A Psychophysical Evaluation of a Gamut Expansion Algorithm Based on Chroma Mapping II: Expansion within Object Color Data Bases

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Abstract

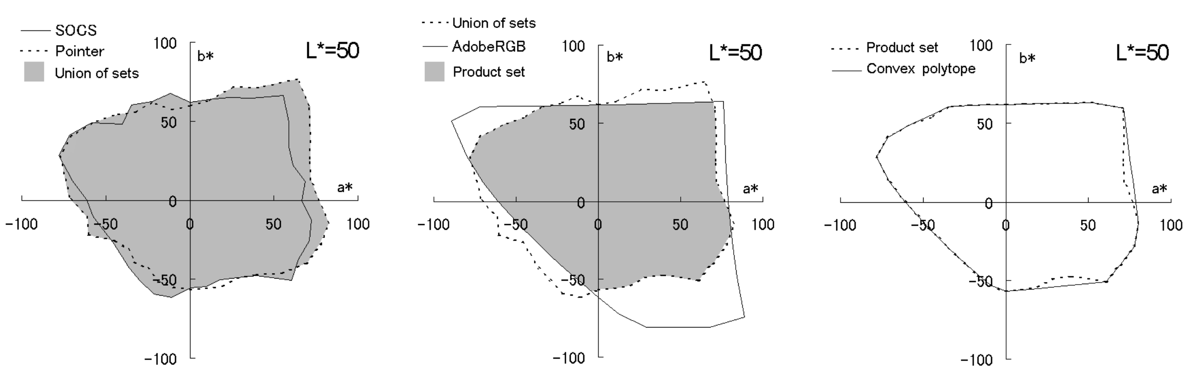
Recently, wide-gamut monitors and printers have begun to appear in the market. However, there are no appropriate tools for evaluating color reproduction in such image output devices. This study describes a method to create the image data for evaluation of the wide-gamut devices. The method expands the gamut of the source image in a manner that a color in the image is mapped into a color with higher chroma, which is restricted within maximum chroma of Standard Object Color Spectra (SOCS) database and Pointers database, and the same hue and lightness, by using a chroma mapping function. The method was applied to sRGB images such as XYZ-SCID images to make the test images for evaluating wide-gamut output devices. In order to find the optimal chroma mapping function, a psychophysical experiment was performed, where the test images made with three types of mapping functions were visually evaluated. Results showed that observers judged the test images expanded with nonlinear functions were the best quality. Moreover, from a cluster analysis of observers it was found that there are two groups that feel high chroma of image natural and nonnatural.

Introduction

Rapidly developing digital cameras and the spread of them into industrial fields such as the graphic arts industry have allowed wide color gamut image data to circulate. With increasing wide gamut image data, wide gamut monitors and printers have begun to appear in the market. However, there are no appropriate tools to evaluate such image output devices. If there exists standard image data that are designed to evaluate the wide gamut output devices, one can recognize the characteristics of the devices by using the image data. The standard image data, XYZ-SCID and CMYK-SCID, have been used for evaluation of conventional image output devices such as sRGB monitors and CMYK printers, but cannot be applicable to the wide-gamut image output devices.

There are two methods to prepare the wide-gamut image data available for evaluating the devices. One is to create wide-gamut image data by using an image input device and an image retouching software. However, this takes much effort and time. The other is to expand the gamut of standardized image data so that they can have larger gamut. This has an advantage in that the quality of the gamut-expanded images can be guaranteed to some extent, as well as we do not need to create completely new image data from the start.

In the previous study, the latter method was adopted [1]. A gamut expansion algorithm was applied to standarad images, whose colors are reproducible on typical monitors, to obtain images with high chroma. There were some strongly high chroma parts in the processed images which were seemed as unrealistic colors. We thought that real object color must be considered at the expansion process. In this study, the method expands the gamut of the source image in a manner that a color in the image is mapped into a color with higher chroma, which is restricted within maximum chroma of real object colors.



(a) (b) (c)

Fig.1 Method obtaining the AdobeRGB color gamut restricted by real object colors

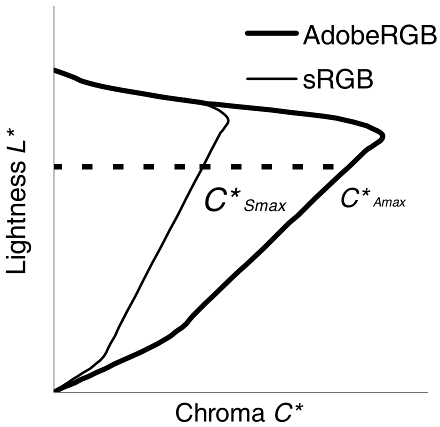


Figure 2. Gamut boundaries in the L-C* plane.*

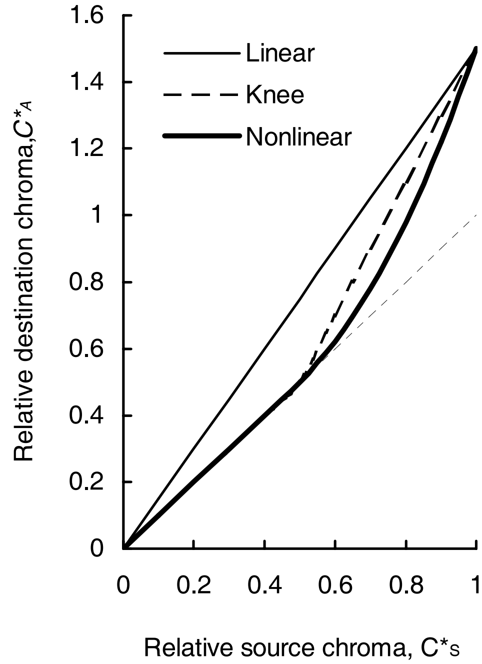


Figure 3. Three types of chroma mapping functions.

Restricted AdobeRGB Color Gamut

In this study we used two data bases of real object color. The first was the gamut collected by Pointer [2]. He had derived a maximum gamut for real surface colors from the analysis of the color coordinates of 4089 samples. The data were compared with the theoretical maximum-color gamut, which was optimal color with surface reflectance of 0.56%, with the gamut produced by a typical dye set used in a photographic paper, and with the gamut of a television-receiver display tube. The second data base was Standard Object Color Spectra (SOCS) database [3]. The SOCS had been published in a ISO technical report, ISO TR 16066. The CD-ROM attached to the ISO-TR contains more than fifty thousands spectra of objects, such as photographic materials, offset prints, computer color prints, paint (not for art), paints (oil paints, water colors), textiles, flowers and leaves, outdoor scenes, and human skin. Color gamut of SOCS had been calculated and compared to Pointer's gamut [4].

Color gamuts of Pointer and SOCS are shown in Fig.1 (a). It should be noted that color gamuts are three dimensional solids, but only cross sections for $L^*=50$ are shown in the figure for convenience. A union gamut was obtained from the two sets of color gamuts. A cross section of color gamut for $L^*=50$ is also shown in Fig.1 (a) as a shaded area. The union gamut was considered as a color gamut of real object colors. Then a product set of the union gamut and the Adobe RGB color gamut was obtained as shown in Fig.1 (b) [5]. The product gamut had concave areas as shown in Fig.1 (c). Because it is rational that there was no sample of the color by chance rather than there was no color in the concave area, the product gamut was convexed. The convex polytope gamut was assumed as the AdobeRGB color gamut restricted by real object colors. This gamut will be called the restricted AdobeRGB color gamut or the restricted gamut in this study.

Expansion of Color Gamut

The gamut expansion algorithm employed in this study is defined in four steps. Although there was a difference in whether color gamut was expanded to the full AdobeRGB gamut or expanded within the restricted AdobeRGB color gamut, the expansion algorithm was the same as the method used in the previous study [1]. Also, the same images used in the previous study, three standard images defined in XYZ-SCID [6], are used in this study. Prior to the expansion, CIE *XYZ* tristimulus values of source sRGB image are loaded from the CD-ROM attached to ISO XYZ-SCID [6].

1. Convert *XYZ* values to *LCh* values representing lightness, chroma, and hue angle values
2. Perform the color gamut expansion with chroma mapping functions at each lightness level
3. Convert *LCh* values of the mapped colors to *XYZ* values
4. Convert *XYZ* values to *RGB* values of AdobeRGB

Step 1: Convert XYZ to LCh

Let the source and destination gamuts can be expressed in a constant hue plane as shown in Fig.2. Let $X_S Y_S Z_S$ denote the *XYZ* tristimulus values of a sRGB image. The values $X_S Y_S Z_S$ are transformed into CIELAB values, L^*_S, a^*_S, and b^*_S. Then hue angle

h_S and chroma C^*_S are calculated from the following equations with the values a^*_S and b^*_S.

$$C_S^* = \sqrt{(a_S^*)^2 + (b_S^*)^2}$$

$$h_S = \arctan(b_S^* / a_S^*)$$

Step 2: Perform gamut expansion

The gamut expansion is performed at each lightness level such that the chroma C^*_S of sRGB image is transformed to the chroma C^*_A in the restricted AdobeRGB color gamut by using a chroma mapping function [6,7]. The three types of functions shown in Fig.2 were used for chroma mapping. In this figure, $C^*_{S\ max}$ and $C^*_{A\ max}$ are the maximum values of C^*_S and C^*_A, respectively.

1. Linear function,

The mapping function is a linear function with a slope of more than one as follows,

$$C_A^* = \frac{C_{A\max}^*}{C_{S\max}^*} C_S^*$$

2. Knee function

This function consists of two linear functions, the first of which has a slope of one and the second expands the remaining range to the maximum chroma in the restricted AdobeRGB gamut, $C^*_{S\ max}$. These two linear functions are joined at the knee point with $C^*_S = C^*_{S\ max} / 2$.

$$\begin{cases} C_A^* = C_S^* & C_S^* \le C_{S\max}^* / 2 \\ C_A^* = C_S^* + (C_{A\max}^* - C_{S\max}^*)\left(\dfrac{2C_S^* - C_{A\max}^*}{C_{S\max}^*}\right) & C_S^* > C_{S\max}^* / 2 \end{cases}$$

3. Nonlinear function

This function increases linearly to $C^*_S = C^*_{S\ max} / 2$ and then exponentially to $C^*_{A\ max}$.

$$\begin{cases} C_A^* = C_S^* & C_S^* \le C_{S\max}^* / 2 \\ C_A^* = C_S^* + (C_{A\max}^* - C_{S\max}^*)\left(\dfrac{2C_S^* - C_{A\max}^*}{C_{S\max}^*}\right)^3 & C_S^* > C_{S\max}^* / 2 \end{cases}$$

Step 3: Convert Lch to XYZ

*L*a*b** values of the expanded image are caluculated from the *Lch* values. Then the *L*a*b** values are transformed into *XYZ* values by CIELAB to *XYZ* color space conversion.

Step 4: Convert XYZ to RGB

The *XYZ* values calculated in previous step are finally transformed into Adobe RGB color space [6].

Psychophysical Evaluation

A psychophysical experiment was performed to determine an optimum chroma mapping function for gamut expansion. As the source images to be tested, “Flower”, “Japanese goods”, and “Threads” shown in Fig.4 were selected from XYZ/sRGB-SCID [6]. These pictorial images contain a wide variety of objects in saturated colors and with rich gradation, which are suitable for evaluating color reproduction in image output devices. Three types of gamut-expanded images were generated by applying gamut expansion algorithm to each source image with three different chroma mapping functions. The images that had been the highest score among three algorithms in the previous study were added to the psychophysical evaluation as the image by the former method. Off course, the former method images were expanded to the original AdobeRGB gamut and not expanded within the restricted gamut. Combinations of two different gamut-expanded images, including the former method images and original images, were evaluated in paired-comparison method. The two gamut-expanded images were displayed on the same position of a monitor successively to exclude the effects of nonuniformity. A Nanao

(a) Flowers *(b) Japanese Goods* *(c)Threads*

Fig.4 Three images of XYZ-SCID used in this study color management monitor ColorEdge CG221, that supports Adobe RGB color space, was used to the evaluation. Eighteen observers, who were students of Tokyo Polytechnic University, took part in the experiment. Each observer was instructed to view a pair of images on the monitor, and to choose an answer from a list: "The former image is natural", " The latter image is natural", and "Can't tell." The viewing distance was about 40 cm and the experiments were performed in a dark room.

Results and Discussions

For each image, the comparison results for each observer were averaged over eighteen observers, being transformed into Z-scores. Case 5 of Thurstone's model was used for the data analysis. The Z-scores is treated as subjective evaluation score. The subjective evaluation score obtained for three images are shown in Fig.5. Although there are some differences among scores for images, the average score of Nonlinear function shows the highest score. This means that the expanded images by Nonlinear function was the most natural one.

While evaluating expanded images, there were an opinion that the higher chroma images look natural, and another opinion that the lower chroma image look natural, from the observers. From these opnions, it was thought that the impressions of the word "Natural" from chroma might differ among observers. The data of eighteen observers were applied to a cluster analysis. The result is shown in Fig.6. Furthermore, the evaluation score for the algorithms were averaged for each cluster at the case of dividing the observers into two clusters. The average scores for two clusters are shown in Fig.7. In Cluster 1, scores are high in order of Original, Nonlinear, Knee, and Linear. This order is an low order of the chroma of the images. In Cluster 2, scores are high in order of Linear, Knee, Nonlinear and Original. This order is a high order of the chroma of the images. The two clusters show completely opposite tendency. From these results, it turns out that there are those who feel that high chroma image is natural, and those who feel that low chroma image is natural. The scores of a completely opposite chroma images were offset by both clusters, and it seems that the score of middle chroma images became a highest one. It is thought that evaluation of Nonlinear function became the highest in the result.

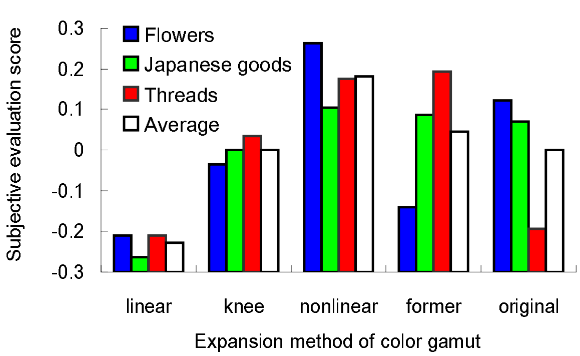


Fig.5 Subjective evaluation score for mapping functions

Summary

An algorithm expanding a narrow color gamut digital image to a large gamut one without spoiling naturalness was developed. The algorithm was applied to three sRGB images of XYZ-SCID with some functions and AdobeRGB images were calculated. The expanded images were evaluated psychophysically for naturalness. The result of the evaluation showed that Nonlinear function expanded images most naturally. Moreover, from a cluster analysis of observers it was found that there are two groups that feel chroma of image, i.e. the one group feel that a high chroma image is natural and the other group feel that a low chroma image is natural.

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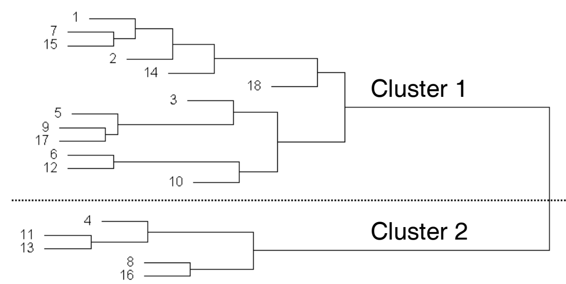

Fig.6 The results of cluster analysis

The numbers show Observer, and the lengths show

the Euclidean distancse between two clusters.

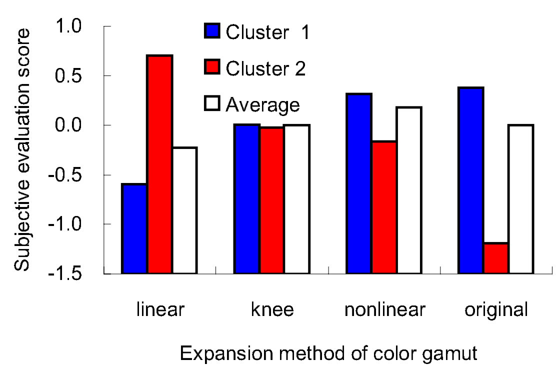

Fig.7 Average scores for Clusters

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