Gamut Extension Modelling Based on Observer Experimental Data

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Abstract

The principal aim of this study is to demonstrate the extended applicability of the experimental tool (GUI) used in the colour imaging manipulation experiment of gamut compression by applying it to the study of gamut extension. Unlike gamut compression, the gamut extension study mainly deals with pleasantness of observers. There has been very little published data about gamut extension so far. The results of the pilot gamut extension experiments in this study not only give worthwhile data but also suggest a methodology for using the observer experimental tool for future gamut extension research.

Introduction

The principal aim of this study is to demonstrate the extended applicability of the experimental tool (GUI) used in the colour imaging manipulation experiment of gamut compression[4,5] by applying it to the study of gamut extension. Two experiments were conducted, *Experiments GE1* and *GE2*. *Experiment GE1* was designed to acquire observer data on the extension of gamuts in terms of colour pleasantness, hence only one initial image was shown and then adjusted (extended) by observers using the computer-controlled interactive software.

Many plots were generated to examine the relationship between the initial and reproduction images in the same manner like the data analysis used for investigating gamut compression in the previous studies.[4,5] The reproduction images were then calculated by averaging each observer data for each image. These images were used to represent the mean visual results.

A GEA, GEA-1, was developed to model the observer experimental data from *Experiment GE1* and its coefficients for lightness and chroma extension were derived using the least square technique. Five variations, i.e. GEA2-6, took the structure of GEA1 and increased the amount of chroma extension so as to verify (1) the amount of extension that the observers have applied was indeed sufficient and (2) they were too cautious with their modifications in the *Experiment GE1*. In *Experiment GE2*, the GEA-1 and its five variations (GEA-2, 3…6) were evaluated using a pair comparison method together with the average observer images obtained in *Experiment GE1*. GEA-1, GEA-2 and the average images by the observers generally out-performed the others.

Interactive Tool

The experimental tool used in the previous studies[4,5] was modified for *Experiment GE1*. Observers were asked to alter the colours of image pixels based on their location in colour space. The colour space used was CIE$L^*a^*b^*$, however other colour spaces could have been used instead. The tool consists of two principal parts: C*olour* R*egion* S*elector* (CRS) for selecting a particular region of colour space and C*olour* A*ppearance* A*djuster* (CAA) for modifying the colour appearance of pixels from the selected colour region via the lightness, chroma and hue angle controls.

At the beginning of each experiment, the reproduction image was obtained using a gamut clipping algorithm (*LCLIP*).[6] The resulting image is referred to as the 'INITIAL' image. Using the tool, observers first inspected which part of the INITIAL image appeared to be the most unpleasant. They then selected their colour region in CIE $L^*a^*b^*$ via the CRS controls and adjusted these colours using the CAA controls. Unlike the compression experiment, just one reproduction image was shown to the observers at one time. They could extend the initial image colours towards the monitor gamut boundary. Provided that an observer extended a colour outside the medium gamut boundary, the tool automatically clipped it onto surface of the gamut boundary.

Procedure of Experiment GE1

Twelve observers took part in this experiment. Before the main experiment, a training session was conducted to verify the experimental procedure and their understanding of lightness, chroma and hue attributes. Observer group

took a training session for one hour. On average, each image took between 25 to 50 minutes to complete the adjustment. Four images, i.e. "IT8", "Ski", "Orchid", and "Smile", were used. This experiment was conducted twice for each image. The results for observer accuracy and repeatability in *Experiment GE1* were given in *Table 1*.

Table 1. Observer Accuracy and Repeatability (Experiment GE1) in $\Delta E_{CMC(1:1)}$ Unit

	Observer Accuracy	*Observer Repeatability*
Min	0.90	0.04
Median	4.85	5.14
Mean	4.96	5.39
Max	17.45	12.03
Standard Deviation	2.55	2.37

Observer accuracy measures the mean colour difference between individual images and observer average image, on the other hand, repeatability measures colour difference between two experiments carried out by one observer. Comparing to accuracy and repeatability of gamut compression experiments, variances of extension experiments are larger than those of compression experiments. Two images, original and reproduction, were shown in compression experiments, though only one initial image was shown in extension experiments, and then observers carried out to adjust the initial image depending on their pleasantness. The larger variance is caused by this difference between two experimental methods.

Analysis of Experimental Results

Seventy-six plots were generated to study the relationship between the initial and observer reproduction images. The reproduction images were calculated by averaging each observer data for each image. Like compression experimental data[4,5] figures of lightness and chroma between the initial and reproduction (extended) images, hue variations plotted between the hue angles and hue differences (ΔH^*), and data on the L^*-C^* planes were analysed. In this study, some typical examples are presented to describe the analysis and development of an algorithm.

A systematic pattern for lightness extension was found for all four of the images. The results from these were combined and plotted in *Figure 1* which also shows a minimum L^* value of about 25. This is caused by the limitation of the initial images generated within the reproduction (printer) gamut boundary having lightness ranging from 24.67 to 100.0. The solid line indicates a perfect agreement between the initial and reproduction results if all data points lie on the line. The results clearly show that the reproduction images are darker and slightly higher in contrast than the initial images.

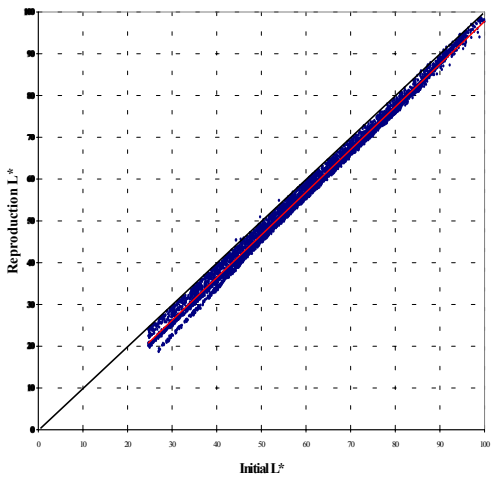

Figure 1. Initial L^* vs. Reproduction L^*, Combination of Four Images

In the similar manner to the L^* plots, the C^* values between the initial and reproduction colours were also plotted for each image. Analysis was also carried out to investigate the hue shift. First, the ΔH^* ($=2\ (C^*_o C^*_r)^{1/2} \times \sin(h_o - h_r/2.0)$) values were calculated and plotted against the hue angles for each image. The trend shows that colours were adjusted mainly in three hue areas red to be bluer, blue to be greener, and magenta to be bluer but almost no change for the other colours such as yellow, green and cyan. However, the magnitudes of adjustment are very small, i.e. between +2 and -2 in ΔH^* units. This implies that the hue shift is not essential for developing GEAs in this experimental domain.

Figures 2 is the L^*-C^* plots for the colour shift before and after the adjustment of the primary and secondary hues for the SKI image. In each plot, the initial and reproduction colours are shown using circle and cross symbols (α, β in *Figure 2*) respectively, and the dashed line represents the image gamut boundary (χ in *Figure 2*). Hue areas were divided depending on the primary and secondary colours of the CRT gamuts. The patterns of colour shifts for the SKI image in each of the primary and secondary hues are very similar to those in the IT8 and ORCHID images, but not the SMILE image. It can be seen that all colours in the SMILE image were adjusted in the lightness direction to become darker, but not in the chroma direction. This indicates that the image content has an impact on gamut extension. The SMILE image includes face of a girl which has different image characteristics to the other images. All the plots were used to develop a new GEA. Most people have a notional skin colour and it seems observers produced a stimulus of this colour in the experiment. 'Memory colour' refers to this phenomenon that recognisable objects often have a prototypical colour that is associated with them.[1]

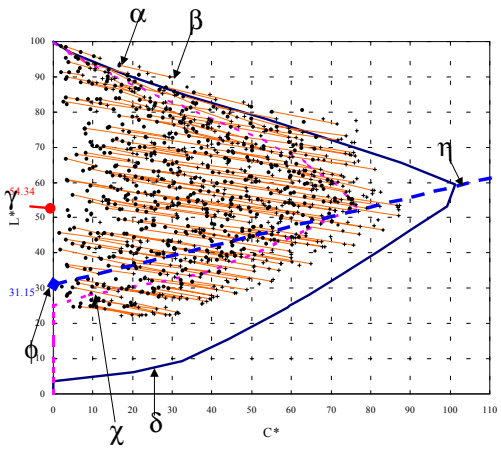

Figure 2 Results of Experiment GE1, Analysis of L-C* , SKI, Red and Yellow (α: Initial Colour; β: Reproduction Colour; χ: Image Gamut Boundary; δ: Original Medium Gamut Boundary; φ: Intercept Point of η; γ: Lightness of Cusp of Reproduction Medium;η: Connecting Cusps between Original and Reproduction Media)*

To investigate hue-dependency in this extension experiment, three different values, i.e. lightness of cusp of original medium ($L^*_{(cusp,\ medium)}$ in *Table 2*), lightness of cusp of image gamut ($L^*_{(cusp,\ image)}$) and slope of extension shift ($(L^*_r-L^*_i)/(C^*_r-C^*_i)$) (Σ in *Table 2*; subscripts *i* and *r* denote initial and reproduction), were calculated. This analysis is aimed to investigate how much information of gamut boundary is statistically related to observer data of *Experiment GE1* data. The higher correlation means that lightness-chroma extension function should be hue variant. *Table 2* shows correlation results.

Table 2. Correlation Results between Gamut Information and Observer Experimental Data

	Correlation between $L^*_{(cusp,\ medium)}$ and Σ	Correlation between $L^*_{(cusp,\ image)}$ and Σ
IT8	0.46	0.60
Ski	-0.29	-0.16
Orchid	-0.18	0.17
Smile	-0.43	-0.91
All Images	-0.10	-0.39

Table 2 shows (correlation) results of individual test images and the case of 'all images' which represents correlation between all observer data against gamut information of four test images. As shown in the *Table 2*, poor correlation results were obtained, such that gamut extension is not related with gamut shape: hue-invariant in this experimental domain (test images and medium gamut). This verifies hue-invariant chroma extension function of GEA-1 (*Eq. 2*).

As shown in *Figures 1*, all initial images were adjusted to become darker and to extend their lightness ranges. A linear function was devised to fit this trend. The results are given in *Table 3* for each individual image and the combined data. In addition, the modelling accuracy is reported in terms of the correlation of determination (R^2). The results clearly show that the model developed for each image is very similar and each model fitted the experimental data well. It was decided that the lightness extension equation, $L_r = 1.02L_o - 4.44$, (where subscripts *o* and *r* denote the original and reproduction respectively) (*Eq. 1*).

Table 3. Regression Results of L* – Gamut Extension

Image	Model	Accuracy of fitting (R^2)
IT8	$L_r=1.04L_o-5.93$	99.99%
Ski	$L_r=0.99L_o-1.38$	99.81%
Orchid	$L_r=1.03L_o-5.34$	99.99%
Smile	$L_r=1.06L_o-8.14$	99.90%
All	$L_r=1.02L_o-4.44$	99.48%

The analysis of chroma data shows that there is a distinct linear gamut extension for three of the test images, i.e. the majority of colours are (linearly) located above the 45° line in "IT8", "Ski", and "Orchid" image. However, in the 'Smile' image, it can be seen that chroma values of the initial and reproduction are divided into two groups: one group lies on the 45° line and the other is located above the 45 ° line. It was found that the group around the 45° line includes colours, red, yellow, and green in the SMILE image. This is a typical example illustrating that the image content has a large impact on observers when performing gamut extension. Lightness dependent chroma extension suggested by Hoshino[2,3] was not observed in the data from *Experiment GE1*.

In the chroma extension modelling, GEA-1 is a basis for further model evaluation. Smile image was not included in modelling GEA-1 due to its anomalous extension pattern, particularly in lower range. Prediction accuracy and linearity of chroma extension in GEA-1 is again acceptable from the statistical analysis point of view (88%: R^2). A coefficient was obtained using least square fitting technique of statistics analysis software (SPSS™ version 6.0).

A gamut extension algorithm (GEA-1) was developed based upon analysis above:

STEP 1: A Linear Lightness Mapping

A linear lightness mapping is defined in the following equation.

$$L_r = 1.02L_o - 4.44 \qquad \text{(Eq. 1)}$$

where subscripts *o* and *r* denote the original and reproduction.

STEP 2: A Linear Chroma Mapping

$$C_r = \theta C_o \qquad \text{(Eq. 2)}$$

where $\theta = 1.33$

Coefficient 'θ' was obtained using least square fitting technique of statistics analysis software.

As mentioned, other models (GEA2-6) were devised for (1) to test GEA-1 and (2) to encompass possible perception of pleasantness in higher extension rates. *Experiment GE1* data shows that observers did not fully adjusted chroma onto CRT gamut boundary. Particularly, developing the group-2 models (*Table 4*) tried to cover the different observer behaviour in the lower chroma levels in the "Smile" test image. This behaviour was analysed as the skin tone colours considered as "memory colour". This was also evaluated in *Experiment GE2*.

Table 4. Five Different Variations of Chroma Extension

Group	GEA	(Extension) Starting Point	Image data used to fit each model	Sub-Group[1]	θ	R^2
1	2	(0, 0)	IT8, Ski, Orchid	2+3	1.57	0.87
	3	(0, 0)	IT8, Ski, Orchid	3	1.93	0.85
2	4	(23, 23)	IT8, Ski, Orchid, Smile	1+2+3	1.48	0.54
	5	(23, 23)	IT8, Ski, Orchid, Smile	2+3	2.05	0.29
	6	(23, 23)	IT8, Ski, Orchid, Smile	3	3.53	0.14

1: Divide group into three sub-groups (1, 2, 3) in terms of the extent of gamut extension , i.e. $a=C^*/C^*_o$ (*Cr*: chroma of reproduction, *Co*: chroma original)

The *Group-1* model was devised from the averaged data of three test images, i.e. "IT8", "Ski" and "Orchid", having the chroma extension pattern from the origin (neutral point). The *Group-2* models were developed using all four averaged data sets. This model is divided into two parts with a point of 23 (of chroma): this value was obtained qualitatively. It assigns C^*_r to be the same as C^*_o for C^*_o less than 23, otherwise $C^*_r = \theta C^*_o$ where θ is the slope obtained from various plots. Each group of models is divided into two or three in terms of the degree of gamut extension determined by the slope of C^*_r/C^*_o which are given in *Table 4*. The models plotted using a solid line represent group-1 where the starting point is zero and the degree of chroma extension is gradually increased from GEA-2 to GEA-3. The models plotted using a dashed line represent group-2 where the chroma of original and reproduction is the same below C^*=23.0 and the degree of chroma extension is gradually increased from GEA-4 to 6.

Experiment GE2

Experimental Procedure

Experiment GE2 was designed to evaluate the performance of the GEA-1 and five its variations together with the averaged observer data obtained in *Experiment GE1*. This experiment was carried out to verify the GEA-1 that the amounts of extension observers have applied was indeed sufficient. Twelve observers (six females and six males) took part in this experiment using the pair comparison technique. A training session was arranged for the observer group. In the main experiment, a pair of images was shown to each observer and their task was to select which of the two was more pleasant.

Even though Hoshino suggested wide range of extension methods in his patent[2,3] his methods could not be included in the experiments of this study as (1) detailed extension procedures were not specified, (2) performance evaluation between the methods was not specified and (3) data of user experiments of this study indeed did not agree with those of his methods.

Result and Discussion

The higher the z-score, the higher degree of pleasantness judged by observers (*Figure 3*). The 95% confidence interval for each z-score was calculated. It can be seen that *GEA-1* and *2* generally performed better than Group 2 algorithms. As expected, the averaged observer data for each image also gave quite satisfactory performance. This implies that the overall experimental design is reliable. A closer inspection of z-score results reveals that *GEA-1* performed the best for the "IT8" and "SMILE" images, but second worst for the "ORCHID" image. This implies that once again the model performance depends upon the characteristics of the image investigated.

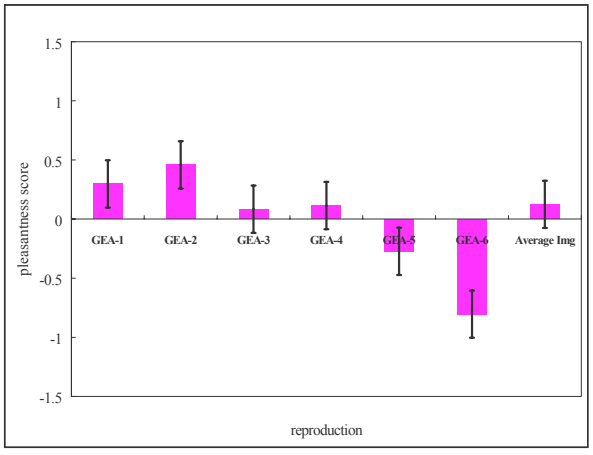

Figure 3 Overall Z-Score Results of Experiment GE2

During the experiment, each observer was also asked to compare the degree of pleasantness in different colour regions of an image. This was normally specified in terms of colour objects in each image. The data was also analysed and the results agree well with individual image data. The difference of z-scores between individual GEAs is not too large, although skin colour cases show dissimilar. This is caused by the fact that observers are sensitive to a familiar (memory) colour such as skin tone, in carrying out the colour extension experiment.

Conclusions

Using the modified computer-controlled interactive software, twelve observers conducted experiments for extending colour gamuts so as to achieve pleasing reproductions. Based on the experimental data, a GEA was developed. After an initial linear lightness extension, five different models were devised according to the degrees of chroma extension.

A subsequent experiment was conducted to evaluate a newly-developed GEA-1, five its variations together with the averaged observer data. The results show that group 1 algorithms generally performed better than group 2 algorithms in terms of colour pleasantness. It was also found that there are larger observer variations in this kind of experiment as there was no reference image for comparison unlike the earlier gamut compression experiments.

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Biographies

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