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DYNAMIC COLOR GAMUT MAPPING BASED ON VISUAL ASSESSMENT

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Abstract. *To improve image quality, the paper proposes two gamut mapping transforms, which extend the color gamut of an underutilized display. The expansion gains are obtained using histograms of input images. The gains are adaptively applied in function of local pixels. In addition, an infinite impulse response (IIR) filter is applied to preventing sudden changes in the color gamut that may occur during video reproduction. To prevent color distortion and image quality deterioration due to excessive applied gain, the maximum value of the gain is limited. The value of the optimal upper limit of the gain was derived through a subjective experiment conducted by 15 experimenters. During the experiment, most of the observers preferred a gain of approximately 1.3 in the image; however, in memory colors such as skin color, they preferred a gain similar to that of the original color with no gain.*
Keywords: Color gamut mapping, Color transform, Chroma transform, Visual assessment

1. **Introduction.** Display technology refers to the technology that presents information on an output device in visual form. With advances in this technology, the expressible color gamut has been expanded. However, the color gamut that is actually used depends on that of the input image. Thus, only a part of the color gamut is used. Several existing studies have extended the color gamut using histograms [1-5]. However, some of them applied a uniform expansion gain. By applying a uniform extension gain to all pixels of the input signal, the contrasts of images can be reduced, resulting in deterioration of image details. Thus, there are several problems and limitations in existing studies. For example, [3] shows different enhancing results depending on hues because gamut boundary descriptors are different for each hue. [4] changes the perceptual hue and brightness of resulting images by mapping in perceptual non-uniform color space. Such problems need to be overcome to use the whole gamut of color that has been made available by state-of-the-art display technology [4,5].

In this study, an algorithm for extending the color gamut while maintaining image detail by dynamically applying a gain to image pixels, and an algorithm for preventing image quality deterioration during color gamut extension were proposed. The algorithm proceeds in a linear RGB color space to reduce hardware complexity.

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Usually, image evaluation methods are largely divided into subjective and objective evaluation methods [6-8]. Objective evaluation methods involve measuring numerical values quantitatively through physical and mathematical modeling; such methods can significantly reduce cost and time compared to the subjective evaluation methods. Moreover, the objective evaluation methods have high reliability for repeatability. Representative methods for objectively evaluating image quality include mean square error and peak signal to noise ratio methods. Although objective evaluation methods are better than subjective evaluation methods, the paper uses a subjective method, because the gamut extension is a part of the image enhancement technology, so there is no suitable objective evaluation.

The typical subjective evaluation method is the mean opinion score (MOS) [8]. MOS is a method in which the observer directly evaluates an image. It has the disadvantage that it requires a significant amount of time and cost. Moreover, it is less reliable than the objective evaluation method because the subjective decisions of observers are included. However, as in the process of evaluating image quality, psychophysical cognitive processes work together, the subjective evaluation method is an effective method for image quality assessment. A method for determining the optimal color gamut expansion gain preferred by humans using the MOS has not been previously studied.

In summary, this paper proposes a color gamut extension algorithm that dynamically applies perceptually optimized gain limits derived from subjective experiments. The remainder of this paper is organized as follows. Section 2 describes a proposed algorithm that extends the color gamut and an algorithm that improves the image quality. Section 3 discusses the experimental subjective evaluation and their results, and explains the optimal gain derived from the results. Section 4 provides the conclusions of this study.

2. **Proposed Algorithm.** Figure 1 shows the flowchart of the algorithm proposed in this study. The original input image in nonlinear RGB format is converted into a linear RGB of the target display with a color space converter according to the standards such as BT.709 or BT.2020 [9,10]. Using the linear RGB signal, a maximum color gamut extension gain mapped to the target display in units of pixels is obtained, and an extension gain histogram for one image frame is also obtained. The color gamut of the image is then extended using the obtained gain. At this time, the out-of-gamut colors, which can occur by excessive gains, are compensated. Then the gamut extended signals are converted to the non-linear RGB using a display opto-electronic transfer function (OETF). More detailed description of algorithms is as follows.

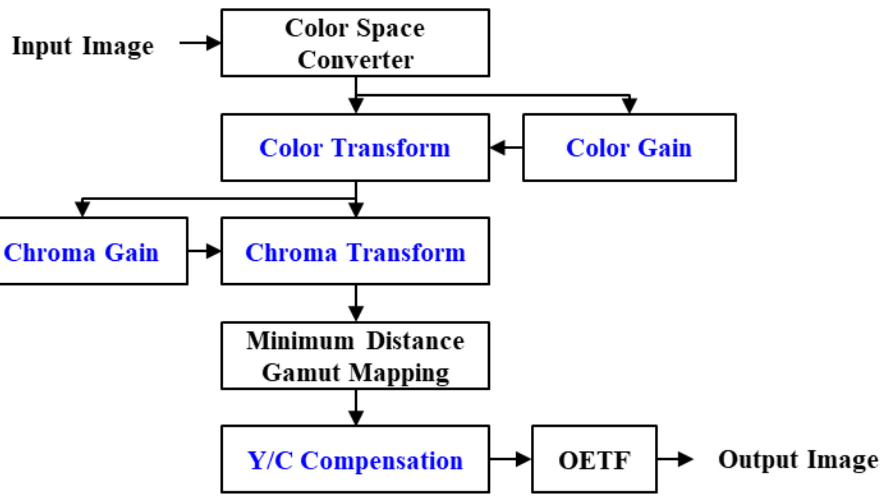

FIGURE 1. (color online) Algorithm flowchart: The new proposals are marked as blue text

2.1. **Color gamut transform.** In this study, color and chroma transforms are proposed as the color gamut extension methods. Color transform is a technique for converting the input signal F0 into a color vector direction that proportionally increases/decreases luminance and chroma without changing the color coordinates in the same saturation direction, as shown in F1 in Figure 2.

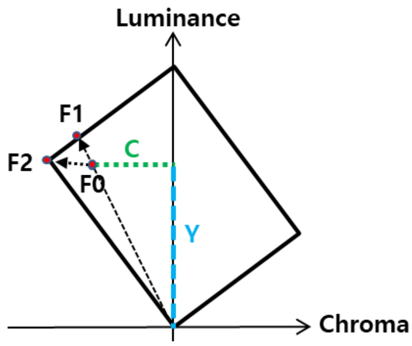

Figure 2. Color (F1) and chroma transform (F2) methods

Contrary to this, chroma transform is a technique of converting only chroma values in the same luminance and hue direction, as shown in F2 in Figure 2. Color transform is a natural color gamut mapping technique that does not change color coordinates, whereas chroma transform is a part of an ascending technique that may improve color saturation of images, and therefore increase preference of observers.

The gain used for color transformation is determined by a display gamut boundary value β and the linear RGB input image F0(R_0, G_0, B_0), and it is extracted by a histogram using the maximum RGB value of each pixel of the input image, that is, the i-th pixel gain k_i is obtained as in (1) using the RGB maximum value of each pixel with respect to the input image, and a histogram of the obtained k_i is plotted.

$$k_i = \beta / Max(R_0, G_0, B_0), \ \beta = 2^N - 1 \text{ for } N\text{-bit RGB signal} \tag{1}$$

When the histogram of the pixel gains is plotted, if k_i is greater than 5, it is a meaningless value because of the over-extension gain, and it is clipped to 5 to save H/W resources and prevent image deterioration. The lower n% point of the histogram normalized from 1 to 5 is used as the global expansion gain (k_1). In this study, a lower $n = 5\%$ point was used. When the lower 5% point is used as a gain, the pixels corresponding to the lower 5% exceed the display gamut; however, 95% of the pixels can be stably expanded within the display gamut range. In addition, 5% of pixels exceeding the color gamut are generally highly likely to be dispersed over the entire image area, making it difficult for the human eye to recognize them. Nevertheless, the excess 5% pixels can be supplemented by pixel unit color gamut mapping, which will be described later. By applying the obtained gain as in (2), the color-converted image F1(R_1, G_1, B_1) is obtained as follows, where k_1 is a global color gain:

$$F1 = F0 * k_1 \tag{2}$$

2.2. **Chroma transform.** The gain used for chroma transform is determined by the display gamut boundary value β and the chroma value of the color-converted image, which is extracted using a histogram of the chroma values of each pixel of the color-converted image. The chroma value is the difference between the pixel RGB maximum and minimum values. A pixel gain is obtained as in (3) using each pixel chroma value of the color-converted image, and a histogram is plotted.

$$k_j = \beta / \left(Max(R_1, G_1, B_1) - Min(R_1, G_1, B_1) \right) \tag{3}$$

Similar to the color transform, when k_j is 5 or more, the lower 5% point of the k_j histogram normalized from 1 to 5 after clipping to 5 is used as a gain (k_j). By applying the obtained gain as in (4), the chroma-transformed image F2(R_2, G_2, B_2) is obtained as follows, where k_2 is a global chroma gain and Y is a luminance:

$$F2 = Y + (F1 - Y) * k_2 \tag{4}$$

In the case of obtaining and applying a gain from the current frame in the transform process, frame delay occurs and the corresponding frame memory is required, thereby increasing the H/W resources. Therefore, the gain is obtained using the previous frame data, and the necessary H/W resource is reduced by obtaining the gain after every five frames (for example) instead of obtaining the gain at every frame. This is because, for an image with a refresh rate of 60 FPS or higher, the change in color gamut between adjacent frames is minimal, except when the screen is completely switched, such that the change in gain is not large. In addition, the gain obtained before frame 5 is not directly applied, but the gain is obtained by multiplying the weight α as in (5) to prevent a sudden change. The experimentally derived α coefficient is in the range 0.7-0.9, where k_p is a gain of previous frame and k_n is a gain of a current frame.

$$k_n = \alpha * k_p + (1 - \alpha) * k_p \tag{5}$$

2.3. **Pixel adaptive mapping.** As described in the Introduction section, when the obtained gain is equally applied to all pixels, the contrast difference between the dark and bright pixels is reduced in some cases, resulting in the deterioration of image details. To prevent this phenomenon and to expand the color gamut effectively, we propose a method of pixel adaptive gain as shown in Figure 3. From 0 to the threshold (low) of the maximum RGB value of a pixel, the gamut extension is not performed using the gain as 1. The gain is adaptively applied, according to the RGB maximum value of the pixel, from the low point to the point at which the value obtained by multiplying the pixel's RGB maximum value by the pixel's RGB maximum value saturates the display's color gamut (high). Values after the high-point use the gain k_n. These points have values that exceed the color gamut of the display by applying k_n to the lower 5% pixels when obtaining the aforementioned gain, but compensate through pixel-by-pixel color gamut mapping.

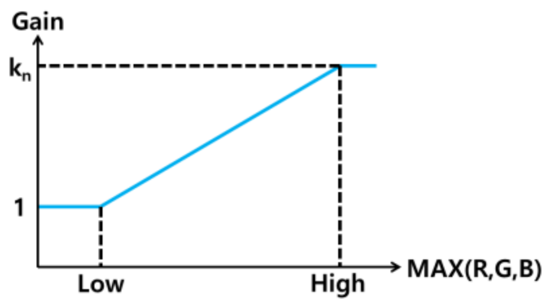

FIGURE 3. Pixel adaptive gain according to pixel RGB max

2.4. **Compensation.** Due to the mentioned transformation, in rare cases pixel values may exceed the color gamut of the display. Out of gamut is a major factor in image quality deterioration and it should be supplemented through color gamut mapping to the inside of the color gamut.

In this study, color gamut mapping was performed using the RGB clipping technique. Although hue shift occurs in this method, as shown in Figure 4 the color difference is minimized using the shortest-distance mapping technique that maps the closest gamut boundary to the current gamut. This is an optimal technique used when the color gamut difference is not large, or when the expansion gain is not high.

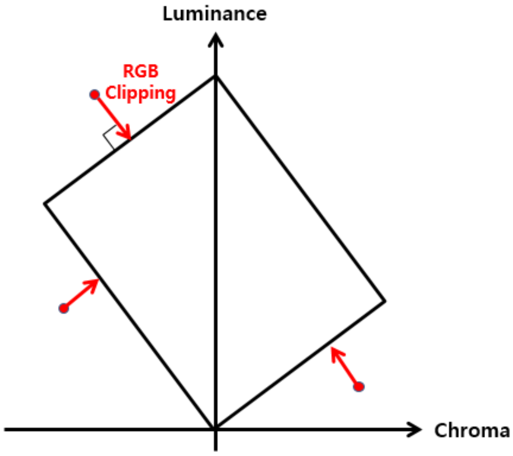

FIGURE 4. Mapping effect of RGB clipping method

In addition, the chroma transform process in the RGB domain, which is a non-uniform color space, requires a process of perceptually compensating for the changed luminance value with the same luminance as the luminance value is changed.

Using (6), the perceived luminance value ΔY changed by the chroma transformation was obtained and compensated. The values of ΔR, ΔG, and ΔB increase or decrease by the chroma transformation, whereas $k_{R,G,B}$ are the luminance transformation coefficients for each standard from RGB to YCbCr, and their sum is 1.

$$\Delta Y = k_R \Delta R + k_G \Delta G + k_B \Delta B \tag{6}$$

By subtracting the obtained ΔY from the RGB minimum value of the pixel, the changed luminance is compensated to maintain the same luminance of the input pixel and chroma-converted signals.

Figure 5 shows an example of the algorithm result. The color gamut expansion and compensation algorithm are applied to the upper left picture, and the upper right picture is output. The bottom figures show the display gamut in linear YCbCr color space of the input and output, where the inner dots are the positions of the pixels of the corresponding images. Consequently, the output image uses a much wider gamut volume compared to the input image, which has a large amount of unused surplus space within the display color gamut.

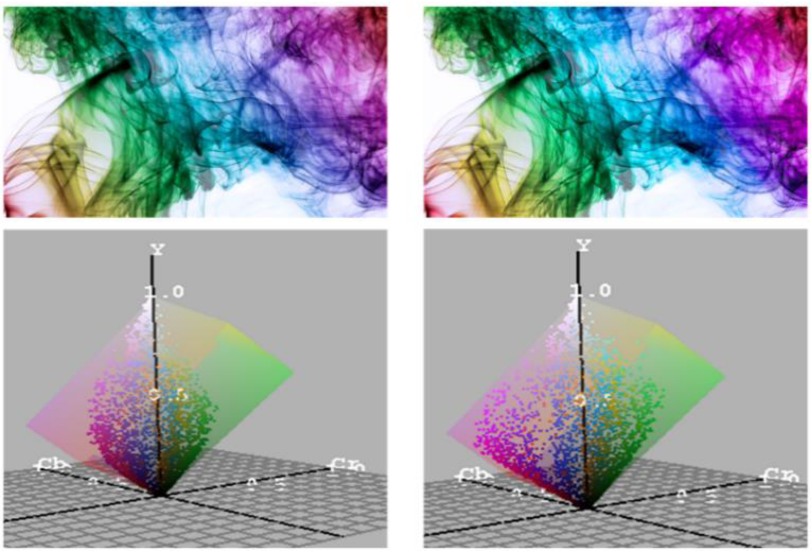

FIGURE 5. (color online) Algorithm applied image (input (left), output (right))

3. **Visual Assessment.** The transform algorithm expands by determining the respective gains of color and chroma. In this case, if the gain is excessive, color distortion occurs, and the image quality deteriorates. To prevent such deterioration, the maximum limit value of the gain was set. However, if the maximum limit of the gain is set excessively low, the range of color gamut expansion is insignificant, and the effect of the algorithm is weakened. Therefore, the following experiment was conducted to determine the optimal gain.

In the visual experiment, the experimenter selects the most preferred image among five images to which gains 1, 1.15, 1.3, 1.45, and 1.6 are applied to the original image. Images to which each gain is applied are placed randomly such that the experimenter cannot determine the gain that is applied to the image using the sequence.

In the experimental environment, according to the standardization method of ITU-R BT.500, the distance between the experimenter and the display is set to 1.6·H (H: Display height). In addition, to eliminate screen reflection when conducting the experiment, it was conducted in a dark room where no natural light entered.

In the described method, an experiment was conducted with 16 sets of images (a-p) kept in a bundle with the original and five images to which the gain was applied. For the selection criteria of 16 images, images with various color distributions, including RGB primary colors and images of various situations such as natural scenery, humans, and cities were selected. Table 1 illustrates the CIE-xy chromaticity distribution of the 16 original images.

Figure 6 summarizes the 16 preferred gains selected by the 15 experimenters. It shows the results of each experimenter as a graph, whereas Figure 6-right shows the total value of the experimenters. As shown in the graphs of Figure 6, there is a difference in preference for each experimenter depending on the difference and inclination of each experimenter's visual characteristics. However, a gain of approximately 1.3 is preferred the most, and as the gain increases or decreases, the preference tends to decrease gradually. This is more clearly observed in Figure 7, which shows a box and whisker statistic graph.

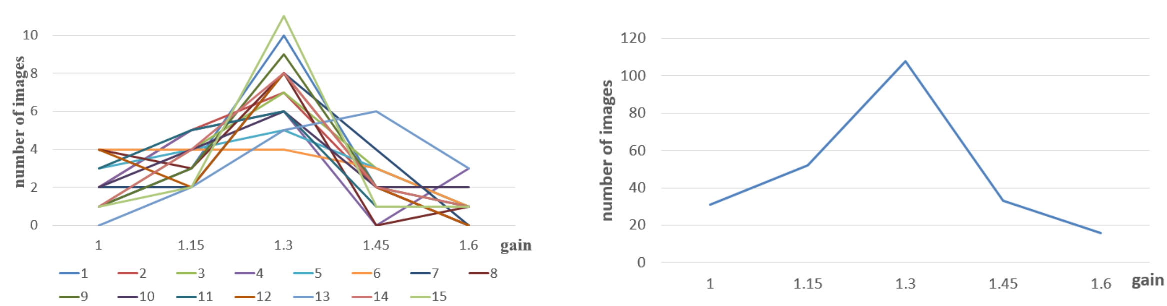

FIGURE 6. (color online) Preferred gain of 15 experimenters (left) and total sum (right)

The red line in Figure 7 represents the average value, whereas the blue line represents the median value. The average value of the 15 experimenters was close to 1.3, whereas the average value of majority of the experimenters was less than 1.3. In addition, in the case of the experimenter No. 13, who preferred the highest gain, the average value of the preferred gain was 1.4. Thus, it was found that humans did not prefer high gain. In fact, if the gain is excessively high, color distortion occurs and the image quality deteriorates, which feels unnatural; therefore, the experimenters were not impressed. Similar results can also be observed in the literature describing the relationship between contrast and colorfulness changes and image quality. Therefore, it is considered that the optimal result image for human preference can be obtained when the maximum color and chroma gain of approximately 1.3 is applied compared to the original image.

Table 1. (color online) 16 experimental images and their color gamut in CIE-xy: Images are ordered a-p from left to right and top to bottom

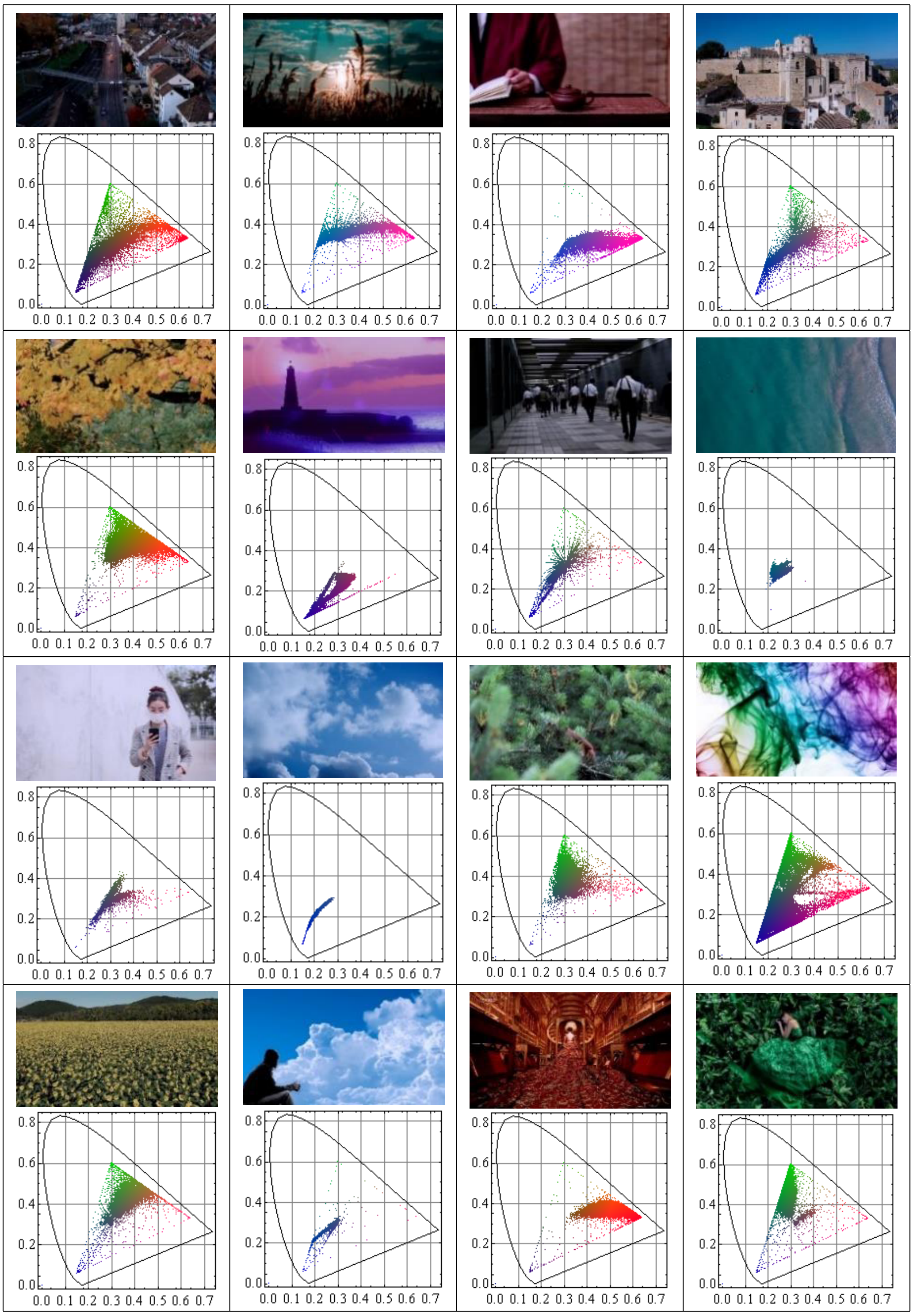

Figure 7-right shows the box and whisker statistical graph by classifying the results by image. The result also favors a gain of approximately 1.3, similar to that of the left figure, but in the case of images c and i, a gain lower than 1.3 is preferred. In the case of c and i, the image containing human skin color changes as the gain increases; thus, the skin color, which is a memory color, changes, and the experimenters prefer a gain close to the original, which is lower than 1.3. Therefore, it is concluded that maintaining the original color is good for image quality in memory color, similar to human skin color. It

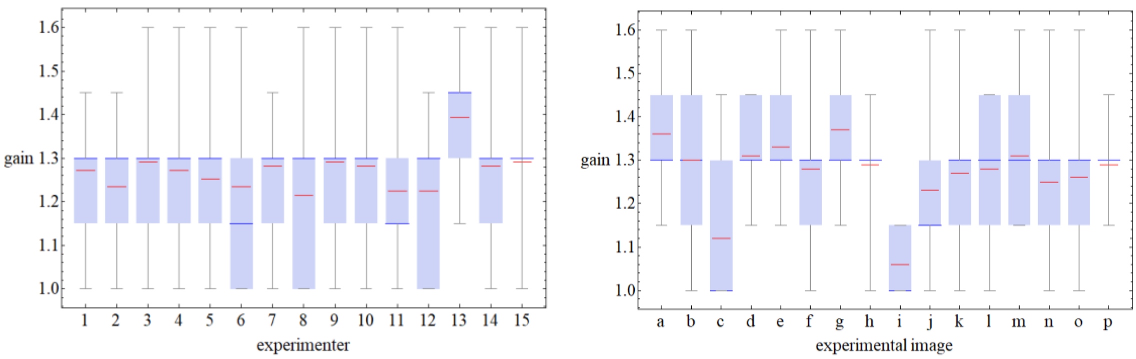

FIGURE 7. (color online) Optimal preferred gain variability by experimenters (left) and images (right)

is desirable to minimize the change in gain in memory colors by using an object detection technique.

4. **Conclusion.** The dynamic color gamut mapping algorithm based on human visual experiments to use the underutilized color gamut is proposed that is left by using only a part depending on the input image rather than using all of the color gamut that can be expressed by the display. The color and chroma transform algorithm to extend the color gamut is applied, and a compensation algorithm to improve image quality deterioration during the transformation process is proposed. In addition, because there is no standardized quantitative measurement method to measure the performance of the algorithm proposed in this paper, a subjective evaluation method was adopted, and a human preference experiment according to the gain was conducted. By analyzing the results of the preference experiment, approximately 1.3 was derived as the maximum optimal value of the human preferred gain.

Future research topics may need to develop algorithms for classifying and detecting memory colors, maintaining these regions, and harmonizing between memory colors and their neighboring regions. Further work will be a performance comparison between the proposed method and an existing algorithm that may require an image quality assessment.

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