

Gamut Compression Algorithm Development on the basis of Observer Experimental Data

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Abstract

An interactive tool was developed for matching a pair of pictorial images having different colour gamuts. Three GCAs (G*amut* C*ompression* A*lgorithms*) were developed based on the experimental data from a panel of 22 observers. Further experiments were conducted to evaluate the performance between the newly-developed and six existing GCAs together with an image based on the average observers' results. One of the new algorithms significantly outperformed the others. A generally usable algorithm was also developed for taking into account all possible application conditions.

Introduction

The process of mapping colours from an original medium to fit the gamut of a reproduction medium is called gamut mapping and can be of two major types - *gamut clipping* and *gamut compression*. Numerous gamut mapping approaches have been proposed and examined in the past, whereby in most studies algorithms were first defined and then evaluated by observers making judgements about the algorithms' suitability for a given reproduction intent. However, there have been very few studies in which observers interactively adjust reproductions of complex images and thereby explore the possibilities of gamut compression.

The aim of this study is to achieve a reliable GCA. Five tasks are included in this study: to develop an interactive experimental tool for the acquisition of experimental data, to develop GCAs on the basis of the experimental data, to evaluate existing and newly-derived GCAs, to develop a generally usable algorithm based on the most preferred one in the previous experiment, and to evaluate the generalised algorithm with some other existing GCAs.

Three experiments were performed. The first Experiment was a matching experiment, in which observers were asked to match an original image (within a CRT gamut) by adjusting a second image (within a printer gamut, which was much smaller than that of CRT) using an interactive tool whereby both images were displayed on a CRT. Based upon the experimental data, three GCAs were developed. The second experiment was aimed to evaluate the performance of the newly-derived and some existing algorithms, i.e. LCLIP, LCUSP, GCUSP, SLIN, LLIN, CLLIN[1] together with an image based on the average observers' results from the first experiment. For the best performed GCA, a generalised algorithm was developed in order to apply it to any original and reproduction media. In the third experiment, the psychophysical experiment was again carried out to verify the generalised GCA.

Interactive Tool

An interactive tool[2] was developed for modifying colour appearance of pictorial images displayed on a monitor, whereby this was performed by altering the colours of their pixels depending on the region of CIELAB colour space into which they belong. The tool consists of two principal parts: one for selecting a particular region of colour space, and another for modifying the colour appearance of pixels from the selected colour region via the lightness, chroma and hue angle controls.

The First Experiment

Four images (i.e. IT8, Ski, Orchid and Smile) were selected in this study. The original and reproduction images were arranged side by side on a CRT display and had very different gamuts. The original gamut was that of a CRT (Sony Trinitron CPD monitor) and the reproduction gamut was that of a printer (IBM LexMark InkJet 4097), respectively. Eleven observers took part in the experiment. . Observers took a training session and passed the Ishihara Vision Test. In the real experiment, each observer did the adjustments twice for each image. On average, each image took about 30 to 60 minutes to complete.

Algorithm Development

Qualitative analysis was carried out by generating plots for visualising the relationship between the original and reproduction images. The reproduction images were calculated by averaging each observer's data pixel-by-pixel for each image whereby these images represent the mean visual results. Comparing the L^* values between original and reproduction colours, almost all images were adjusted to be brighter for the reproduction images. There is a distinct curve for colours close to dark end. This is caused by the limitations of dark colours for the printer devices, i.e. the printer black is not dark enough. This suggests that contrast is more important than maintaining differences between lightness levels. The trend of hue shifting is quite clear that red should be bluer, green and magenta be bluer, respectively. However, the magnitudes of hue adjustment were small, i.e. between +2 and -2 ΔH^* units.

The first attempt for developing an algorithm was performed basically by modifying the CLLIN algorithm.[3] The chroma mapping procedure of CLLIN is given below:

$$C_r^* = \begin{Bmatrix} C_o^* \times \left(\dfrac{C^*_{cusp,r}}{C^*_{cusp,o}} \right); C^*_{cuspo} \geq C^*_{cuspr} \\ C_o^*; C^*_{cusp,o} < C^*_{cusp,r} \end{Bmatrix} \qquad (1)$$

where subscripts o and r denote the original and reproduction gamuts respectively. Comparing the chroma of average observer images and data transformed via the CLLIN algorithm, it was found that the resulting relationship was not linear, while lightness compression followed a linear function. Hence the core for deriving GCA-1 was to include a non-linearity chroma compression as given in equation (2).

$$C_r^* = \begin{Bmatrix} (1-\alpha)\times C_o^* + \alpha \times [C^*_{cusp,r} - (C^*_{cusp,o} - C_o^*) \times \left(\dfrac{C^*_{cusp,r}}{C^*_{cusp,o}} \right); \\ for\ C^*_{cusp,o} \geq C^*_{cusp,r} \\ C_o^*; otherwise \end{Bmatrix}$$

$$\alpha = 1.0 - (1 - \alpha_{\min}) \times e^m \qquad (2)$$

where

e: Euler's number ($ln^{-1}1$)
$L_a = 0.797 \times L^*$ *of reproduction medium cusp;*
$C_a = 0.563 \times C^*$ *of reproduction medium cusp;*
$\alpha_{min} = 1.84 \times (C_a / C^*$ *of original medium cusp);*
δ*: 22 (arbitrary disperse parameter)*

$$m = -\left(\frac{L^* - L^*_\alpha}{\delta} \right)^2 - \left(\frac{C^* - C^*_\alpha}{\delta} \right)^2$$

After the chroma compression, the lightness is linearly map along lines of constant chroma using equation (3).

$$L^*_r = L^*_{r2} + (L^*_o - L^*_{02}) \times (L^*_{r1} - L^*_{r2}) / (L^*_{r01} - L^*_{02}) \qquad (3)$$

where the subscripts $o1$ and $o2$ denote the maximum and minimum respectively of the original gamut and $r1$ and $r2$ denote those of the reproduction. Derivation of the chroma compression formulae depends on the assumption that chroma compression follows a non-linear way relative to the gamut boundaries and this non-linear function follows the normal distribution determined by three different parameters, i.e. chroma, lightness and α. Formulae for determining L_α, C_α, α_{min} were derived by observing the relationship between α and the cusp's lightness (or chroma) in the qualitative plots. The primary shortcoming of this algorithm is that the procedure used for deriving was too heuristic and complex.

Algorithm 2 (GCA-2) Development

Further observing the L^*-C^* plots between original and observer data, it was found that compression patterns can be grouped into three in terms of their converging vectors towards the L^* axis. *Figure 1* shows the modelling of this phenomenon.

The GCA-2 was developed according to figure 1. Its procedure is described below.

[STEP 1] Lightness Mapping

The lightness mapping function was derived by modelling the relationship between the lightness of original and observer data. This takes into account the media used in the experiment by having as parameters the minimum L^* point, which is the point where slope is changed, and the maximum L^* point. A piece-wise linear interpolation function, connecting these three points, was then derived to model the relationship as follow.

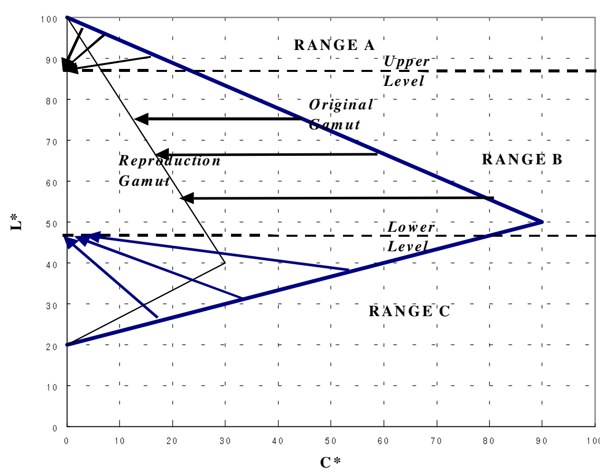

Figure 1. Three Different Patterns and Two Convergent Points

if $L^*Min,o \leq L^*o \leq L^*Min,o + ((16.9/A)\ (L^*Max,o - L^*Min,o))$

$$L_r^* = \left[L^*_{Min,r} + \frac{1.8}{A} \left(L^*_{Max,r} - L^*_{Min,r} \right) \right]$$

$$-\frac{10.65}{A}\left[\left(L^*_{Min,o}-L^*_o\right)+\frac{16.9}{A}\left(L^*_{Max,o}-L^*_{Min,o}\right)\right]\left(\frac{\left(L^*_{Max,r}-L^*_{Min,r}\right)}{\left(L^*_{Max,o}-L^*_{Min,o}\right)}\right)$$

*else if (L*Min,o +(16.9/A) (L*Max,o - L*Min,o))≤L*o≤ L*Max,o*

$$L^*_r=L^*_{Max,r}-1.18\left(L^*_{Max,o}-L^*_o\right)\frac{\left(L^*_{Max,r}-L^*_{Min,r}\right)}{\left(L^*_{Max,o}-L^*_{Min,o}\right)} \quad (4)$$

where subscripts o and r denote the original and reproduction respectively

[STEP 2] Determining Convergent Point

Investigating 24 L^*-C^* plots (6 hues × 4 test images), three patterns in terms of their converging vectors on the L^* axis were revealed. Two convergent lightness points were determined by the L^* of the original medium's cusp. The two convergent points are named upper and lower level points, which are calculated below

<2-1: Lower convergent point>

If original medium cusp's L^* <= 30 then lower convergent point is 31.54 (L^*)

Otherwise

Lower convergent point = 19.42+0.404 × original cusp's L^*

<2-2: Upper level convergent point>

If original medium cusp's L^* <= 49 then upper convergent point is 70.12 (L^*)

Otherwise

Upper convergent point = 49.297 +0.425 × original cusp's L*

[STEP 3] Chroma Compression

Comparing chroma as predicted by LLIN[1] with the chroma of observer data, the relationship shows that observer chroma reaches its maximum at C^*=11.93 which is 17% of the original cusp's chroma, and about 1.90 times greater than that of LLIN. The chroma compression of GCA-2 follows this non-linear way as shown in Figure 1. It can be seen that the convergent point is determined by whether the lightness of the colour is higher than the upper level convergent point, or lower than the lower level convergent point. Between the two convergent points the colour is mapped along lines of constant lightness.

In summary GCA-2 consists of these three steps: (1) piece-wise linear lightness mapping, (2) the determination of convergent points, and (3) lightness-chroma compression along either constant lightness lines or lines towards convergent points. In terms of accurately modelling observer experimental data GCA-2 outperforms GCA-1. However, there are shortcomings for GCA-2 as described below. Unwanted artefacts were found particularly in darker blue areas in 'Ski' image. This indicates that the lower level convergent point needs to be further improved. In addition, chroma compression function does not fit precisely to the experimental data, especially for higher chromatic region.

Algorithm 3 (GCA-3) Development

The procedure of GCA-3 is identical to that of GCA-2 except for modifications to steps 2 and 3.

[STEP 2]

To circumvent the shortcomings in GCA-2, the distance between lower and higher level convergent points was extended, that is, making the higher convergent point higher and the lower point lower. A new set of equations were defined:

<Lower convergent point>

If original medium cusp's L* <= 30 then lower convergent point is 28 (L*)
Otherwise
Lower convergent point = 45 × (original cusp's L*/100)^2-2.8(original cusp's L*/100)+24.8

<Higher convergent point>

If original medium cusp's L* <= 30 then lower convergent point is 75 (L*)
Otherwise
Lower convergent point = 67 × (original cusp's L*/100)^2-51.97(original cusp's L*/100)+84.8

[STEP 3]

For chroma compression, a new equation was derived as given in equation 5.

$$C_{compressed}=-1\times\left(\frac{7.8}{B}\right)\times(C^*)^2+\left(\frac{122.78}{B}\right)\times(C^*)+3.409 \quad (5)$$

where B=1000 (constant)

The Second Experiment

Twelve observers took part in the second experiment using the pair comparison method and the four images used in the first experiment were again used. These images were mapped through the three newly- derived and six existing algorithms (i.e. LCLIP, LCUSP, GCUSP, LLIN, CLLIN and SLIN) together with an image based on the average observers' results in the first experiment. In the experiment, an original image was shown to an observer, after 20~30 seconds, two images by different compression algorithms were given to the observer in order for him or her to select which of the two is closer to the original. If an observer could not make decision immediately, then the original was shown again. Based on Thurstone's law of comparative judgement.[4] Overall accuracy results are shown in *Figure 2* in terms of Z score. It can be seen that the newly-derived algorithms together with the average observer image significantly outperform the existing algorithms. Amongst the new algorithms, GCA-3 is the best and even better than the average observer image. For the existing algorithms, GCUSP outperforms the other five. The results of the overall case are very similar to those of individual images.

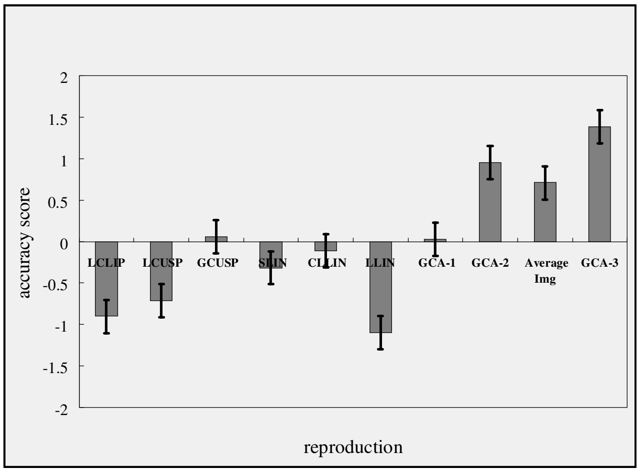

Figure 2. Overall scores averaged for four images: the second experiment (Error bars represent 95% confidence interval)

Development of Generally Usable Algorithm

From the second experiment, GCA-3 was evaluated as the most preferred one. Though, as this algorithm was developed depending upon the media gamuts of the original and reproduction used in the first experiment. Hence, GCA-3 would most probably not give consistently good colour matching results for other reproduction media. To overcome this problem, *algorithm generalisation* was performed as follows.

[STEP 1] Lightness Compression

This step is the same as step 1 of GCA-2.

[STEP 2] Convergent Point Determination

- Upper Level

if $L^* < K_0$ then Upper convergent point is $f(K_0)$

otherwise

$$upper\ point = f(x) = 45 \times \left(\frac{(x - K_0)}{100} \right)^2 + K_1$$

-Lower Level

if $L^* < K_1$ then Upper convergent point is $g(K_1)$

otherwise

$$g(x) = 45 \times \left(\frac{x}{100} \right)^2 - 2.8 \times \left(\frac{x}{100} \right) + k_2$$

where

x: original gamut cusp's lightness of a colour

K_0: lowest lightness values in the cusps' lightness of six primary and secondary reproduction gamuts

K_1: mean of lightness values of six primary and secondary reproduction gamuts × 1.40

K_2: lowest lightness of reproduction gamut

This step was obtained by optimising individual parameter, then fit it on experimental data.

[STEP 3] Re-compress Lightness and Chroma Simultaneously

$$d_3 = 1.12 \times \left(\frac{d_1 \times d_2}{d_0} \right) \qquad (6)$$

where

d_0: Distance between convergent point and original media's ga mut boundary

d_1: Distance between convergent point and original colour

d_2: Distance between convergent point and reproduction media's gamut boundary

d_3: Distance between convergent point and compressed point.

When joining line between a colour (d_1) and a convergent point *(l)* from Step 2, d_0 and d_2 can be defined using one-dimensional equation derived on the (d_1, l). Coefficient of 1.12 was obtained by fitting the experimental data.

The Third Experiment

In the third experiment, twelve observers conducted psychophysical experiments using pair comparisons to verify the performance of the generalised algorithm. The four images used in the second and third experiments were again used. Each image was processed using six algorithms: *GCUSP*, *GCA-1*, *GCA-2*, *GCA-3*, *GCA3-h*, *GUGCA (Generally Usable Algorithm)* together with the average observer image. *GCA3-h* is GCA-3 extended by modelling the hue shifting behaviour from the first experiment. Overall Z score (accuracy) results are shown in Figure 3 based on Thurstone's law of comparative judgement.[4] It can be seen that the *GCA-3, GCA-3-h, GCA-2, GUGCA* together with the average observer images have very similar accuracy scores taking into account confidence level. Hue shifting did not give better results than the non-hue-shifting algorithms. It is encouraging that GUGCA performed even slightly better than GCA-3.

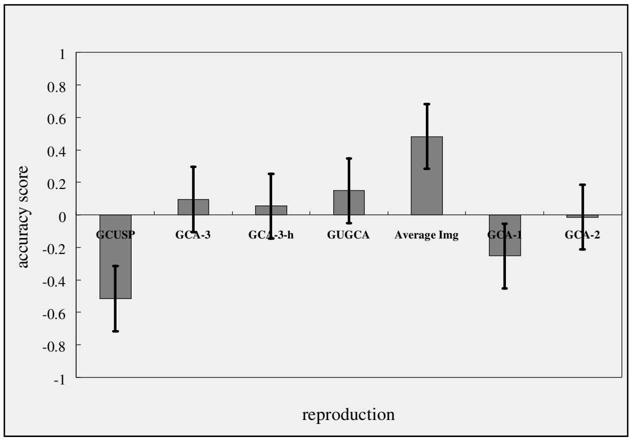

Figure 3. Overall scores averaged for four images: the third experiment (Error bars represent 95% confidence interval)

Conclusions

An interactive tool[2] was developed for selecting a particular colour region of a pictorial image in CIELAB colour space and for modifying this image to match the original image using colour controls based on CIELAB attributes. The original and reproduction images were limited by the colour gamuts of a CRT and a printer. The results were used for evaluating and developing GCAs. The experimental results were represented by average each individual observer's image pixel by pixel and were analysed by generating various plots to reveal the colour shifts between the averaged and original images. Three different algorithms were developed. The psychophysical experiments were conducted to verify these algorithms. The best algorithm was then generalised. It was further evaluated. The results showed that its colour matching performance was similar to that of the best algorithm.

References

1. J. Morovic, *To Develop a Universal Gamut Mapping*, Ph.D. Thesis, University of Derby, UK (1998).
2. B. H. Kang, M. S. Cho, J. Morovic, and M. R. Luo, Gamut compression algorithm development using observer experimental data, *Proceedings of the 7th IS&T/SID Color Imaging Conference*, pg. 295-300. (1999).
3. J. Morovic, and M. R. Luo, Gamut mapping algorithms based on the psychophysical experiments, *Proceedings of the 5th IS&T/SID Color Imaging Conference, pg. 24-49.* (1994)
4. L. L. Thurstone, A law of comparative judgement, *Psychology Review* 34:273-286 (1927).

Biography

Byoung-Ho Kang received his M.Sc. degree in Computer Science from the University of Georgia in 1993 and is a Ph.D. candidate at the Colour & Imaging Institute, University of Derby. Since 1989, he has worked at the Electronics Telecommunications Research Institute, Korea.

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