

Gamut Compression Analysis Based on Observer Experimental Data

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Abstract

An interactive tool was developed for modifying the colour appearance of pictorial images displayed on a monitor, whereby this was done by altering the colours of their pixels depending on the region of colour space into which they belonged. Using this tool, eleven observers took part in the experiments in which they modified the colours of four images processed through a gamut mapping algorithm. Observers first inspected which part of the reproduction image gave the most unsatisfactory match, then selected the corresponding region of CIELAB, and finally adjusted the image pixels from that region. Data analysis was then carried out to compare the original and reproduced images by generating various plots.
Keywords: Gamut compression, interactive psychophysical experiment

Introduction

In colour image reproduction across different media, each medium can produce only a subset of the visible colour space - the medium gamut. Hence, it needs to be ensured that all colours are transformed to colours which can be reproduced. The process of mapping colours from a 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. Gamut clipping alters out-of-gamut colours so as to render them reproducible, whereas gamut compression is applied to all original colours and can modify even colours which by themselves would be reproducible so as to distribute gamut differences across the entire range [1].

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. An alternative to this approach is to give the observers the possibility to adjust image colours so as to make them a better representation of the original. This is in fact the approach taken by Ebner and Fairchild [2], who asked observers to adjust the colour of uniformly-coloured simple images from a smaller gamut so as to make them more similar to corresponding original images from a larger gamut. The result of this study was experimental data on how human observers perform gamut clipping. As far as gamut compression is concerned, the most similar kind of data comes from the study of Johnson et al. [3] which analysed reproductions made by skilled scanner operators and then attempted to model the results. However, there has as yet been no study in which observers had the possibility to interactively adjust reproductions of complex images and thereby explore the possibilities of gamut compression.

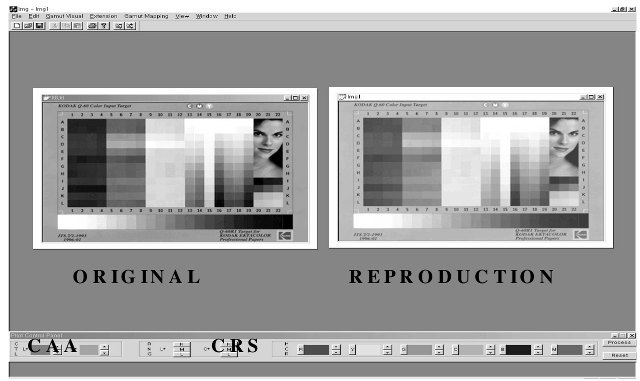
One of the reasons for the absence of direct experimental data on which to base gamut compression is the increased complexity of the task as compared to what needs to be done for gamut clipping. Firstly, gamut compression is determined not only by the reproduction gamut (as is the case for gamut clipping) but also by the original gamut and by the nature of the relationship between the two. Secondly, the evaluation of gamut compression requires the use of complex, multi-colour images and it is not applicable to the reproduction of single colours. Thirdly, the functionality required of an experimental apparatus for letting observers adjust the nature of gamut compression also represents a difficulty as does the choice of the starting point in the process. The principal aim of this study is to present an interactive experimental tool developed for the creation and acquisition of experimental data on gamut compression. This tool will be described in detail, and an experimental setup will be introduced from which an example of the results will be presented. Having this kind of data will aid the development of gamut compression techniques and enable them to be more closely related to human judgement.

An Interactive Gamut Compression Tool

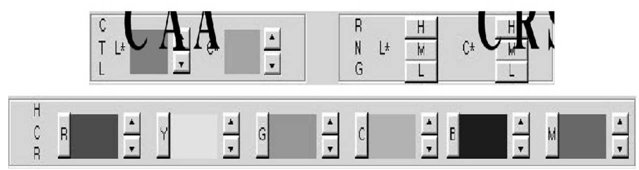
An interactive tool was developed for modifying the colour appearance of pictorial images displayed on a monitor, whereby this is done by altering the colours of their pixels depending on the region of colour space into which they belong. Note, that in this case the colour space used was CIELAB, however, other colour spaces could easily be used instead. The tool consists of two principal parts: one for selecting a particular region of colour space, designated Colour Region Selector (CRS), and another for modifying the colour appearance of pixels from the selected colour region via the lightness, chroma and hue angle controls, designated Colour Appearance Adjuster (CAA). The overall interface of the experimental display (showing the original and user-adjusted reproduction images) is illustrated in Fig. 1a and the CRS and CAA tools are shown in more detail in Fig. 1b.

In the beginning of each experiment, the reproduction image is obtained using a gamut mapping algorithm, whereby this image is referred to as the initial image. Using the tool, observers first inspect which part of the reproduction image gives the most unsatisfactory match. They then select the corresponding colours in CIELAB via the CRS controls, and then adjust all image pixels from that region using the CAA controls. For example, an observer sees that the high key neutral colours in an image are too dark and have a yellow tint. He or she needs to first select the high lightness and low chroma region in CIELAB and adjust it to be lighter and bluer, or less colourful.

As shown in Fig. 1, the CRS tool includes three selectors: lightness, chroma and hue. Lightness and chroma are each divided into three colour regions - the high, medium and low ranges, i.e. L* of 0-35, 35-65 and 65-100, and C* of 0-25, 25-50 and 50 to the maximum achievable chroma respectively. Hues, on the other hand, were divided into six different sectors: red, yellow, green, cyan, blue, and magenta, ranging from 356.5-59.0, 59.0-128.0, 128.0-180.5, 180.5-226.0, 226.0-291.0, and 291.0-356.5 degrees respectively, whereby this division is based on the hue angles of the unique hues.



(a)



(b)

Fig. 1: Experimental display: A) Tool,
(B) CRS controls and CAA controls.

The CAA controls allow subjects to modify colours by increasing or decreasing a particular colour by steps of two units for lightness and chroma, and one unit for hue. Observers can select and modify colours using one attribute, e.g. first select high chroma region and increase or decrease its chroma, or using more than one attributes, e.g. select low chroma and high lightness region, and increase or decrease one of three attributes (i.e. lightness, chroma, hue).

The procedure for applying the changes indicated by observers can be written using the following notation which shows lightness changes as example:

$$L^{*\prime}=f(L^{*}0,\ PL^{*}Low,\ PL^{*}Medium,\ PL^{*}High)$$

$$L^{*\prime\prime}=g(L^{*\prime},\ PC^{*}Low,\ PC^{*}Medium,\ PC^{*}High)$$

$L^{*}''' = h(L^{*}'', PH^{*}Red, PH^{*}Yellow, PH^{*}Green, PH^{*}Cyan, PH^{*}Blue, PH^{*}Magenta)$

Here $L^{*}0$ is the lightness from the initial gamut-mapped image, Pij is the observer-selected lightness adjustment parameter for interval j of colour attribute i. Analogous equations apply to chroma and hue angle as well. These transformations are always applied to the initial gamut-mapped image and the transformation coefficients (e.g. Pij) are refined by the observers. The nature of the iterative adjustment is shown in the following example: if one is changing the lightness of the low lightness region (i.e. PL*Low) by +1, +2, +10 and −2 then the resulting change applied to the initial gamut-mapped is a simple sum of these-i.e. 11.

The resulting change affects not only the desired colour region but also has a slight effect on colours in neighbouring regions. This is done intentionally to avoid discontinuities between colour regions defined by CAA controls. Once the operating procedure for modifying a colour region is completed, observers press the ' *PROCESS* ' button. This leads to the initial gamut-mapped image being processed and displayed to replace the reproduction image. If the colours selected are out-of-gamut, they are automatically clipped onto the CRT gamut boundary using the same Gamut Mapping Algorithm (GMA) as used for the initial image.

The Experiment

Four images were used in this study: IT8, Ski, Orchid and Smile. The original and reproduction images were arranged side by side on a CRT display as shown in Fig. 1 and had very different gamuts. The original gamut was that of a CRT and the reproduction gamut that of a printer, i.e. a Sony Trinitron CPD monitor and an IBM LexMark InkJet 4097 Printer respectively (for their gamuts see Figs. 2 and 3).

The coordinates of the primary and secondary colours for each device are plotted in a*b* diagram as shown in Fig. 2 together with the gamut boundaries of the original and reproduction devices. Figs. 3a to 3f are the gamut boundaries for each of the primaries and secondaries plotted in an L* vs C* diagram. All figures show that the gamuts of the two devices are quite different not only in volume but also in shape. The CRT gamut is much larger than that of the printer, except for the cyan region.

The LMT C1210 colorimeter was used for measuring the CRT which was modelled using the GOG model developed by Berns et al. [4] whereby the white point was set to D65. A test was then carried out by comparing the measured and model predicted results based upon 729 testing colours which covered entire colour gamut. The results show an average colour difference of 0.6 with a maximum of 1.7 ΔE CMC(1:1) units. For characterising the printer, the tristimulus values were measured by an Xrite 938 spectrophotometer. A third-order masking equation was derived between the printer's CMY and XYZ values. Another test was carried out using 729 colours. The results show a mean prediction error of 3.7 with a maximum of 8.4 ΔE CMC(1:1) units under D65 for the CIE 1931 standard colorimetric observer. This degree of accuracy is considered to be quite reasonable especially as the printer characterisation model was only used for calculating the simulated reproduction gamut boundary.

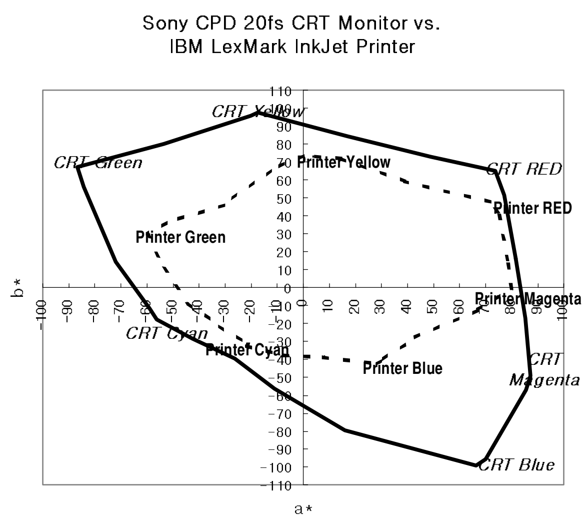


Fig. 2: Colour gamut differences between the original (CRT) and reproduction (printer) devices

Eleven observers, who were staff of the CSTL, ETRI, took part in the experiment which was carried out in a darkened room. Each observer took a training session prior to the real experiment. They all passed the Ishhara Vision Test. In the real experiment, each observer did the adjustments twice for each image. These results were used to investigate the observer repeatability. On average, each image took about 30 to 60 minutes to complete. For each image, there were two initial images, which were gamut compressed using the LCLIP and LCUSP GMAs [5]. These results will be used for investigating whether the experiment is initial image dependent.

Results

Observer Variation

Observer variation was evaluated in terms of accuracy and repeatability. Observer accuracy was calculated in terms of ΔE CMC(1:1)[6] between the mean image and each individual observer adjusted image. The mean, minimum and maximum ΔE CMC(1:1) values for all four images combined are given in Table 1 . The observer repeatability results were calculated between two repetitions by each observer. Again, the mean, minimum and maximum results are summarised in Table 1. The results in Table 1 are quite encouraging in that all observers performed fairly consistently and there was no sign of observer repeatability and accuracy depending on different image content.

Table 1. Observer accuracy and repeatability

	Observer Accuracy	Observer Repeatability
Mean	2.94	3.88
Max	6.55	7.09
Min	1.43	1.35

Gamut Compression Results

Many plots were generated for visualising the relationship between the original and reproduction images. The reproduction images were calculated by averaging each observer's pixel-by-pixel data for each image. These images then represent the mean visual results. The results from the IT8 image using the LCLIP GMA as the initial image are given in this paper. Each data point in the following plots represents the average L*, C* and hue angle values for each colour patch in the IT8 image.

Lightness comparison

The L* values of the original and reproduction colours are given in Fig. 4. The L* value of 100 for the original and reproduction devices corresponds to the white point of the monitor and the paper substrate of the printer respectively. The solid line indicates a perfect agreement between the original and reproduction results. As shown in the Fig. 4, almost all data were adjusted to make the reproduction image brighter. 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 black is not dark enough and suggests that contrast was considered more important than maintaining differences between lightness levels.

Chroma comparison

The C* values of the original and reproduction colours are plotted in Fig. 5. The results clearly show that there is gamut compression for almost all colours, i.e. the majority of colours are located below the 45^{o} line.

Hue comparison

The ΔH* values are plotted against the hue range of the original and reproduction images are given in Fig. 6. These values were calculated between the original and reproduction images. The trend in Fig. 6 is quite clear that red colours were modified to become bluer, green and cyan colours were adjusted to make them bluer, and blue and magenta colours were made greener and bluer respectively. However, the magnitudes of adjustment were small, i.e. between +2 and -2 ΔH* units.

Converging points in L* vs C* plots

It was seen that a plot of L* vs C* was very useful for analysing the results. Again, the original and reproduction results are plotted in L* vs C* diagrams for each of the primary and secondary hues. In addition a vector was drawn between the original and reproduction colour. These plots are shown in Figs. 3a to 3f for red, yellow, green, cyan, blue and magenta hues respectively. For each vector, their convergence point (intercept with the L* axis) was also calculated. The median convergence point was also plotted in Figs. 3a and 3f and indicated by an arrow. In addition, the L* of the cusp from the reproduction gamut and the intercept between two cusps of the two gamuts are also shown using circle and square symbols respectively. The data displayed in each figure makes comparing current results with GMAs proposed by Morovic and Luo [5] easier. To compare the convergence point for each of the primary and secondary hues, the results indicate that LCUSP performs well for yellow and green and LLIN performs well for cyan, blue and magenta. However, the results for red show very small changes. The current results seem to support a hybrid GMA.

Conclusions

The interactive tool developed in this study allows for selecting a particular colour region of a pictorial image in CIELAB colour space and for modifying this image in comparison 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 investigating and developing different gamut mapping algorithms. The L* C* and hue results were averaged for each colour patch of the IT8 image. These were compared between the original and reproduction images by generating various plots.

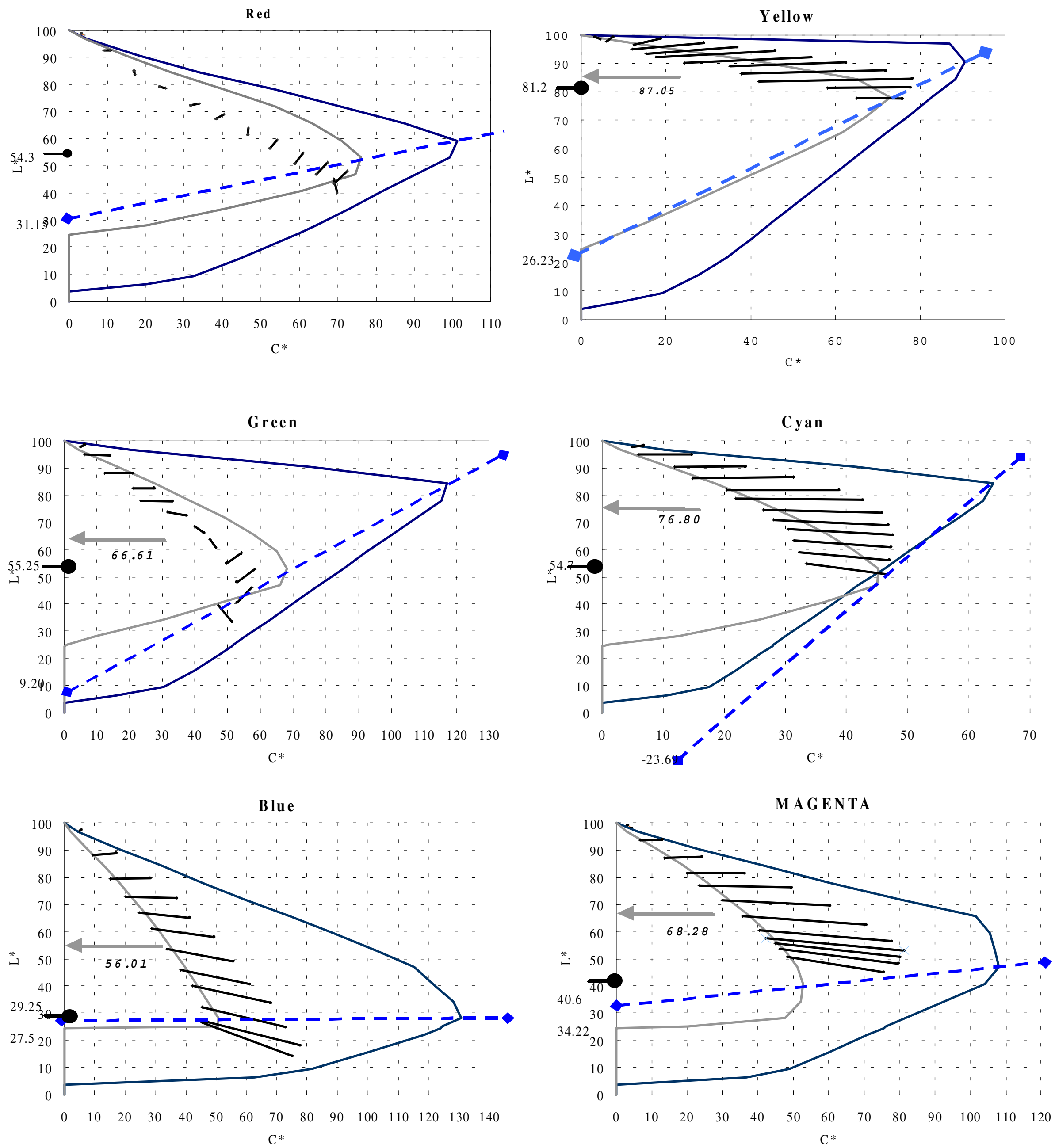


Fig. 3: Colour gamut differences between the original (CRT, outside) and reproduction (printer, inside) devices for red (a), yellow (b), green(c), cyan (d), blue (e) and magenta (f) hues. The dashed line represents the line going through the cusps of two gamuts. The arrow indicates the average convergence point in L axis. The closed circle represents the L* of the reproduction cusp.*

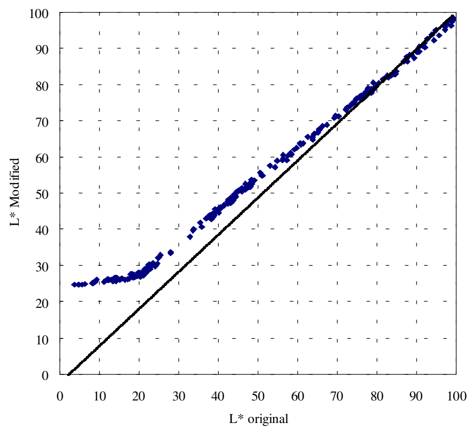


Fig. 4. The plot of L (original-reproduction).*

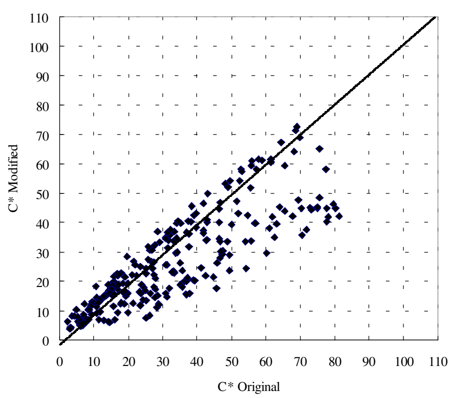


Fig. 5 The plot of C (original-reproduction).*

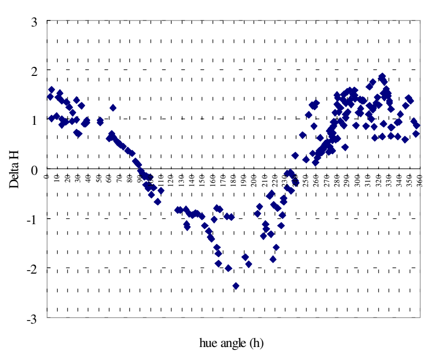


Fig. 6 The plot of ΔH (original- reproduction).*

In comparing the L* results, these show that there is a clear linear relationship for brighter colours and a non-linear one for dark regions. The C* results show that there is significant compression of the reproduction image due to gamut limitation.There is a distinct pattern for hue changes, but the magnitudes are quite small. This seems to indicate that there is no need for hue modification. Comparing the convergence points for primary and secondary hue regions, the results support a hybrid gamut comparison algorithm. The other three images will also be analysed in a similar fashion

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