on perceived image quality," *IEEE Trans. Electron. Dev.* **36**(9), 1865–1869 (1989).
8. P. Ndajah et al., "SSIM image quality metric for denoised images," in *Proc. 3rd WSEAS Int. Conf. on Visualization, Imaging and Simulation*, pp. 53–58, World Scientific and Engineering Academy and Society, Stevens Point, Wisconsin (2010).
9. Z. Wang and A. C. Bovik, "A universal image quality index," *IEEE Signal Process. Lett.* **9**(3), 81–84 (2002).

10. Z. Wang et al., "Image quality assessment: From error visibility to structural similarity," *IEEE Trans. Image Process.* **13**(4), 600–612 (2004).
11. K. Miyata et al., "Improvement of sharpness and graininess for color image by computer processing and its image quality measurement," in *Proc. IS&T PICS Conf. 99*, pp. 236–240, Society for Imaging Science & Technology, Savannah, Georgia (1999).
12. K. Miyata and Y. Miyake, "Evaluation of sharpness and graininess in digital imaging system and its application to improve total image quality," *Proc. SPIE* **4300**, 290–299 (2001).
13. T. Hasegawa et al., "Photometric approach to surface reconstruction of artist paintings," *J. Electron. Imaging* **20**(1), 013006 (2011).
14. P. Vangorp, J. Laurijssen, and P. Dutre, "The influence of shape on the perception of material reflectance," *ACM Trans. Graph.* **26**(3), 77: 1–10 (2007).
15. H. Seetzen et al., "High dynamic range display systems," *ACM Trans. Graphics* **23**(3), 760–768 (2004).
16. W. Matusik et al., "Printing spatially-varying reflectance," *ACM Trans. Graph.* **28**(5), 1–9 (2009).
17. Y. Akao et al., "Characterization of white paper sheets by BRDF model parameters estimated in the specular reflection plane," *J. Imag. Sci. Technol.* **54**(6), 060503 (2010).
18. G. Wyszecki and W. S. Stiles, "Color Science," 2nd ed., p. 180, John & Wiley (1982).
19. I. Nimeroff and J. A. Yurow, "Degree of metamerism," *J. Opt. Soc. America* **55**(2), 185–190 (1965).
20. F. H. Imai, M. R. Rosen, and R. S. Berns, "Comparative study of metrics for spectral match quality," in *Proc. European Conference on Colour Graphics, Imaging, and Vision*, pp. 492–496, Society for Imaging Science & Technology, Poitiers, France (2002).
21. J. A. S. Viggiano, "The comparison of radiance ratio spectra: assessing a model's "goodness of fit"," in *Proc. Advanced Printing of Conference Summaries: SPSE's 43rd Annual Conference*, pp. 222–225, Society of Photographic Scientists and Engineers, Rochester, NY (1990).
22. J. A. S. Viggiano, "A perception-referenced method for comparison of radiance ratio spectra and its application as an index of metamerism," in *Proc. AIC 2001*, pp. 701–704, International Colour Association, Rochester, NY (2001).
23. H. Pauli, "Proposed extension of the CIE recommendation on uniform color spaces, color difference equations, and metric color terms," *J. Opt. Soc. America* **66**(8), 866–876 (1976).
24. K. Miyata et al., "A technique for detecting metameric color areas for the investigation of historical materials," *Proc. SPIE* **6062**, 60620L (2006).
25. K. Miyata et al., "Application of spectral information to investigate historical materials-detection of metameric color area in icon images," in *Proc. 14th Scandinavian Conference SCIA*, pp. 369–378, Scandinavian Conferences on Image Analysis, Joensuu, Finland (2005).
26. M. Nishibori, N. Tsumura, and Y. Miyake, "Why multispectral imaging in medicine?" *J. Imag. Sci. Technol.* **48**(2), 125–129 (2004).
27. H. Laamanen et al., "Imaging spectrograph based spectral imaging system," in *Proc. European Conference on Colour in Graphics, Imaging and Vision*, pp. 427–430, Society for Imaging Science & Technology, Aachen, Germany (2004).
28. N. Tsumura, H. Haneishi, and Y. Miyake, "Estimation of spectral reflectance from multi-band images by multiple regression analysis," *Jpn. J. Opt.* **27**(7), 384–391 (1998) (In Japanese).
29. P. Stigell, K. Miyata, and M. Hauta-Kasari, "Wiener estimation method in estimating of spectral reflectance from RGB images," *Pattern Recogn. Image Anal.* **17**(2), 233–242 (2007).
30. V. Bochko, N. Tsumura, and Y. Miyake, "A spectral color imaging system for estimating spectral reflectance of paint," *J. Imag. Sci. Technol.* **51**(1), 70–78 (2007).
31. K. Miyata, U. Oyabu, and M. Kojima, "Museum as an integrated imaging device -Visualization of ancient Kyoto cityscape from folding screen artifact," *Proc. SPIE* **8291**, 82911B (2012).
32. K. Miyata and N. Tsumura, "Detection of image quality metamers based on the metric for unified image quality," *Proc. SPIE* **8293**, 829310 (2012).
33. M. Melgosa, "Testing CIELAB-based color-difference formulas," *Color Res. Appl.* **25**(1), 49–55 (2000).
34. H. Wang et al., "Evaluation of colour-difference formulae for different colour-difference magnitudes," *Color Res. Appl.* **37**(5), 316–325 (2012).
35. R. Berns, *Billmeyer and Salzman's: Principle of Color Technology*, 3rd ed., p. 128, Wiley-Interscience, New York (2000).
36. P. Urban, "Distributions of paramers and paramer mismatch gamuts," in *Proc. Color Imaging Conference*, pp. 143–148, Society for Imaging Science & Technology, Albuquerque, New Mexico (2009).

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