Journal of Imaging Science and Technology® 61(4): 040401-1–040401-8, 2017.

PuRet: Material Appearance Enhancement Considering Pupil and Retina Behaviors

Midori Tanaka
College of Liberal Arts and Sciences, Chiba University, Chiba, Japan
E-mail: midori@chiba-u.jp

Ryusuke Arai and Takahiko Horiuchi▲
Department of Imaging Sciences, Chiba University, Chiba, Japan

Abstract. *In addition to colors and shapes, factors of material appearance such as glossiness, translucency, and roughness are important for reproducing the realistic feeling of images. In general, these perceptual qualities are often degraded when reproduced as digital color images. Therefore, it is useful to enhance and reproduce them. In this article, the authors propose a material appearance enhancement algorithm for digital color images. First, they focus on the change of pupil behaviors, which is the first of the early vision systems to recognize visual information. According to their psychophysiological measurement of pupil size during material observation, they find that careful observation of surface appearance causes the pupil size to contract further. Next, they reflect this property in the retinal response, which is the next system in early vision. Then, they construct a material appearance enhancement algorithm named "PuRet" based on these physiological models of pupil and retina. By applying the PuRet algorithm to digital color test images, they confirm that perceived material appearance, including glossiness, transparency, and roughness, in the images is enhanced by using their PuRet algorithm. Furthermore, they show possibilities to apply their algorithm to a material appearance management system that could produce equivalent appearance qualities among different imaging devices by adjusting one parameter of PuRet.*

[DOI: 10.2352/J.ImagingSci.Technol.2017.61.4.040401]

INTRODUCTION

Imaging technology for reproducing appropriate material appearance factors such as glossiness, translucency, and roughness has recently become desirable in the color-imaging industry. We are faced with a major problem in that the material appearance obtained from actual objects and their rendered images among several devices are not equivalent. In our previous study, we clarified the difference in the perceptual qualities of material appearance obtained from 34 actual objects, including ten material categories (stone, wood, metal, paper, fabric, plastic, leather, glass, ceramic, and rubber), and their rendered images with different reproductions displayed on a monitor by conducting psychophysical experiments.[1] The results showed that the reproduced images of some materials affected their perceptual qualities.

Color management technologies have enabled us to realize true-color reproduction using different color-imaging devices. High-dynamic-range (HDR) imaging technologies have realized realistic image reproduction under HDR scenes. The development of high-resolution display devices has enabled us to realize precise image reproduction. However, using these current imaging technologies, it is still difficult to accurately represent the material appearance of real-world objects on a display device. In our everyday life, there are many experiences that result in changes to the impression of real-world objects by displaying them on a monitor. In Ref. 2, one of the present authors advocated that it was important to newly develop "shitsukan" (material appearance and its subjective value) management technology to control a human's sensibility for material perception.

Research on the reproduction of the appearance of the surface of a material has been performed in the fields of engineering, vision and neuroscience, psychophysics, and so on. In particular, in recent years, realistic approaches to treating material appearance with high fidelity or high favorability are remarkable for implementation in industrial applications. One of the approaches is to contrive a new measurement or to generate a system for representing material appearance. For example, in Ref. 3, a printing technology for gold-foil-like metallic color was developed. An imaging technology for treating material appearance by digitizing the actual material appearance information such as glossiness and solidity for printing was developed. However, it might take a long time to release this to consumers due to several restrictions such as versatility and cost. Another approach is to improve the image quality in image processing. Many imaging technologies such as image quality improvement, image compression, and the tone mapping for HDR scenes have flourished by using image-processing algorithms to consider human vision properties. For example, in Ref. 4, an algorithm was developed to improve the visibility and image quality by local contrast enhancement based on the Retinex theory.[5] However, although these techniques can improve global image quality, nothing is mentioned about improving the appearance of individual materials.

▲ IS&T Member.

Received Feb. 24, 2017; accepted for publication May 31, 2017; published online June 30, 2017. Associate Editor: Marius Pedersen.
1062-3701/2017/61(4)/040401/8/$25.00

In the research field of psychophysics, which is about material appearance recognition, the relationship between the image information and the perceptual material appearance has gradually become clearer. Some studies have investigated the mechanism of how material sensations are processed in the human brain. Motoyoshi et al. reported that adjustment of the luminance histogram could control the perceptual glossiness obtained from images.[6] Boyadzhiev et al. also indicated the possibility of image-based material editing by manipulating the frequency information of images.[7] However, these studies on the control of material appearance mentioned only specific materials and specific material appearance, and did not assume the general scene including multiple materials with several material appearances.

In this article, to enhance the material appearance in a general scene including many different objects with different surface appearances, we focus on the change in pupil behavior, which is the first early vision system to recognize visual information. Changes in pupil diameter are known to be caused by the brightness of the surrounding illumination environment. In recent studies, it has been reported that human internal conditions such as interest,[8,9,17,18] memory,[8–12] and stress[13] can affect the pupil diameter. We first check the effects of careful observation of the surface appearance of materials on the change of pupil size. Then, by reflecting the pupil property in the retinal response, we construct a material appearance enhancement algorithm called "PuRet" based on these physiological models of the pupil and retina.

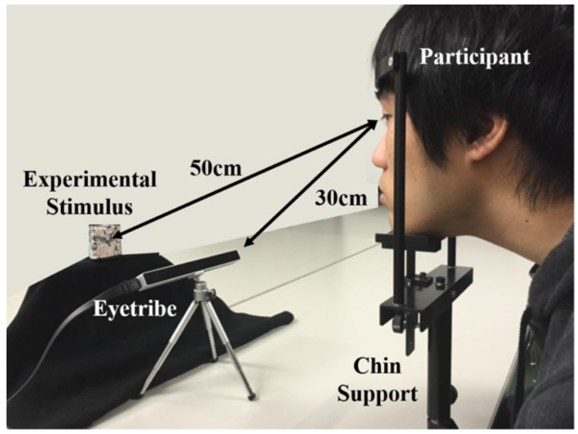


Figure 1. Snapshot of the viewing environment in the psychophysiological experiment to measure pupil behavior.

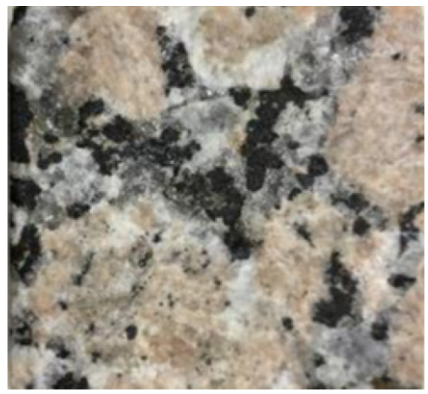


Figure 2. Experimental stimulus (Texas pink granite stone).

MEASUREMENT OF PUPIL BEHAVIORS

In this study, we hypothesize that the diameter of the pupil changes when humans pay attention to the material appearance of the object surface. To clarify the hypothesis, we conducted a psychophysiological experiment measuring pupil behavior.

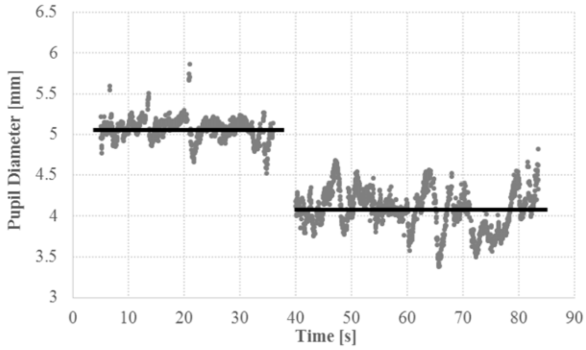
Experimental Method

We carried out a psychophysiological experiment to measure pupil diameter because it has not been realized how real pupil diameter changes when humans pay attention to the appearance of the material surface. An eye-tracking measurement system (The Eye Tribe Tracker; The Eye Tribe)[14] was used to detect changes in pupil size in participants' eyes. Before starting measurement, the eye-tracking system was calibrated for each participant. The measurement values obtained from the eye-tracking system were converted from pixels into millimeters in advance. In our experimental environment, the measurement precision and the resolution of the eye-tracking system for measuring pupil diameter were 8.1×10^{-2} mm and 1.4×10^{-5} mm, respectively.

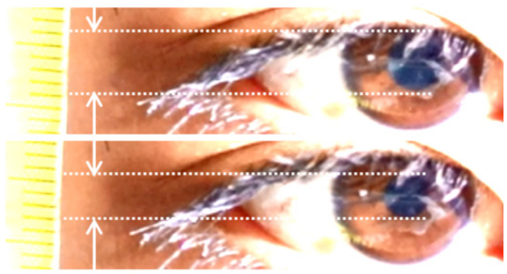
Figure 1 shows a snapshot of the viewing environment for the psychophysiological experiment. The participants were asked to observe the experimental stimulus for more than 10 seconds in accordance with two different observation items. During the first half (defined as condition A), participants saw the entire experimental stimulus unintentionally to measure physical characteristics. During the second half (defined as condition B), they carefully gazed at the surface appearance of physically the same stimulus to measure psychological characteristics. The size of the stimulus was 5 cm square and the viewing distance was 50 cm (viewing angle 5.7°). The participant's head was fixed using a chin support. The psychophysiological experiment was conducted in a room under stable illuminant conditions at 195 lx where there was no interruption from outside noise. Therefore, influence from other factors such as illumination conditions and sound was prevented in these experimental conditions. The experimental stimulus is shown in Figure 2. We used a Texas pink stone, which is a kind of granite, with several material appearance factors such as glossiness, transparency, and colorfulness. The surface was uneven due to its polished finish, and it had glossiness caused by the flat surface and its structural components such as biotite. In addition, it contained translucent minerals such as quartz and feldspar.

Experimental Results

Eleven students including ten people with normal color vision and one colorblind person participated in the psychophysiological experiment. Every participant had normal



(a)



(b)

Figure 3. An example of change in pupil diameter. (a) Measured pupil size changes (first half, condition A; second half, condition B). (b) Captured images (top, condition A; bottom, condition B).

eyesight with/without glasses and contact lenses. Figure 3 shows an example of data regarding pupil diameter changes. In Fig. 3(a), the horizontal and vertical axes show the temporal elapsed time in the measurement and the measured pupil diameter, respectively. Each dot shows a measured value, and the two black solid lines show the average pupil diameter during condition A in the first half and condition B in the second half, respectively. Fig. 3(b) shows a frame of the captured image (top: condition A; bottom: condition B). As shown in Fig. 3, we confirmed that the pupil size contracted during the second half. The scatter in measured values occurred because the pupil diameter slightly changed when the participant blinked or moved the gaze point for stimulus. However, these measured sizes contracted generally from condition A to B.

Experimental results for the percentage contraction in pupil size between condition A and B for all participants are shown in Table I. The average contraction percentage was 7.6% (maximum 19.3%, minimum 1.9%). We also confirmed the contraction in pupil size during observation for other materials such as wood, fabric, and leather in a preliminary experiment. From these findings, we found that careful observation of the surface appearance of materials caused further pupil size contraction.

PuRet: Material Appearance Enhancement Algorithm

We propose the PuRet algorithm as a material appearance enhancement algorithm based on the measured characteristic of pupil diameter in the previous section. Figure 4 shows a schematic diagram of the concept of our method. In general, digital color images captured by a camera are generated through various image-processing techniques based on visual properties. The detailed algorithms in commercial cameras are black boxes. In this study, we focus on the response of the retina, which light reaches after passing through the pupil. As shown in the top pipeline in Fig. 4,

Table I. Percentage contraction in pupil size for all participants.

Participant No.	Condition A [mm]	Condition B [mm]	Contraction percentage [%]
1	5.28	4.83	8.5
2	6.72	6.33	5.9
3	5.34	4.59	14.0
4	5.04	4.06	19.3
5	6.43	6.23	3.0
6	5.94	5.26	11.5
7	6.18	5.86	5.1
8	6.16	5.93	3.7
9	5.85	5.61	4.0
10	5.00	4.69	6.3
11	5.85	5.74	1.9

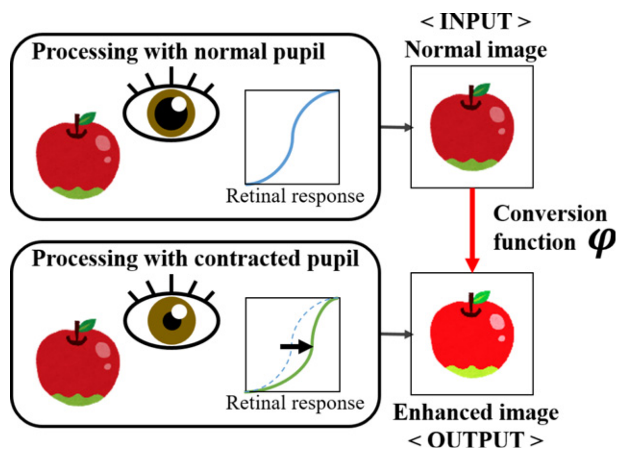


Figure 4. Concept of the PuRet algorithm.

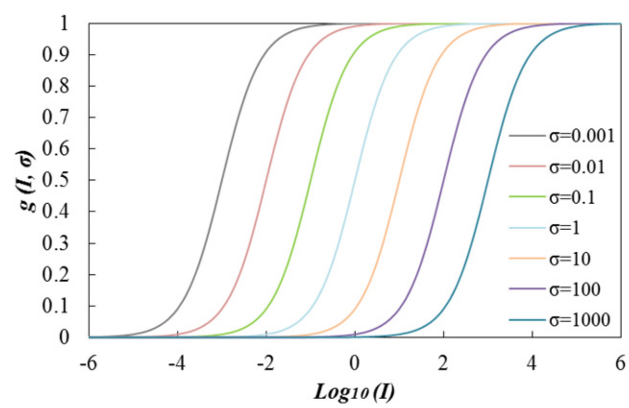


Figure 5. Retinal response curves for each adaptation level σ of luminance.

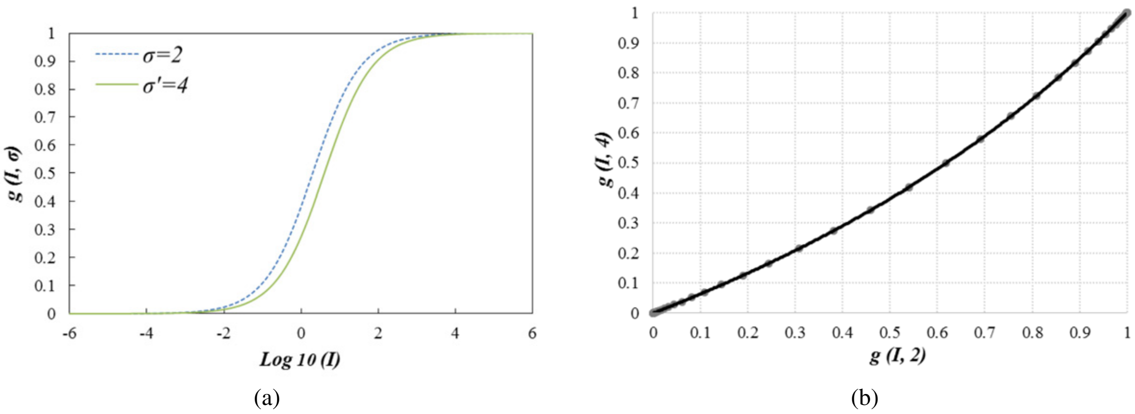


Figure 6. An example of the conversion function from g(I,2) to g(I,4). (a) The retinal response curves for each adaptation level ($\sigma = 2, \sigma' = 4$). (b) Conversion function.

a normal color image is generated regardless of changes in the pupil diameter. However, according to the new findings from the previous section, material appearance enhancement images must be generated by assuming scene acquisition under contracted pupil size, as shown in the bottom pipeline in Fig. 4.

If raw data are captured, the desired enhanced image can be generated by applying the bottom pipeline processing. However, normally there are no raw data and only the image processed using the top pipeline exists. In this study, we convert the normally processed image into the enhanced image through the conversion function φ.

Retinal Response Model

Numerous image-processing algorithms for improving the perceptual image quality considering the human visual system have been developed.[19] The most widely used is the retina response model that was defined by Naka and Rushton.[15] We also use this model in this study. In the equation for the retinal responses model of Naka–Rushton, the responses $g(I, \sigma)$ to the intensity of the incident light I are

$$g(I, \sigma) = \frac{R}{R_{\max}} = \frac{I^n}{I^n + \sigma^n}, \tag{1}$$

where $R(0 < R < R_{\max})$ denotes the response of the photoreceptors, $R_{\max}$ denotes the maximum value of the responses, and I denotes the luminance value, respectively. The parameter σ is the R value when $R = 0.5 \times R_{\max}$, which corresponds to the adaptation level for the illumination. The parameter n is a sensitivity control exponent, which has a value generally between 0.7 and 1.0 (see Ref. 16). Figure 5 shows the retinal response curves when the adaptation level σ varies from 0.001 to 1000 ($n = 0.7$). The retinal response describes the sigmoid curve, and shifts when the adaptation level σ increases corresponding to the luminance level with the retina accepting more light energy.

PuRet Algorithm

The proposed PuRet algorithm mimics the output image from the retina when an observer carefully gazes at the surface appearance of an object. We assume that images are captured by using a digital color camera reproduced on the basis of the Naka–Rushton retinal response model under an

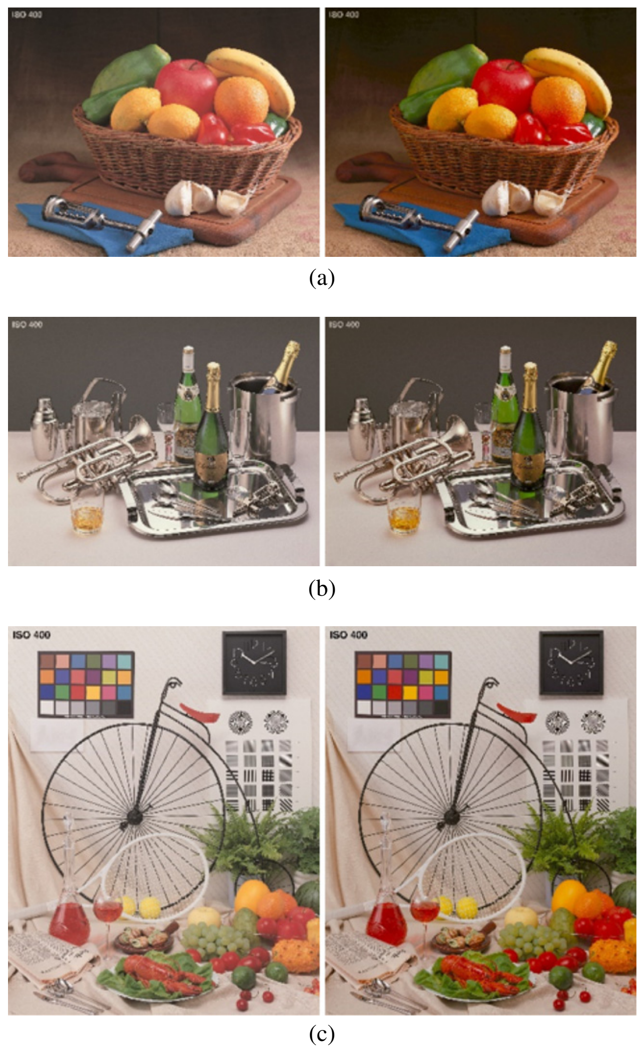


Figure 7. Results of simulated images (left, original image; right, enhanced image): (a) N3, (b) N4, (c) N5.

Figure 8. Close-ups of the simulated images (left, original image; right, enhanced image): (a) metal, fabric and wood in N3; (b) fruits in N3; (c) liquid in a glass and a metallic object in N4; (d) metal in N4; (e) metals, fabric and paper in N5; (f) food in N5.

adaptation level σ. This image is equivalent to the normal image in Fig. 4. As the pupil size contracts due to careful observation, we suppose that the adaptation level σ increases by a level $\sigma'(\sigma < \sigma')$. This hypothesis is reasonable, because the contraction of the pupil size induces a false recognition that light of stronger luminance and intensity is incident, resulting in deterioration of the photoreceptor. Therefore, the conversion function φ is written as

$$g(I, \sigma') = \varphi(g(I, \sigma)). \tag{2}$$

The parameter σ is determined by the brightness of the actual scene, and the parameter σ' is determined depending on both the amount by which the pupil diameter contracts and the luminance of the reproduction display. If Exchangeable Image File Format (EXIF) data are attached to the image, the brightness of the scene can be estimated. If there are no brightness data, it is appropriate to set σ within 1–2 for an indoor scene and within 3–4 for an outdoor scene. Here, as an example, we set $\sigma = 2$, $\sigma' = 4 (n = 0.7)$ and simulated the material appearance enhanced images. The retinal response curves for each adaptation level are shown in Figure 6(a). As shown in the figure, as σ increases from 2 to 4, the sigmoid curve shifts to the brighter adaptation level, and the retina adopts more light energy. For example, when $I = 1$ ($\log_{10}(I) = 0$), $g(I, \sigma) = 0.38$, but $g(I, \sigma') = 0.27$. To improve the captured image under the parameter σ to the enhanced image under the parameter σ', we have to convert the luminance value 0.38 to 0.27. The derived conversion function φ from $\sigma = 2$ to $\sigma' = 4$ is shown in Fig. 6(b). The horizontal and vertical axes represent $g(I, 2)$ and $g(I, 4)$, respectively. The approximation curve for the conversion function φ in the fourth function is shown as

$$y = 0.1106x^4 - 0.0105x^3 + 0.2664x^2 + 0.6124x, \tag{3}$$

where x and y correspond to $g(I, 2)$ and $g(I, 4)$, respectively. In this way, we can easily derive conversion functions for any combination between $g(I, \sigma)$ and $g(I, \sigma')$ $(\sigma < \sigma')$. When people are only looking passively at the image, $\sigma = \sigma'$ in the PuRet model, and the PuRet model merely agrees with the Naka–Rushton model.

Image-Processing Experiments

The enhanced images for improving material appearance were produced by applying the conversion function φ to the luminance components of digital color images. In our PuRet algorithm, first the luminance value component Y in YC_bC_r space converted from the input color image was applied for the conversion function φ. By using the converted value

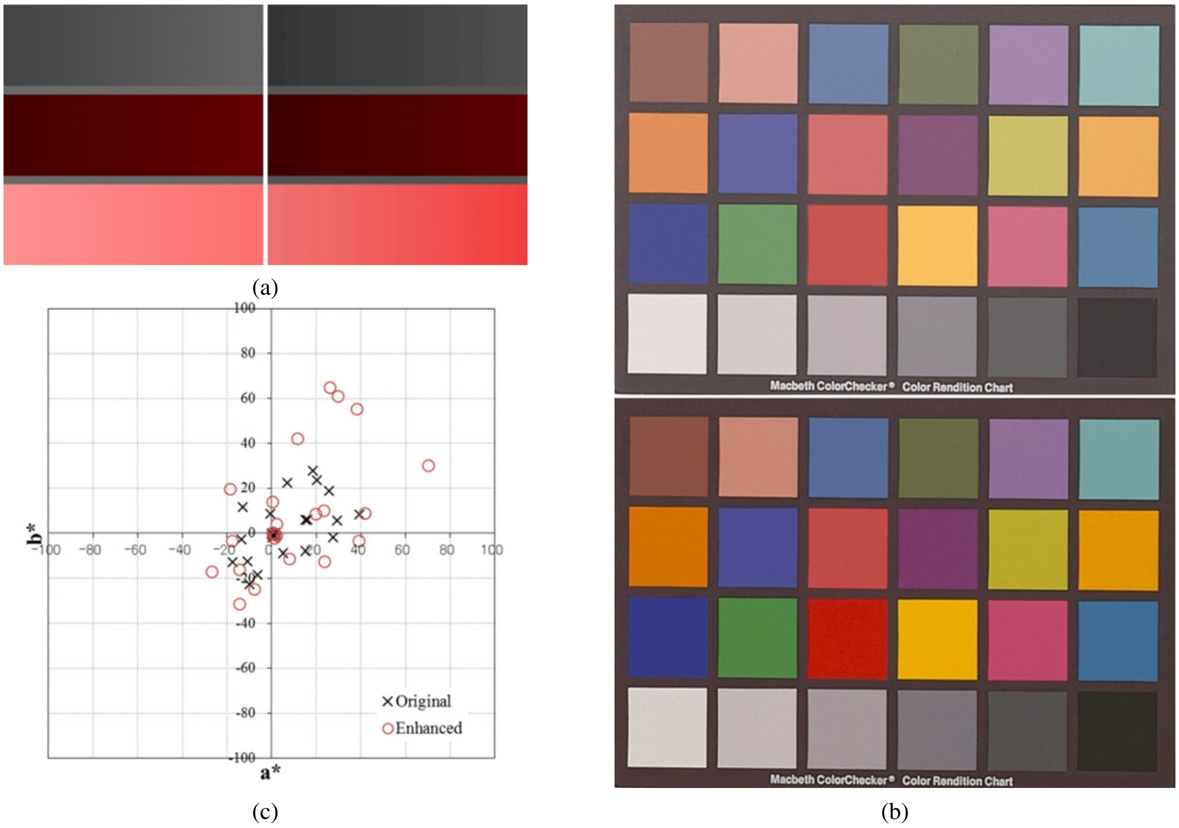


Figure 9. Resulting images indicating the color and tone reproduction performance. (a) Gradation scale of black and red gradation (left, the original image; right, the enhanced image). (b) Color checker in N5 (top, the original image; bottom, the enhanced image). (c) Color distribution in CIELAB space for each patch in Fig. 9(b).

Y', the enhanced color image was produced by the inverse conversion process from $Y'C_bC_r$. We adopted PuRet on test images to confirm the feasibility of enhancing the material appearance on displayed images.

Enhancement Test using Natural Images

We tested PuRet using various standard test images. Figure 7 shows a partial set of test images, ISO/JIS-SCID N3, N4, and N5, with resolutions of 2560 × 2048, 2560 × 2048, and 2048 × 2560, respectively. The enhanced images are also shown in Fig. 7. As shown in this figure, we can confirm the improvement in the appearance of the entire image. To compare the changes in the material appearance in the images before and after processing, close-up images that were trimmed with a resolution of 512 × 512 focusing on each object are shown in Figure 8. By applying the PuRet algorithm to the standard images, the glossiness on the metallic objects was emphasized and improved in comparison with before and after processing images, as shown in Fig. 8(a), (c), (d), and (e). In particular, rugged shapes and textures such as the hairline finish on metallic objects are improved by PuRet, as shown in Fig. 8(a) and (c), respectively. The transparency obtained from the enhanced image was also improved by confirming the glass, as shown in Fig. 8(c). The enhanced image had a higher impression of appealing transparency of the glass than the original image. With regards to the fabric and wood, as shown in the close-up images (Fig. 8(a) and (e)), we can recognize fine roughness on these objects' surfaces due to the enhancement of the weave for the fabric and the grain for the wood. As shown in Fig. 8(b) and (f), we also confirmed the improvement of the material appearance of foods that had complicated material appearance including glossiness, transparency, and uneven texture with irregular surface and shape. An apple and a lobster were felt to be more delicious.

Color and Tone Reproduction Performance

We evaluated the color and tone reproduction performance. Figure 9 shows the original and enhanced images of a gradation scale and color patches. As shown in Fig. 9(a), with PuRet, there is a tone jump due to the nonlinearity of the conversion function and color becomes deeper. The results for the color checker image are shown in Fig. 9(b). Fig. 9(c) represents the color distribution in CIELAB space for each patch. Every color shifts in the vivid and clear direction, and each color could be easily discriminated from other similar colors (No. 2 and No. 9; No. 7, No. 12, and No. 16; No. 19, No. 20, and No. 21).

Consideration of Material Appearance Management

The material appearance obtained from the displayed image on different monitors changes depending on the characteristics of the display. We now demonstrate material

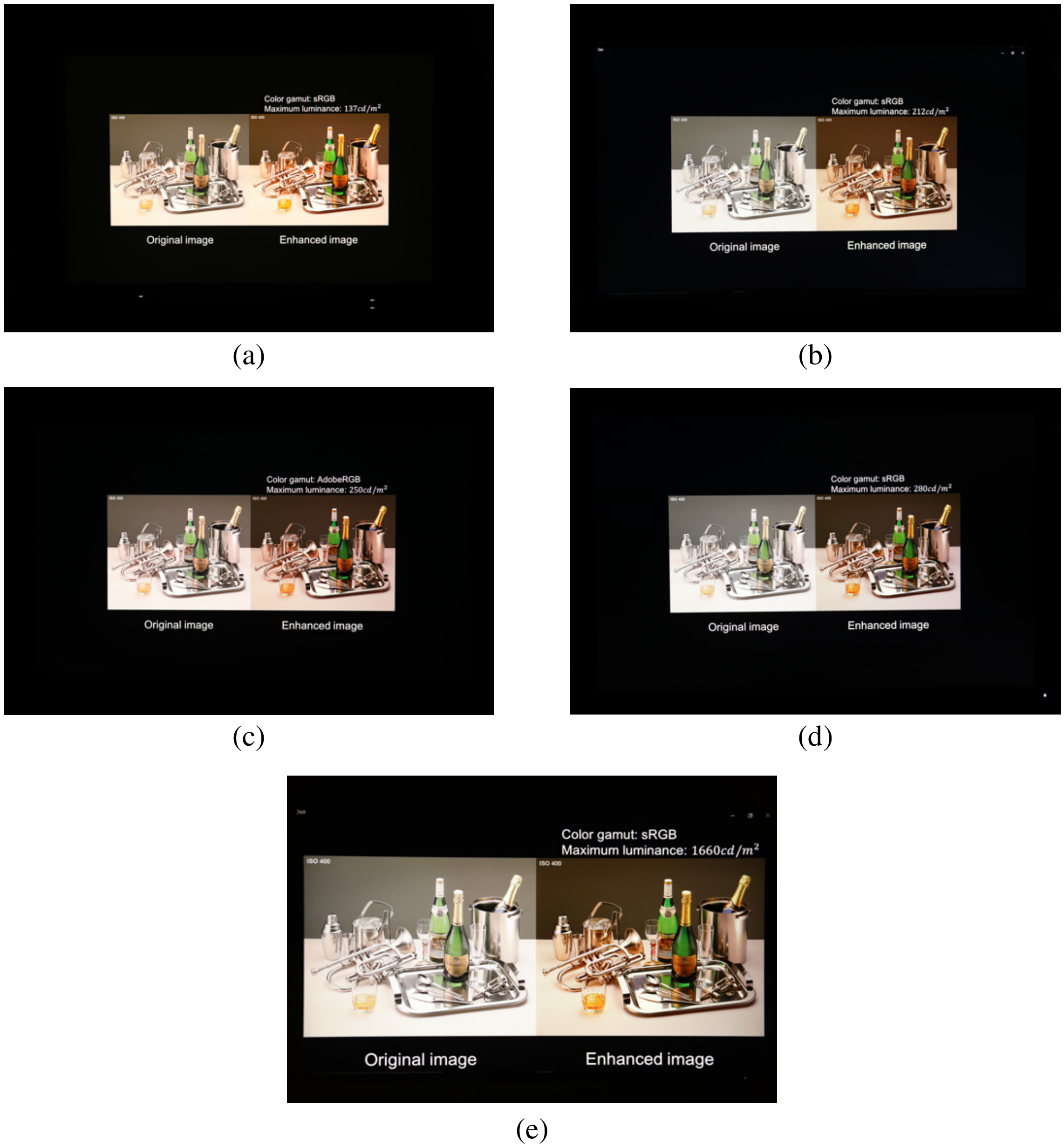


Figure 10. Results for managing the material appearance of rendered images displayed on different monitors (left, the original image; right, the managed image): (a) EIZO ColorEdge CG221 ($\sigma' = 4.00$, exposure time 1/40 s); (b) EIZO ColorEdge CS230 ($\sigma' = 4.30$, exposure time 1/80 s); (c) EIZO ColorEdge CG 277 ($\sigma' = 3.50$, exposure time 1/80 s); (d) ASUS ProArt PA248Q ($\sigma' = 4.70$, exposure time 1/80 s); (e) Sharp PN-A601 ($\sigma' = 4.40$, exposure time 1/500 s).

appearance management among several display devices by applying the PuRet algorithm. We used five different displays with different characteristics, as given in Table II.

We displayed an original image and the enhanced image side by side for each display and manually adjusted only one parameter, σ', of PuRet with each display so that all of the displayed images appeared the same. When we adjusted the parameter σ', the original image was set with the parameter $\sigma = 1$ as the fundamental value, because we could not predict the luminance of the real-world scene. Figure 10 shows photographs of displayed images captured in a darkroom using a Canon 5D Mark IV camera with a resolution of 6720×4480 pixels. Each figure was down-sampled to a resolution of 640×512 as a quarter of the original image size for displaying horizontally side by side, and represented without enlarging the photographed picture. All images were captured with the same settings with only the exposure time varying, to match the maximum luminance of the display. The displayed images on the left-hand side in Fig. 10(a)–(e) are exactly the same as the original images. We can confirm that the material appearance and impression obtained from the images differ greatly. The images on the right-hand side show the managed images by adjusting the parameter of PuRet. We can confirm that the material appearance such as glossiness, transparency, and roughness is enhanced. The results indicate that material appearance was equally

Table II. Characteristics of the displays used in the demonstration.

Display	Max. lum. [cd/m^2]	Color gamut	Resolution [pixel]	Pixel pitch [mm]	Display size [inch]
EIZO ColorEdge CG221	137	sRGB	1920 × 1200	0.249 × 0.249	22.2
EIZO ColorEdge CS230	212	sRGB	1920 × 1080	0.265 × 0.265	23
EIZO ColorEdge CG277	250	Adobe RGB	2560 × 1440	0.233 × 0.233	27
ASUS ProArt PA248Q	280	sRGB	1920 × 1200	0.270 × 0.270	24.1
Sharp PN-A601	1660	sRGB	1920 × 1080	0.692 × 0.692	60

enhanced by applying our PuRet technique to normal images, so we could also manage the material appearance among different displays with different characteristics.

CONCLUSIONS

In this article, we proposed a new image-processing algorithm, PuRet, for enhancing the material appearance such as glossiness, transparency, and roughness obtained from digital color images. In our proposed algorithm, we focused on changes in pupil diameter and retinal response, which were first handled in a human visual system to recognize an image. First, we measured the changes in the pupil diameter of observers before and after they paid attention to the material appearance on the object surface by conducting a psychophysiological experiment. Through this experiment, it was found that the pupil diameter decreases when observing the material appearance on the object surface. Second, we drew up the new algorithm for enhancing material appearance perception by contracting the pupil diameter based on a retinal response model proposed by Naka–Rushton and confirmed the effectiveness by applying the algorithm to general digital color images. As a result, we confirmed that perceived material appearance factors such as glossiness, transparency, and roughness obtained from the processed images were emphasized by applying our proposed model. Finally, we proved the effectiveness of the material appearance management system, which can be perceived as equivalent appearance qualities among several different imaging devices by adjusting the parameters of our proposed model.

The parameter σ' needs to be optimized depending on the dynamic range in a scene, display specifications such as resolution and size, and observation conditions such as viewing distance. Optimum parameter tuning is an important future research topic. Furthermore, we need to develop higher-level image-processing algorithms such as tone mapping and gamut mapping to reduce artifacts.

ACKNOWLEDGMENTS

This work was supported by JSPS KAKENHI Grant Number JP15H05926 (Grant-in-Aid for Scientific Research on Innovative Areas "Innovative SHITSUKAN Science and Technology").

REFERENCES

1 M. Tanaka and T. Horiuchi, "Investigating perceptual qualities of static surface appearance using real materials and displayed images," Vis. Res. **115**, 246–258 (2015).

2 M. Tanaka, *Analysis of Material Appearance using Real-World Objects and Rendered Images*, Doctoral Dissertation (Chiba University, 2016).

3 K. Iida and T. Okubo, "Metallic image forming method," Japanese Unexamined Patent Application Publication No. JP 2016-196183 A (2016).

4 M. Bressan, C. R. Dance, H. Poirier, and D. Arregui, "Local contrast enhancement," Proc. SPIE **6493** (2007).

5 E. H. Land, "The retinex," American Scientist **52**, 247–264 (1964).

6 I. Motoyoshi, S. Nishida, L. Sharan, and E. H. Adelson, "Image statistics and the perception of surface qualities," Nature **447**, 206–209 (2007).

7 I. Boyadzhiev, K. Bala, S. Pris, and E. Adelson, "Band-shifting decomposition for image based material editing," ACM Trans. Graph. **32** (2015).

8 M. M. Bradley and P. J. Lang, "Memory, emotion and pupil diameter: Repetition of natural scenes," Psychophysiology **52**, 1186–1193 (2015).

9 W. S. Peavler, "Pupil size, information overload, and performance differences," Psychophysiology **11**, 559–566 (1974).

10 S. D. Goldinger and M. H. Pepesh, "Pupil dilation reflects the creation and retrieval of memories," Psychol. Sci. **21**, 90–95 (2012).

11 A. Kafkas and D. Montaldi, "Recognition memory strength is predicted by pupillary responses at encoding while fixation patterns distinguish recollection 30 from familiarity," Q. J. Exp. Psychol. **64**, 1971–1989 (2011).

12 M. Naber, S. Frassle, U. Rutishauser, and W. Einhauser, "Pupil size signals novelty and predicts later retrieval success for declarative memories of natural scenes," J. Vision **13** (2013).

13 X. Jian, M. S. Atkins, G. Tien, B. Zheng, and R. Bednarik, "Pupil dilations during target-pointing respect Fitts' Law," *Proc. ETRA2014, Florida, US* (ACM, New York, NY, USA, 2014).

14 The Eye Tribe, https://s3.eu-central-1.amazonaws.com/theeyetribe.com/theeyetribe.com/index.html.

15 K. I. Naka and W. A. H. Rushton, "S-potential from colour units in the retina of fish (Cyprinidae)," J. Physiol. **185**, 587–599 (1966).

16 J. E. Dowling, *The Retina: An Approachable Part of the Brain* (Belknap Press, Cambridge MA, USA, 1987).

17 H. H. Eckhard, *Attitude and Pupil Size* (Scientific American, New York, 1965), Vol. 212, pp. 46–54.

18 M. L. Vô, A. M. Jacobs, L. Kuchinke, M. Hofmann, M. Conrad, A. Schacht, and F. Hutzler, "The coupling of emotion and cognition in the eye: Introducing the pupil old/new effect," Psychophysiology **45**, 130–140 (2008).

19 T. Horiuchi and S. Tominaga, "HDR image quality enhancement based on spatially-variant retinal response," EURASIP J. Image Video Process. **2010**, 438958 (2010).