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Ján Morovic

M. Ronnier Luo

Colour & Imaging Institute

Kingsway House, Kingsway

Derby DE22 3HL, United Kingdom

http://colour.derby.ac.uk/

EVALUATING GAMUT MAPPING ALGORITHMS FOR UNIVERSAL APPLICABILITY

ABSTRACT

The aim of this paper is to present the evaluation of gamut mapping algorithms (GMAs) in a series of three experiments intended for serving as the basis for developing solutions that are accurate and universally applicable. An evolutionary gamut mapping development strategy is used in which five test images are reproduced between a CRT and printed media obtained using different GMAs. Initially, a number of previously published algorithms were chosen and psychophysically evaluated whereby an important characteristic of this evaluation was the separate evaluation for individual colour regions within test images. New algorithms were then developed on this experimental basis, subsequently evaluated and the process was repeated once more. In this series of experiments the new GCUSP algorithm, which consists of a chroma–dependent lightness compression followed by a compression towards the lightness of the reproduction cusp on the lightness axis, gave the most accurate and stable performance overall. The results of these experiments were also useful for improving the understanding of some gamut mapping factors – in particular gamut difference between media.

Key words: gamut mapping, cross–media reproduction, psychophysical evaluation

INTRODUCTION

Providing colour reproduction with a scientific basis is an aim shared by a large number of researchers engaged in studying its various aspects and developing solutions for the problems encountered. In general the study of colour reproduction can be divided into an investigation of the types and contexts of information dealt with (e.g. spectral data, appearance attributes; unrelated colours, complex images), the media on which this information is present, the intents pursued by the colour reproduction process and the transformations carried out to reproduce given colour information between given media so as to achieve a given intent.[1] Colour information is transformed in five[2] or six[3] stages (Fig. 1.) consisting primarily of **device characterisation** (the modelling of the relationship between device–dependent data and resulting visual stimuli), **colour appearance modelling** (the prediction of appearance attributes of visual stimuli), **image enhancement** (e.g. sharpening, contrast enhancement, etc.), and **gamut mapping** (the assigning of colours from a reproduction medium to colours from an original medium or image).

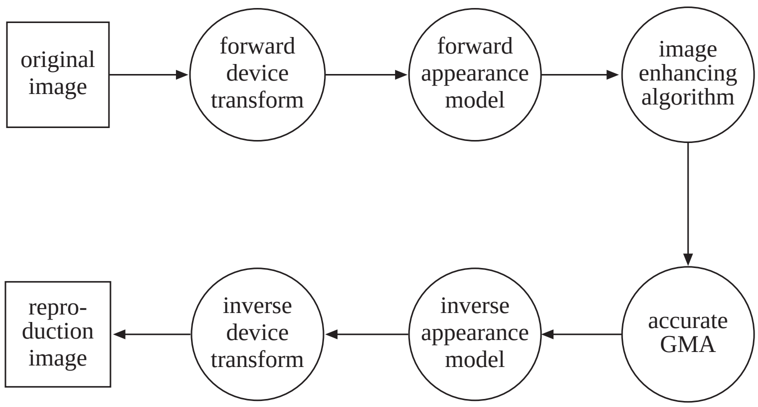


Fig. 1. Six–stage colour reproduction transform.

In this context, the present paper intends to provide more detailed results of a set of three experiments carried out as part of a study by the authors[4] for the purpose of developing gamut mapping algorithms (GMAs) that could be used under a wide range of conditions and would therefore be in some sense universal.

Various methods have previously been used for developing GMAs whereby in a few cases the starting point was a set of experimental data which was then modelled. However, in the majority of studies a model was first formulated and then tested experimentally (or the model's parameters were established on that basis). The approach taken in this study is a combination of these two styles whereby the starting point is a selection of existing GMAs which are then experimentally evaluated. The experimental method used in this study has a special feature which is that in addition to evaluating overall images, individual regions within them are also evaluated. These **image regions** are chosen so as to have characteristic colours and their evaluation therefore gives information about the performance of GMAs in different parts of colour space. This kind of information is a solid and quantitative basis for making alterations to GMAs.

The results of the evaluation of existing GMAs then serve as a starting point for the development of new algorithms and this method therefore fundamentally lends itself to iteration. Hence, the study including the experiments described in this paper therefore had two main parts – psychophysical experimentation (which will be covered here) and GMA development (which has been published previously[4]). Note, that the nature of this method is in some ways analogous to evolution, whereby individuals are substituted by GMAs and natural selection by their performance in terms of psychophysical evaluation. This is also why the "generation" of an algorithm is referred to in the context of this study.

What will be included in this paper are (1) a brief overview of the aims and assumptions behind the work presented here, (2) an outline of the experimental framework used, (3) the results of three psychophysical gamut mapping evaluation experiments and (4) their analysis for the purpose of developing more widely applicable GMAs.

More details on the background against which this study was carried out, the terminology used and a discussion of gamut mapping and its parameters as a whole have been published previously[5] and both publications[4,5] mentioned in this section are needed in addition to the present paper to have a good picture of the above mentioned study. While this is the case, the present paper is nonetheless self–contained as far as methods for evaluating the performance of gamut mapping algorithms and the subsequent analysis are concerned.

ASSUMPTIONS AND AIMS

The algorithms whose evaluation is discussed here intend to reproduce the appearance of original images that have pleasant appearance in an accurate way and have therefore no image enhancing intents. One could argue that it is often a pleasant reproduction, which is needed and as this is an important question, the relationship between the pleasantness and accuracy of reproductions made with GMAs dealt with here was also investigated and published previously.[6] It further needs to be noted that this study focuses on **gamut compression** – i.e. gamut mapping from a larger to a smaller gamut, as this is most often needed in situations where a universal gamut mapping would be used at present.

Before going any further, it is of great importance to clearly understand that the aim of this study is the development of **universal gamut mapping algorithms** and experimental results will be analysed for this purpose. Here a universal GMA will be defined as giving consistently good results for a wide range of media combinations and original images. It is not meant to be a method that gives the best result for every image under every possible set of conditions. Instead, it ought to be seen as a default method, which can be used for the majority of images and media combinations and which can be supplemented by proprietary solutions for use in special applications.

Finally, no claims as to the universality of any algorithm evaluated in this paper are made as the range of media and images used here is limited. Instead, universality, as explained above, is used as the criterion for GMA performance analysis.

EXPERIMENTAL FRAMEWORK

Experimental Apparatus

The colour reproduction system used in this study comprised primarily of a CRT and a printer whereby a *VeriVide* viewing booth, whose walls were achromatic and had a lightness of approximately L*=50, was used for viewing printed reproductions. These were illuminated with fluorescent tubes simulating *CIE Standard Illuminant D50*. A diffuser was placed in front of the light source and its density was chosen so that the luminance of printed substrates viewed in the booth was similar to the luminance of the CRT's white point, which was approximately 85 cd/m^2. The variation of luminance across the back panel of the viewing booth had a standard deviation which was 19 *per cent* of the maximum whereby vertical variation was five times larger than horizontal variation.

To display the images, which were taken to be the originals in the colour image reproduction system used here, a *Barco Reference Calibrator* CRT monitor was used. It's CRT was 20" in diameter, had a 0.31 mm pitch and 1280 x 1024 addressable pixels. The chromaticity of the monitor's white point was set so as to be close to the chromaticity of the illuminant used in the viewing booth. In terms of spatial uniformity the CRT had a variation in L* of approximately 25 *per cent* from the brightest area (centre) and no visual hue variation. The CRT was driven by a 24–bit display card in a *Sun SPARCstation* workstation running *X–Windows 11* under *Unix* (*SunOS*™ Release 4.1.3_U1). The choice of this CRT was influenced in particular by its closed–loop calibration feature, which facilitates long–term stability and repeatability. Most importantly, it was also easy to calibrate this CRT before each experimental session. Measurements of the CRT were made with a *Bentham* telespectroradiometer (TSR) and the PLCC model[7] was used to characterise the CRT. The model had a mean prediction error of 0.4 ΔE units which was therefore considered to be satisfactory (all colour differences given here were calculated using the CMC (1:1) formula[8]).

Reproductions of images displayed on the original CRT were made on an *Hewlett Packard* (HP) *DeskJet 850C* inkjet printer having a resolution of 600×600 *dots per inch* (dpi) for black and 300×300 dpi for cyan, magenta and yellow. The substrates used with this printer were *HP Glossy Paper* (a plastic substrate), which was used in all experiments and in Experiment 3 *HP Premium Inkjet Paper* (an uncoated paper substrate) was used in addition to it. To obtain printed reproductions, data was sent to the printer via HP's software driver from an *Apple Macintosh*™ computer running *Adobe Photoshop*™ (versions 3.0.5 – 4.0) under *MacOS*™ (versions 7.5.5 – 8.1). This printer was chosen as it represented the performance of printing devices most widely used in the consumer and business markets at the time of the first experiment. Measurements of prints were made with an *X–Rite 938* spectrophotometer having a 0°/45° measuring geometry. The printer was characterised using third order masking equations with greyscale correction[9] and the mean error of this model was 5 ΔE units with a maximum error for a set of 125 test colours being 13 ΔE units. In the initial experiment the masking equations were used without greyscale correction and the model had a maximum error of approximately 23 ΔE units while having a similar median error. The errors of the printer characterisation were influenced by the printer's repeatability error being approximately 2 ΔE units. While these characterisation errors might seem large, their being random makes the systematic changes introduced by GMAs observable as will be shown in the discussion of Table VI.

To obtain individual reproductions, the appearance of a particular image on the CRT was taken to be the original. Hence an image's RGB values were first transformed into XYZ tristimulus values using the CRT's characterisation model from which colour space coordinates were calculated. Gamut mapping was then carried out in CIELAB for Experiments 1 and 2 and in CIECAM97s for Experiment 3 whereby gamut boundaries were calculated using the methods described in another paper.[10] The resulting $L^*C^*h_{ab}$ or JCh coordinates were transformed back to XYZ. Finally, the resulting tristimulus values were transformed into colorant amounts using the printer characterisation model.

Experimental Method

Inasmuch as there is as yet no satisfactory model for quantifying the appearance of complex pictorial images and neither is there a good model for the quantification of their differences, the paradigm chosen for the evaluation of the performance of GMAs is psychophysics. As GMAs cannot be directly judged in terms of how accurate they are, judgements are made on reproductions made with various GMAs and since everything else is kept the same for these reproductions, their accuracy is considered to be that of the corresponding GMAs. It is in this sense that the accuracy of GMAs is understood in this study. The psychophysical method used here is **pair comparison**, which is based on Thurstone's law of comparative judgement[11] whereby the assumptions made for data analysis are those described as Case 5 in that paper.

The pair comparison experiments were carried out using the **simultaneous binocular** viewing technique.[12] Using this technique observers sat at approximately 100 cm from the CRT and prints, which when shown in a viewing booth had similar chromaticities and luminances for the media white points. To reduce differences in adaptation further, a white border was displayed around the images, which had a chromaticity similar to the white border of printing substrate left around the printed reproductions. The background against which the images were shown had a luminance that was 20 *per cent* of the adopted white's luminance. Finally, the pair of printed reproductions and the original image on the CRT were approximately co–planar and equal in size, the viewing geometry was such that the diffused illuminant was not directly visible to observers and the whole scene was viewed in a dark room.

To obtain the differences between *n* chosen GMAs using the pair comparison method, observers were shown all pair combinations of reproductions made with them under the viewing conditions described above. Note, that to each observer pairs of reproductions were shown in a different and random order. For each pair, observers were asked to make a judgement as to which reproduction was closer to the original shown on the CRT in terms of appearance. Note, that observers were not forced to make a choice in these experiments and therefore had the option to say that both reproductions were equally close to the original. For details of the calculation of interval scale accuracy scores reported in the following section see an earlier paper.[4] Briefly, this accuracy scale is based on z–scores calculated from raw observer data under the Case 5 assumptions mentioned above.

In addition to making judgements about overall accuracy, observers were asked to make that judgement for individual regions within the images whereby each region had a characteristic colour (Fig. 2.). The evaluation of such regions in colour images was previously used by MacDonald and Morovic[13] and provides a solid, quantitative basis for understanding the performance of GMAs in different parts of colour space.

Fig. 2. Colour regions in MUS image.

Test Images

As one of the requirements of a universal GMA is to give good results over a wide range of originals, it is necessary to use a representative set of test images. To this end five images (Fig. 3.) were chosen, which covered a range of image content types and which had various image gamut characteristics useful for the evaluation of GMAs. In terms of **image contents** four of the images were scanned photographs where three images (SKI, DOL and MUS) had colours from the majority of hues and one image (NAT) was predominantly green and blue. The fifth image (BUS) was a computer generated business graphic whose colours were the most chromatic primary and secondary colours obtainable on the original medium.



MUS **SKI** **NAT**

BUS **DOL**

Fig. 3. Overview of test images.

A useful statistic for the description of image gamuts is **chroma range**, which is defined as the area in the *a*b** plane delimited by the cusps at each hue angle (whereby for a given hue angle the **cusp** is the colour with maximum chroma). In this study, chroma range was calculated by finding the largest chromas at 60 equally spaced hue angles and calculating the area of the 2D polygon formed by them. The relative chroma ranges (i.e. in this case image chroma range divided by medium (CRT) chroma range) of the five test images are shown in Table I. as they had a very good correlation with the performance of GMAs in Experiment 2.

Image	**BUS**	**DOL**	**SKI**	**MUS**	**NAT**
Relative chroma range	82%	78%	71%	28%	10%
Out–of–gamut pixels	67%	49%	61%	45%	28%

Table I. Sample test image statistics in CIELAB.

The percentages of **out–of–gamut pixels** (in this case relative to the gamut of prints from Experiment 2) can in some cases have an impact on the performance of GMAs and are also shown in Table I. When investigating differences between individual test images in terms of the accuracy of reproductions obtained using various GMAs, the above parameters (i.e. image contents, chroma range and the percentage of out–of–gamut pixels) can often be of use. For lightness and chroma histograms of the test images see Appendix A.

Observers

Varying numbers of observers took part in each of the three experiments described here whereby all of them were either staff or students at the Colour & Imaging Institute. Details of their age, sex and number are given in Table II.

	Number of observers	**Female/male ratio**	**Age range**
Experiment 1	12	5:7	22–38
Experiment 2	13	5:8	23–39
Experiment 3	10 (2×)	4:6	23–40

Table II. Observer statistics per experiment.

EXPERIMENT 1: INITIAL GMAS

The experiments described here were preceded by a literature survey of gamut mapping algorithms[3] whereby the majority of the surveyed GMAs could be categorised as being either **sequential** or **simultaneous** in their compression of lightness and chroma. Sequential mappings treat these two attributes separately, whereas simultaneous methods map them together. The algorithms evaluated in this experiment were chosen on the basis of the survey and have the following general characteristics (for a schematic overview see Appendix B and for details see Morovic and Luo[4]):

Mnemonic	Type	Description
LCLIP	sequential	L* compression + C* clipping
LLIN	sequential	L* compression + linear C* compression
LNLIN	sequential	L* compression + non-linear C* compression
LSLIN	hybrid	L* compression + SLIN
SLIN	simultaneous	Compression to L*=50
SLINLLAB	simultaneous	SLIN in LLAB[15]
CUSP	simultaneous	Compression to L* of cusp

Table III. Overview of GMAs evaluated in Experiment 1.

As can be seen, three of the algorithms (SLIN, SLINLLAB and CUSP) do not have an initial lightness compression, which was done to test the correctness of the (sometimes implicit) assumption, made by previous studies – with the exception of Ito and Katoh[16] – that an overall lightness mapping needs to be the first step of a GMA. This assumption arises from the results of investigations where colour reproduction could only be controlled via tone–reproduction curves of individual colorants. Under such conditions, it is indeed linear compression of lightness, which gives the best results, as has also been shown in a study carried out by Johnson and Birkenshaw.[17] Whether this still holds when individual attributes of a colour can be controlled independently of each other and of the attributes of other colours is a hypothesis which can by no means be declared *a priori* correct.

In addition to the above algorithms, another GMA was evaluated and was meant to be an implementation of the gamut mapping algorithm proposed by Johnson *et al.*,[14,15] however, it will not be discussed here, as it turned out to be an incorrect interpretation and as it did not perform well. Its details can be found in Morovic and Luo[9] where it was labelled JOHNSON.

Overall Results

The following analysis and interpretation of experimental results will exclude the reproductions made with SLINLLAB. This is done, as SLIN and SLINLLAB both represent the same algorithm (their difference being only the colour space in which it is implemented) and as the inclusion of both would in effect give SLIN a larger weighting. This would be contrary to the aim of this study, which is the investigation of GMAs and not that of colour spaces. Note, however, that both SLIN variations gave a very similar performance and were in fact not statistically significantly different at the 95 *per cent* confidence level.

Excluding SLINLLAB from the data analysis results in the accuracy scores shown in Fig. 4. which will serve as the basis for drawing conclusions from Experiment 1. From there it can be seen that the simultaneous algorithms (CUSP and SLIN) performed significantly better than the sequential ones. This suggests that the use of an overall lightness compression as the first step does not give optimal results and it indicates that maintaining chroma is of greater importance than was previously thought. Hence, the lightness–compression hypothesis discussed above does not hold for the present set of algorithms.

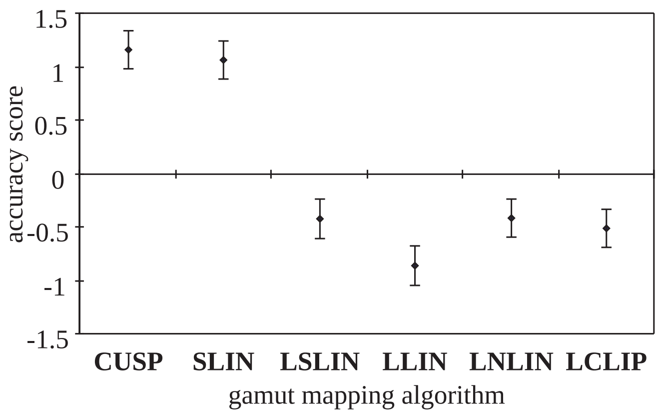


Fig. 4. Results of initial experiment based on judgements made.

for the overall accuracy of five test images reproduced by algorithms implemented in

CIELAB (including 95 per cent confidence intervals).

The reason for the failure of overall lightness compression can be found in the shapes of the original and reproduction gamuts which, in planes of constant hue angle, usually resemble triangles (the vertices being L^*_{min}, L^*_{max} and the cusp) and in the lightnesses of the original gamut's cusps being higher than those of the reproduction. Therefore, compressing lightness linearly (i.e. increasing the lightness of all colours) moves many – especially highly chromatic – colours into a region where the maximum achievable chroma is significantly lower than at the original colour's lightness (Fig. 5.a). This had a particularly marked effect on the reproduction of highly chromatic yellow colours which were reproduced as virtually achromatic using the LLIN, LCLIP and LNLIN algorithms – resulting in obvious artefacts.

Having established that simultaneous algorithms (which give more importance to chroma) perform better, it is important to note their main shortcoming, which is that they give worse results for the reproduction of dark colours and those around the achromatic axis than algorithms which have overall lightness compression. This was also confirmed by the results obtained for individual colour regions. The reason for the worse performance of SLIN and CUSP in these regions is that they in effect use a piece–wise linear lightness compression, which more heavily compresses colours below the centre–of–gravity and does not compress those above it at all (Fig. 5.b). Clearly this results in a loss of detail for dark colours.

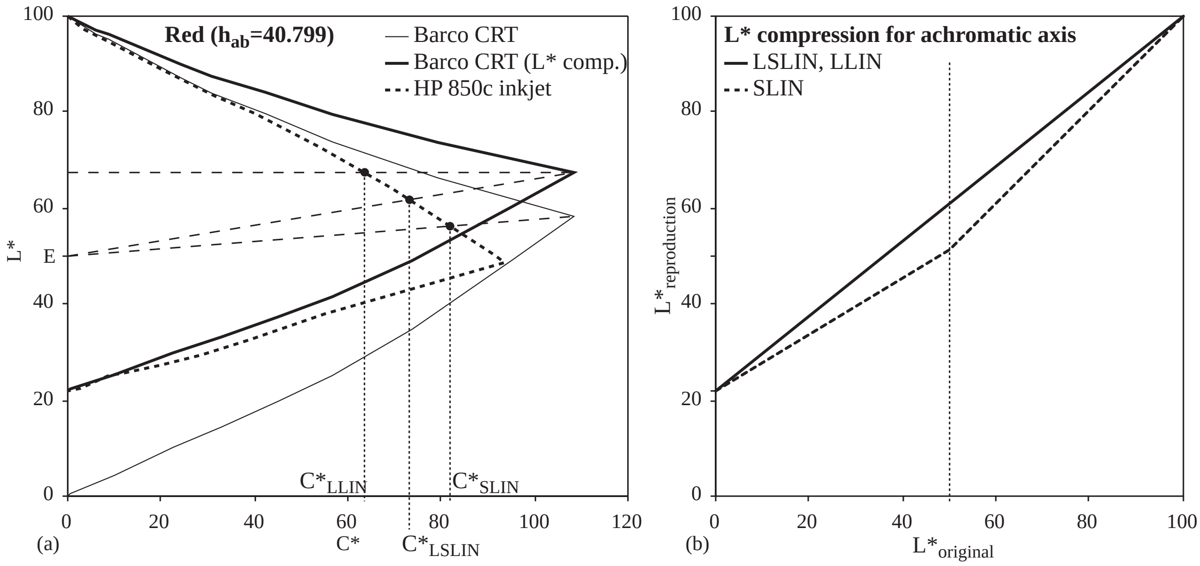


Fig. 5. Effect of using initial lightness compression demonstrated by comparing SLIN, LSLIN and LLIN: (a) chroma of gamut mapped colours, (b) effective lightness compression for achromatic axis.

Results for Colour Regions

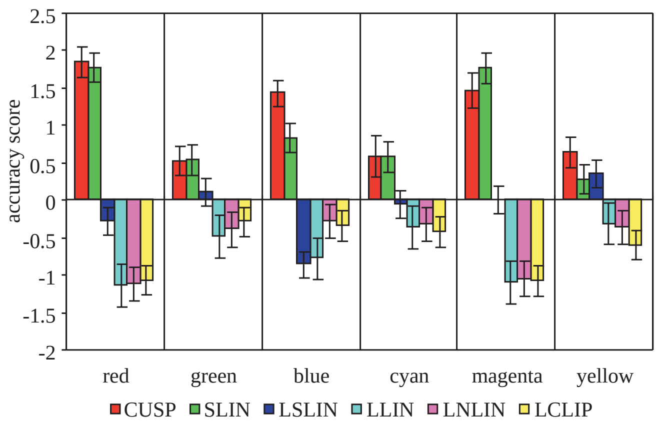


Fig. 6. Results for colour regions by colour region.

As can be seen from Fig. 6., the results for individual algorithms are not significantly influenced by the colour region of colours transformed with them. However, it can be seen that the range of accuracy scores does depend on colour region, whereby the ranges for red, blue and magenta are significantly larger than those for green, cyan and yellow. This means that there are larger differences between the algorithms in the first set of regions than in the second and that the choice of algorithm is therefore more critical for the former rather than the latter set. One of the differences between these two sets is that the lightnesses of the original cusps in the first set are lower than those in the second set (Fig. 7.) and are therefore more influenced by lightness compression (or its absence). In other words, the criterion which divides these two sets of colour regions is **relative gamut shape**.

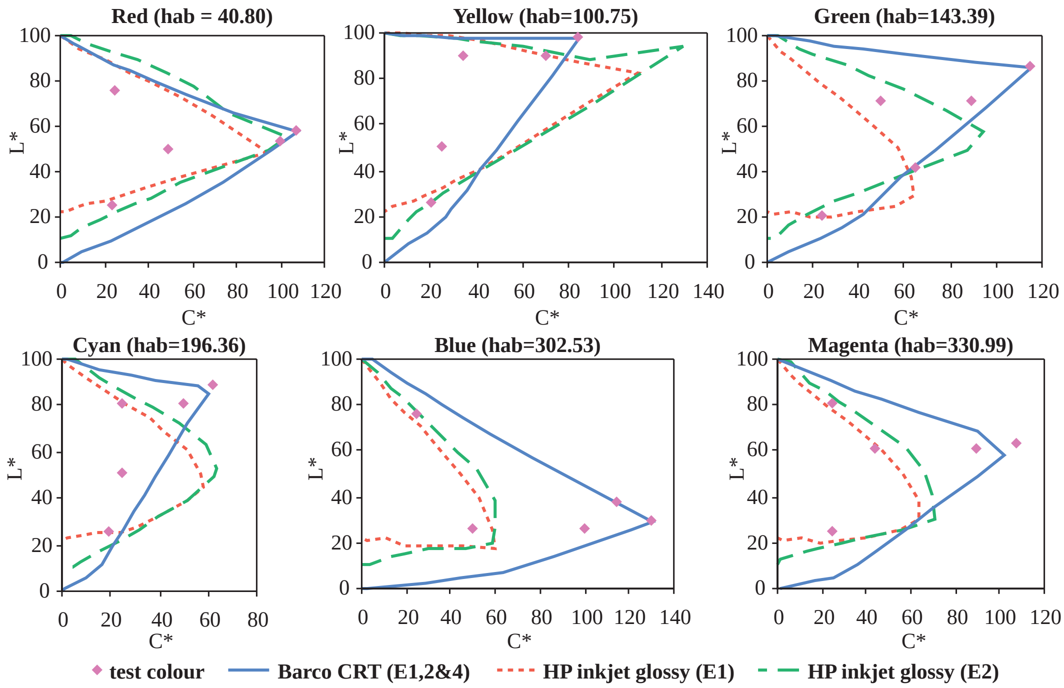


Fig. 7. Gamuts at primary and secondary hue angles in CIELAB and coordinates of test colours (differences between printer gamut in Experiments 1 and 2 is due to different characterisation model).

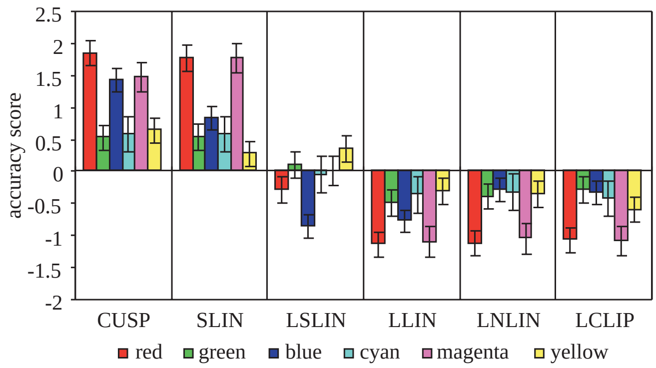


Fig. 8. Results for colour regions by GMA.

Further, it is also useful to see the data from Fig. 6. grouped by GMA, as this shows how variable a given algorithm is (Fig. 8.). It can again be seen that the performance of algorithms evaluated here is not influenced by colour region. Further, this view more clearly shows that the hybrid algorithm LSLIN is an exception to this whereby it performs well in some regions where sequential algorithms perform badly (e.g. yellow) and badly where simultaneous algorithms perform well (e.g. blue).

Results for Individual Images

Overall, the results in Fig. 9. show a strong correlation between the accuracy scores of GMAs for SKI, DOL and BUS, whereas the other two images have different overall patterns. This grouping is very similar to that of the images' **chroma ranges** which are in the region of 15,000 to 18,000 units for SKI, DOL and BUS and 6,000 and 2,000 for MUS and NAT respectively whereby these values are the areas of the gamuts' projections onto an a*b* plane. This indicates a link between the size of an image's gamut and the performance of GMAs in terms of its reproduction. However, it is of importance to note that some algorithms (in particular CUSP and SLIN) perform well for all of the five test images and also for the colour regions discussed in the previous section. The above data can also be grouped by GMA (Fig.

10.) and the resulting overall pattern is again similar to that for colour regions (with the exception of the NAT image).

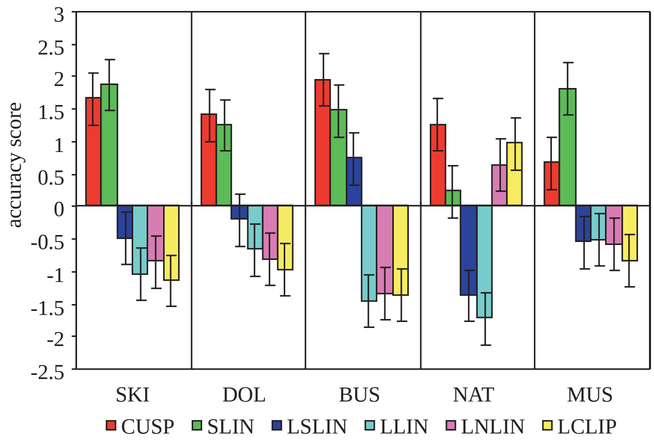


Fig. 9. Results for test images by image.

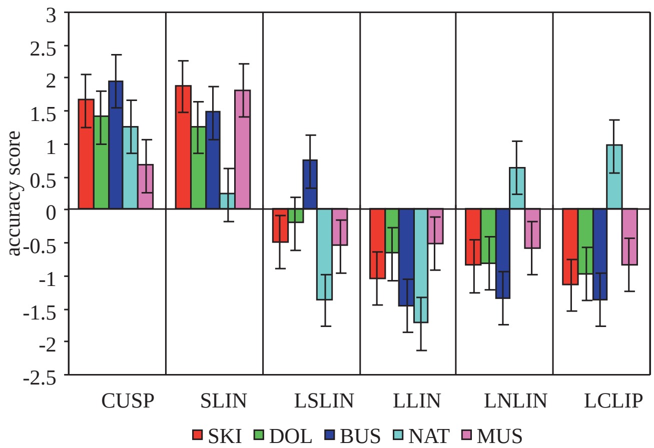


Fig. 10. Results for test images by GMA.

Summary of Experiment 1

The simultaneous algorithms – CUSP and SLIN – performed significantly better overall as well as for most colour regions and individual test images. An exception to this is their performance for the neutral axis and for dark colours, where sequential algorithms were more accurate.

EXPERIMENT 2: EVALUATION OF NEW GMAS

The aim of the algorithms developed after the initial experiment is to combine the behaviour of sequential algorithms for the neutral axis with the behaviour of simultaneous algorithms for the remainder of colour space. In other words the lightness of achromatic colours ought to be mapped linearly while the chroma of highly chromatic colours ought to be maintained to a greater extent than was the case with sequential algorithms.

Three new GMAs – GCUSP, CLLIN and TRIA – were developed and a fourth GMA (CARISMA), which is the second attempt of implementing the GMA proposed by Johnson *et al.*, was also used. CARISMA, as described here, is in line with the original authors' intentions as well as being in line with the findings of Experiment 1. Note, that all algorithms (except for CLLINLLAB) were again implemented in CIELAB and all but CARISMA keep hue unchanged (for details see Morovic and Luo[4]). The reproductions made using these second generation algorithms (GCUSP, CLLIN, CLLINLLAB, TRIA and CARISMA) were compared with reproductions made using some of the initial GMAs (SLIN and LLIN) and the default reproductions obtained by sending the original monitor RGB values directly to the printer via its driver software (these are referred to by the mnemonic **DEF**). An overview of all algorithms evaluated in this experiment is given in Table IV. (for a schematic overview see Appendix B and for details see Morovic and Luo[4]).

Mnemonic	Description
GCUSP	C* dependent L* compression + CUSP
CLLIN	C* range compression + L* compression at fixed C*
CARISMA	L* compression + hue shift + relative, gamut shape dependent mapping
SLIN	Compression to L*=50
LLIN	L* compression + linear C* compression
TRIA	Triangular monotonic cusp–to–cusp mapping
DEF	Monitor RGB values sent to printer using its own driver software

Table IV. Overview of GMAs evaluated in Experiment 2.

Overall Results

Again the reproductions made with the algorithm implemented in two colour spaces (CLLIN in CIELAB and CLLINLLAB in LLAB) were not different from each other at the 95 *per cent* significance level and were excluded from further analysis as this would have meant that more weight would have been given to the CLLIN algorithm. The overall results of Experiment 2 are therefore the following (Fig. 11.).

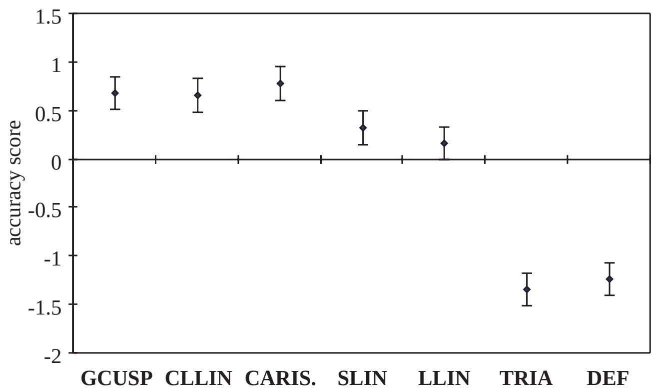


Fig. 11. Overall results of algorithms implemented in CIELAB and evaluated in Experiment 2.

From these results it can be seen that three of the four new algorithms (GCUSP, CARISMA and CLLIN) performed significantly better than the algorithms tested in the previous experiment. Further, the algorithms form three distinct groups, which are significantly different from each other and within which the difference between algorithms is not significant. The top group contains the three successful new algorithms, this is followed by the SLIN and LLIN algorithms from Experiment 1 and lastly by TRIA and DEF. As SLIN was in the top group of algorithms in Experiment 1, the algorithms which performed better than SLIN would also very likely have performed better that the other initial algorithms. The inclusion of LLIN was done so as to represent the worst results from Experiment 1 and any algorithm which has a lower score that LLIN would probably have performed worse than the algorithms from Experiment 1.

The nature of changes made by the individual algorithms was investigated so as to better understand the reasons for the above results. To do this, 30 colours were chosen (Fig. 7.), gamut–mapped and their original and gamut–mapped *LCh* values were compared. Note, that the gamut–mapped values are not the *LCh* values of the reproduced colours, but are the values which would be transformed via the printing medium's characterisation model and then printed. That is, they do not include characterisation and printer variation errors. As gamut–mapped values were not available for the reproductions made with DEF, that method is not considered here.

The above set of 30 colours was chosen so that there were five colours for each of the primary and secondary hues of the CRT whereby each of these sets of five colours included the cusp at the corresponding hue angle. Differences between original and gamut–mapped colours were expressed in terms of median ΔE_{ab}, median $|\Delta L^*|$, median $|\Delta C^*|$, the median $\Delta(C/L)$ which represents changes in saturation and the median $|\Delta C^*|/|\Delta L^*|$ ratio (Table V.). The last of these attributes was chosen, as it expresses the weight given to lightness *versus* chroma in a given GMA and the median was used as a measure of central tendency instead of the mean as the distributions of these values were skewed.

GMA	med. ΔE_{ab}	med. $\|\Delta L^*\|$	med. $\|\Delta C^*\|$	$\Delta(C/L)$	$\|\Delta C^*\|/\|\Delta L^*\|$	Rank
GCUSP	12.22	4.79	8.10	-0.18	1.69	2
CLLIN	15.59	7.37	9.66	-0.23	1.31	3
CARISMA	12.45	6.59	3.77	-0.05	0.57	1
SLIN	11.02	5.24	7.60	-0.14	1.45	4
LLIN	11.97	5.30	11.69	-0.29	2.20	5
TRIA	20.05	6.63	14.84	-0.10	2.24	6

Table V. Median changes made by GMAs in Experiment 2.

First of all it needs to be noted that the data in Table V. does not follow the grouping of algorithms in terms of accuracy scores – in particular, there is a difference in the attributes of SLIN and LLIN, which is not paralleled in the accuracy scores. The differences between the above data and the overall experimental results might well be due to the small sample–size of the former. Nonetheless, the above data is useful for understanding the performance of the algorithms it describes. Note also that the median ΔH for the CARISMA algorithm was 6.13.

It is of interest to note that the median $|\Delta C^*|/|\Delta L^*|$ ratio seems to correlate well with the ranking of the algorithms (Table V.) – the Pearson correlation coefficient being 0.85. This suggests that, within the set of algorithms considered here, those algorithms which in relative terms maintain more chroma (at the expense of lightness) are judged to be more accurate. This trend is somewhat different from the results of many other studies and the source of this difference is likely to be the fact that the experimental conditions used here resulted in larger chroma range differences than were the case in some other studies.

Of interest is also the correlation between median ΔE_{ab} and the accuracy score, which is -0.78 and suggests that the algorithms which make the smallest change (within the set of algorithms considered here) also give the most accurate reproductions.

It is also of interest to note that the algorithm (CARISMA) which made the smallest $\Delta(C/L)$ (saturation) change is also the most accurate algorithm and that this indeed agrees with what was found in other studies.[18] However, it can also be seen that maintaining saturation is not a sufficient criterion on its own to ensure accuracy as the TRIA algorithm makes the second–smallest change but performs worst. Overall, the correlation between saturation changes and accuracy scores (or their ranks), which is –0.18 and –0.30 respectively, can be considered to be fairly weak.

Further, the data from Table V. also gives a possible explanation of the TRIA algorithm's failure, which could be due to it making changes which on average are about twice as large as those made by most other algorithms. Note, however, that it is not the algorithm with the smallest overall change (SLIN) which performs best – for if that were the case then the best gamut mapping algorithm would be gamut clipping which maps out–of–gamut colours onto the nearest colour on the reproduction gamut's boundary. Instead of this minimisation approach, TRIA tries to maintain relative characteristics of colours within corresponding gamuts and have a monotonic relationship between original and reproduced colours. However, this doesn't work either, as it is done at the expense of unacceptably large absolute changes to the gamut–mapped colours. This would suggest that the solution is somewhere in–between minimisation and the maintenance of relative characteristics, which is indeed what happens in the case of GCUSP, CARISMA and CLLIN.

To put the values in Table V., which show differences between original and gamut mapped colours, into context, it is useful also to know the differences between the individual GMAs (Table VI.). Further, it is also useful to compare these values with the accuracy of the characterisation model used, which had a median error of prediction of 5 ΔE and a maximum error of 13 ΔE. It can be seen that some GMAs, which had differences smaller than the characterisation model's accuracy (e.g. GCUSP and SLIN) were judged to be significantly different from each other. This is probably due to characterisation errors being randomly distributed, whereas differences between GMAs being systematic and due to systematic differences being noticeable even after random errors in their reproduction.

	GCUSP	CLLIN	CARISMA	SLIN	LLIN	TRIA
TRIA	8.57	9.64	9.52	9.58	12.51	
LLIN	6.74	7.19	8.57	6.54		
SLIN	3.04	5.55	5.47			
CARISMA	6.23	6.25				
CLLIN	5.09					
GCUSP						

Table VI. Median ∆E differences between individual GMAs.

Another important characteristic of GMAs is the variance of their performance for different image contents, which should be as small as possible for universal gamut mapping algorithms. The variance of the accuracy scores of the seven algorithms considered here was therefore calculated on the basis of all judgements made for them (i.e. the images overall and all the colour regions within each image).

	GCUSP	CLLIN	CARISMA	SLIN	LLIN	TRIA	DEF
variance	0.359	0.623	0.405	0.537	0.749	0.365	0.877

Table VII. Variances of accuracy scores.

It can be seen from Table VII. that the GCUSP, TRIA and CARISMA algorithms perform more stably than the other algorithms. In the case of TRIA, this means a consistently low accuracy, whereas the accuracy of GCUSP and CARISMA is consistently high.

Results for Colour Regions

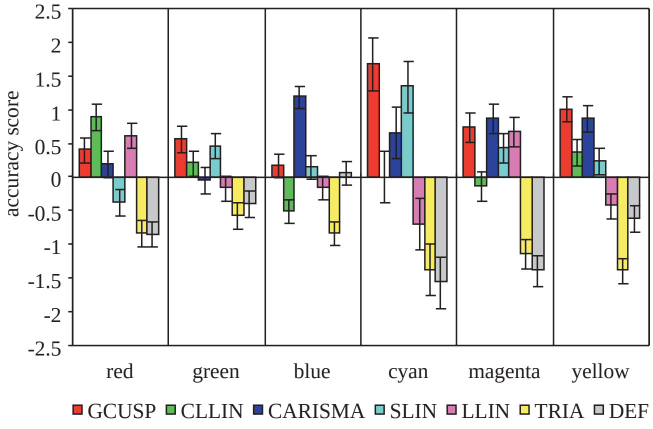


Fig. 12. Results for colour regions by colour region.

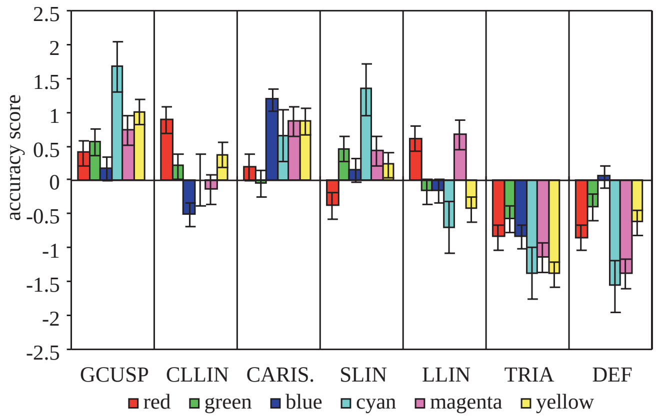


Fig. 13. Results for colour regions by GMA.

It can be seen from Figs. 12. and 13. that the results of this experiment are less homogeneous than the results of Experiment 1. Nonetheless, it can be seen that GCUSP and CARISMA perform well for all colour regions (with the exception of CARISMA for green) whereas TRIA and DEF perform consistently badly and the performance of CLLIN and LLIN (and to a lesser extent SLIN) is strongly influenced by colour region.

This indicates that, out of the algorithms dealt with here, GCUSP and CARISMA are closest to the aim of universal applicability. Even though CLLIN has good overall accuracy scores, it was shown in the previous section that its performance varies significantly with respect to colour region and this would make it an unreliable choice.

As far as comparisons with Experiment 1 are concerned, it also needs to be noted that they can only be made in terms of relative differences between pairs of algorithms which were evaluated in both experiments (i.e. only SLIN and LLIN). Comparing the absolute scores of algorithms evaluated in both Experiment 1 and Experiment 2 is not meaningful as the score for a given GMA is its distance from the mean of the set of GMAs with which it was compared and as the distance between the means of the two experiments is not known. However, as already mentioned, it is valid to compare the performance of SLIN and LLIN in the different experiments. Here it can be noted that the results are similar (in relative terms) except for the red colour region, which is probably due to the difference between the two experimental conditions in terms of relative gamut boundaries at this hue angle. In Experiment 2 the red gamut boundaries for the original and reproduction are significantly more similar than they were for Experiment 1 and as LLIN seems to be better suited for overcoming small gamut differences, it now performs better for colours in this region.

Results for Individual Images

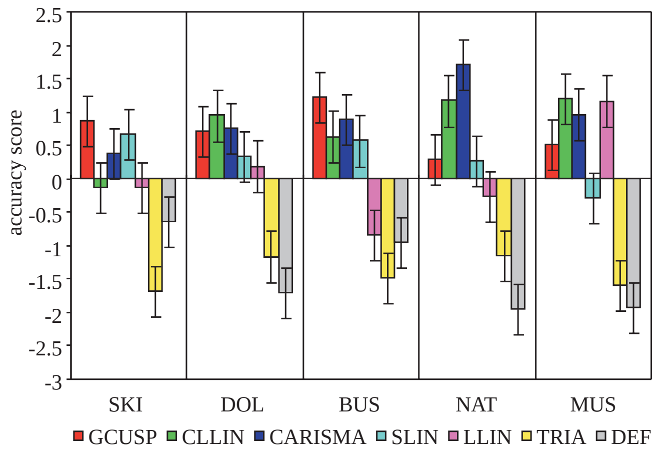


Fig. 14. Results for test images by image.

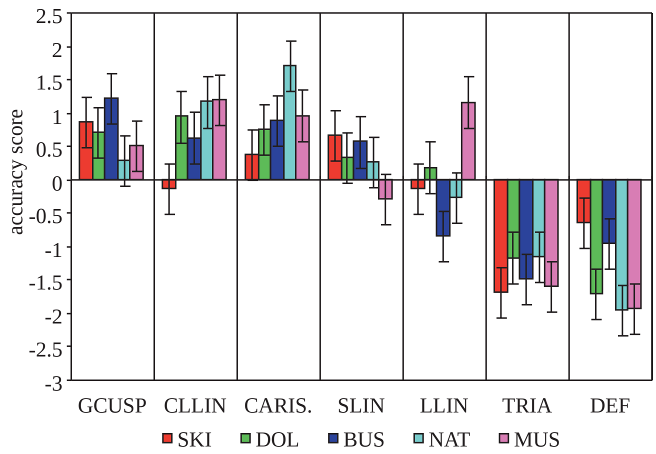


Fig. 15. Results for test images by GMA.

The results obtained for individual images again show a similar trend to the results from the colour regions, which is not surprising as the colour regions looked at in the previous section can be considered to be images themselves. The good performance of GCUSP and CARISMA, the worse performance of TRIA and DEF and the variable nature of the performance of the other algorithms can be seen again (though CLLIN is less influenced by the test images than it was by colour regions).

Comparing these results with results from Experiment 1, it can be seen that LLIN performs better for the DOL and MUS images than it did in the previous experiment. This could again be due to the same reason, which makes LLIN perform better for red colours, as it is these which are dominant both in the DOL and MUS images.

The data shown in Figs. 14. and 15. can also be looked at in terms of the ranking of significantly different groups. As the algorithms cannot always be divided into groups for which each member of one group is significantly different from the members of all other groups, the grouping is done by first selecting the top algorithm and including in its group all algorithms which are not different from it. The second group is then formed by that remaining algorithm which has the highest score and the algorithms, which are not significantly different from it and which are not in group one (the other groups are then formed analogously).

The ranking of algorithm groups formed in the above way is shown in Table VIII. It is particularly encouraging to see that the CARISMA algorithm is always in the top two groups (whereby for the SKI image it is not significantly different from the CLLIN algorithm, which is in the top group). Further, it can be seen that the GCUSP algorithm is in the top group for images which have large chroma ranges.

	BUS	**DOL**	**MUS**	**NAT**	**SKI**	**mean**
GCUSP	1	1	2	3	1	**1.6**
CLLIN	2	1	1	2	3	**1.8**
CARISMA	1	1	1	1	2	**1.2**
SLIN	2	2	3	3	1	**2.2**
LLIN	3	2	1	4	3	**2.6**
TRIA	4	3	4	5	5	**4.2**
DEF	3	3	4	6	4	**4.0**

Table VIII. Ranking of GMA groups for five test images.

Summary of Experiment 2

The results of this experiment clearly show that the performance of CARISMA and GCUSP makes them good candidates for being accepted as universal gamut mapping algorithms, as their accuracy scores are consistently high for the images and colour regions looked at in this experiment.

EXPERIMENT 3: VERIFICATION OF GMAS USING DIFFERENT COLOUR SPACES AND MEDIA

Two new GMAs were developed on the basis of results for individual colour regions from Experiment 2 whereby this was done by developing a hybrid algorithm combining the behaviour of the algorithms which performed best for each colour region. A number of previous algorithms were also evaluated and they are all summarised in Table IX. (for a schematic overview see Appendix B and for details see Morovic and Luo[4]).

Mnemonic	**Description**
GCUSP	C dependent J compression + CUSP
CARISMA	J compression + hue shift + relative, gamut shape dependent mapping
UniGMA	hue shift + relative, gamut shape dependent J compression and mapping
LCUSPH	J compression + hue shift + CUSP
LLIN	J compression + linear C compression

Table IX. Overview of GMAs evaluated in Experiment 3.

Experiment 3 was then conducted with the following four aims in mind:

1 to evaluate the new, third–generation **UniGMA** and **LCUSPH** algorithms,

2 to investigate the effect of changing the gamut mapping colour space from CIELAB to **CIECAM97s**[19] on CARISMA, GCUSP and LLIN,

3 to obtain additional information about the performance of **CARISMA** and **GCUSP** (which performed best in Experiment 2) and

4 to study the influence of the magnitude of **gamut difference** on the performance of the selected algorithms.

To facilitate aims 3 and 4, reproductions were made both on *HP Premium Inkjet Paper* (this will be referred to as **plain paper**) and on *HP Glossy Inkjet Paper* (this will be referred to as **glossy paper**). The reason for using two substrates with the same printing device is, that the resulting pair of gamuts are similar to each other in terms of shape, but have different lightness ranges. This makes it possible to understand how the reduction of a gamut's lightness range affects the performance of gamut mapping algorithms.

The differences between CIECAM97s and CIELAB were found to be significant[20] and will serve as a good basis for seeing whether algorithms implemented in CIELAB can successfully be implemented in another colour space.

Overall Results

The overall results in Fig. 16. show that CARISMA and GCUSP gave significantly more accurate reproductions than the other three algorithms. Within the group of the bottom three algorithms the UniGMA algorithm performed best, while being on the boundary of the LLIN algorithm's 95 *per cent* confidence interval.

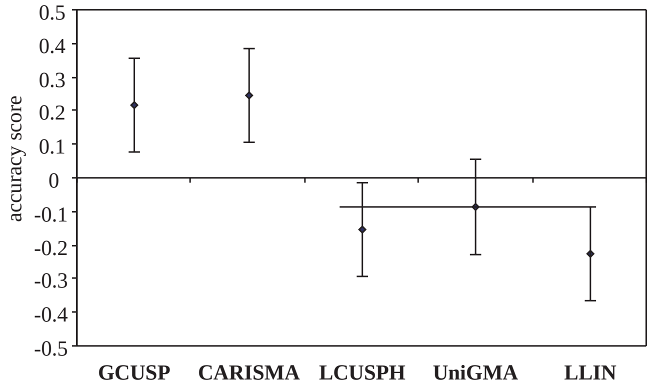


Fig. 16. Overall results of Experiment 3.

From these results it would seem that the two third–generation algorithms have failed completely, as they are significantly outperformed by CARISMA and GCUSP. However, a look at all the judgements made for the GMAs evaluated here shows that the new algorithms (in particular UniGMA) had lower variances (Table X.), which means that their performance was less influenced by colour region and test image. In addition to this, it is important to note that the accuracy scores dealt with here are relative within a given group. Hence, average scores on a relative scale do not have to imply average scores on an absolute scale. Nonetheless, CARISMA and GCUSP perform better overall and one would ideally want an algorithm which combines their good performance with the low variance of UniGMA. The variance scores also suggest a notable advantage of GCUSP over CARISMA, as it has a much lower variance, which means that it is more stable.

	GCUSP	**CARISMA**	**LCUSPH**	**UniGMA**	**LLIN**
variance	0.341	0.901	0.329	0.192	1.186

Table X. Variances of GMAs evaluated in Experiment 3.

To have a better understanding of the five algorithms looked at here, the 30 colours from Experiment 2 were used again (Fig. 17.) and the changes made to them by the GMAs were studied. Note, that these 30 colours had the same monitor RGB values as the colours used in Experiment 2 and that they were also analysed in the same way.

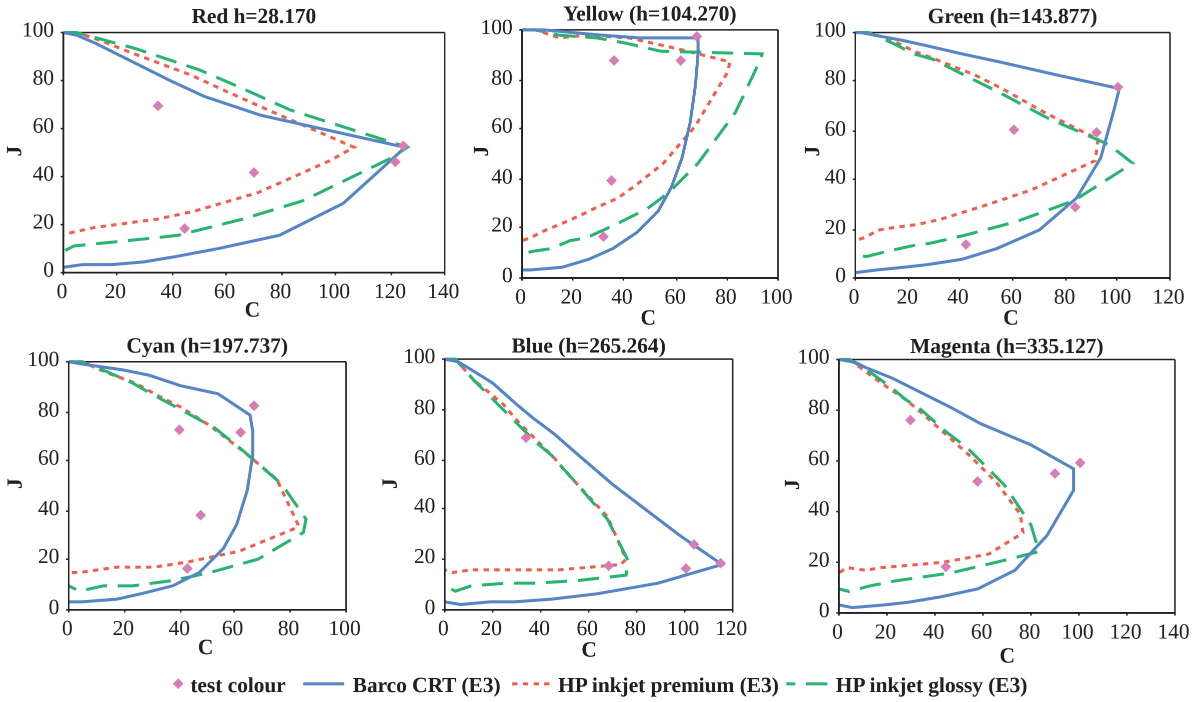


Fig. 17. Test colours used for investigating the changes made by GMAs in Experiment 3 (shown in CIECAM97s JC diagrams).

The statistics of the differences made to these colours by the five GMAs – combined for both printed media – are shown in Table XI whereby the median ΔH value for both CARISMA and UniGMA was 5.90 (it was identical as both algorithms use the same hue shift). It is encouraging to see that the Pearson correlation coefficient between the median |ΔC|/|ΔJ| ratio and the GMAs' ranking is 0.94, which suggests the same principle as was found in Experiment 2 and already indicated in Experiment 1; i.e. to maintain more chroma at the expense of lightness (in relative terms). However, it needs to be noted that this correlation is much lower when the two printed media are considered separately (0.60 and 0.39 for the glossy and plain paper media respectively). Another difference compared with Experiment 2 is that for the GMAs looked at here there is as strong correlation between saturation changes and accuracy scores whereby those GMAs which reduce saturation least are judged to be most accurate.

At the same time, it is interesting to note the strong negative correlation between the accuracy score and the median ΔE_{97s} colour difference (i.e. Euclidean distance in the orthogonal space corresponding to CIECAM97s *JCh*), which is –0.82, –0.72 and –0.92 for the combined, glossy and plain media respectively. This suggests that (within the group of five GMAs considered here) the algorithms, which make the smallest change give the most accurate reproduction. It is also encouraging to see that the correlation between these two parameters is strong for the printed media both individually and collectively as well as for the results from Experiment 2.

GMA	**median ΔE_{97s}**	**median $\|\Delta J\|$**	**median $\|\Delta C\|$**	**$\Delta(C/J)$**	**$\|\Delta C\|/\|\Delta J\|$**
GCUSP	11.20	4.20	9.94	-0.24	1.52
CARISMA	13.51	6.19	1.81	-0.03	0.32
LCUSPH	15.44	4.57	6.05	-0.30	1.82
UniGMA	15.27	3.27	8.32	-0.22	1.67
LLIN	14.93	5.57	12.78	-0.48	2.68

Table XI. Statistics of changes made by GMAs to 30 test colours.

To sum up, it can be said that the accuracy of the CARISMA and GCUSP algorithms was significantly higher than that of the other results, whereby the GCUSP algorithm performed more stably, made a smaller overall change to the colours of the five test images used here and it is much easier to implement it than CARISMA.

Overall Results for Plain and Glossy Media

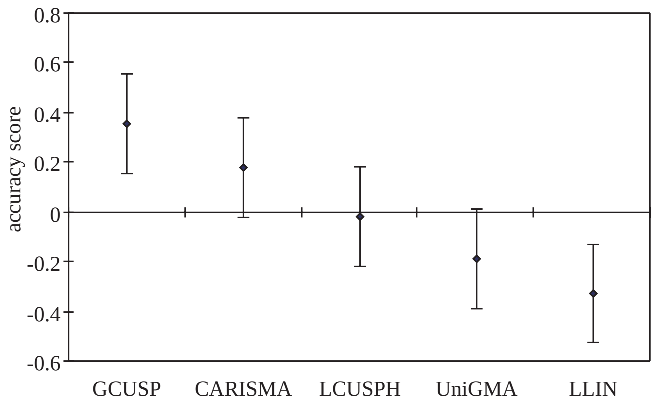


Fig. 18. Overall results for plain paper.

Even though the overall results for the two media show significant differences, there are some common features in them (Figs. 18. and 19.). For both, the CARISMA and GCUSP algorithms are ranked first and second and the LLIN algorithm is always ranked among the bottom two. It can also be seen that LLIN performs better when the gamut difference is smaller and GCUSP when it is larger, whereby the performance of GCUSP is in–line with its results from Experiment 2 where it performed best for the SKI, BUS and DOL images which had the largest chroma ranges.

When looking at the individual accuracy scores obtained in this experiment, it can be seen that the range of accuracy scores is larger for plain paper than for glossy paper. This is the case for 80 *per cent* of all judgements made for overall images and colour regions within them and the ratio of plain paper accuracy–score range to glossy paper accuracy–score range is 1.6. This means that there are larger differences between the reproductions made on plain paper than between the reproductions on glossy paper, or, in other words, that the choice of GMA is more critical when the gamut difference is larger.

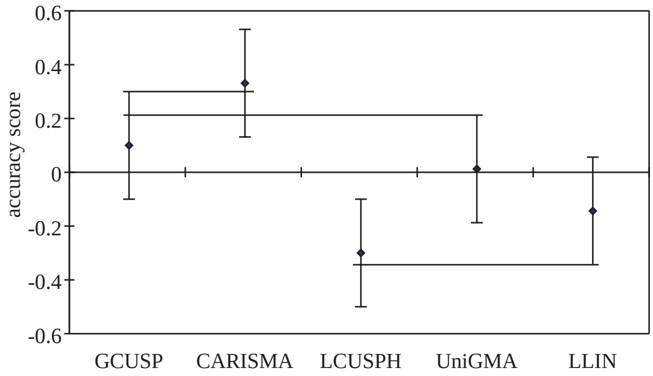


Fig. 19. Overall results for glossy substrate.

The relationship between the lightness range difference of the two media and the resulting accuracy–score range difference is also of interest. Here it can be seen that the plain printed medium has a lightness range which is seven *per cent* smaller than that of the glossy substrate and that this difference results in an accuracy–score range which is 60 *per cent* larger. This clearly suggests the importance of gamut difference for the evaluation of gamut mapping algorithms and differences in this parameter might well have been the causes of differences in the results of experimental studies from different sources.

Results for Colour Regions

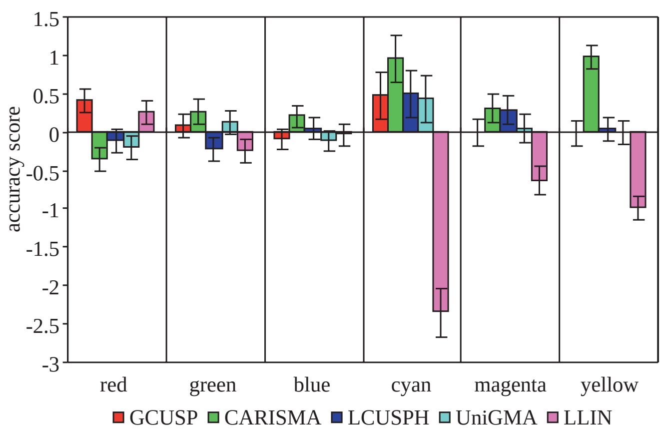


Fig. 20. Results for colour regions by colour region.

From the results for colour regions, shown in Figs. 20. and 21., it can be seen that the CARISMA algorithm performs well for all but the red region and that the LLIN algorithm performed badly for all but the red region. It can also be seen that the LLIN algorithms performs best for the regions (red and blue) where the original and reproduction gamuts are most similar in terms of shape (i.e. the lightness or the two cusps is similar – see Fig. 17.).

The results for individual colour regions also show an influence of the colour space in which gamut mapping is carried out. It can be seen by considering the results for the red colour region for which the algorithms which had no hue shift (i.e. GCUSP and LLIN) performed better than those which had a hue shift. This could be a consequence of CIECAM97s' hue predictor non–uniformity in that region as a result of which the hue of red colours becomes bluish when their lightness and chroma predictors are changed. Hence the reproductions made with the algorithms which had a hue shift performed worse, as the hue shift specified by the algorithms was towards blue. This meant that it added to the hue shift already inherent in the colour space and caused the combined hue shift to be unacceptable.

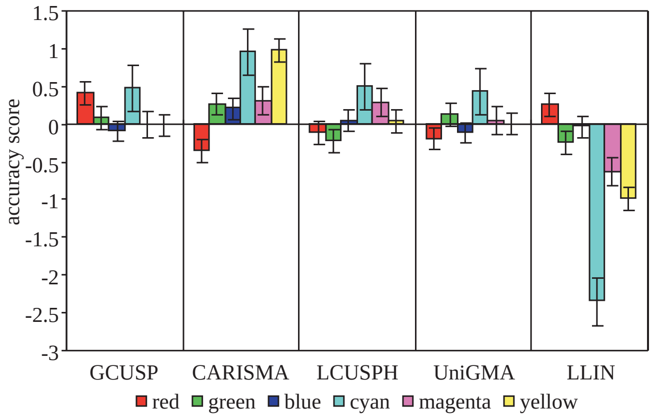


Fig. 21. Results for colour regions by GMA.

The results shown in this section again confirm the findings presented in the section about overall results. It can be seen that the CARISMA and GCUSP algorithms perform best and that the GCUSP algorithm has a low variance relative to the colour region from which it maps colours.

Results for Individual Images

In this experiment the results for individual images, which are shown in Figs. 22. and 23., do not exhibit such homogeneity as was the case with the results from Experiment 1. However, there are some characteristics of GMAs, which can be seen in spite of this. The performance of CARISMA is worse for the images which have a significant red–contents (DOL and MUS) and GCUSP does well for images which have a large chroma range (with the exception of SKI where it is in the second–best group).

Further, it can be seen that the ranges of accuracy values are fairly limited for all but the BUS image (in this experiment the accuracy score range of the other four images was approximately 1 to 1.5 whereas in Experiment 1 the range was 2 to 3 accuracy units). The fact that the differences between algorithms are small in this experiment is a consequence of comparing algorithms which perform similarly – four of the five algorithms looked at here (i.e. except for LLIN) are either the best ones from Experiment 2 or were developed from them.

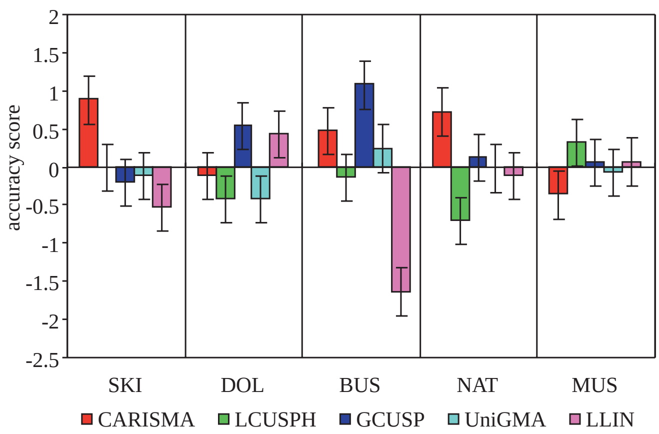


Fig. 22. Results for test images by image.

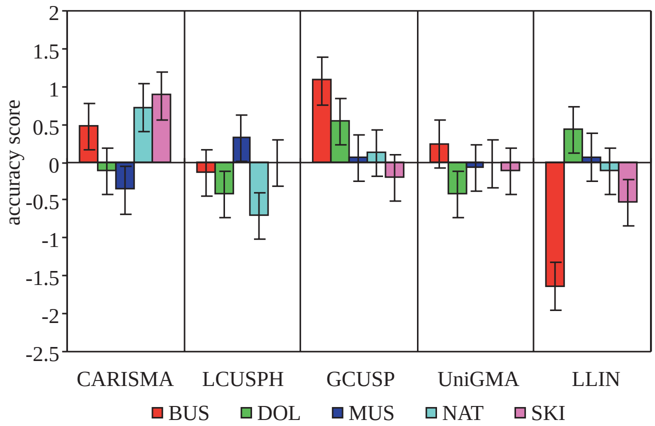


Fig. 23. Results for test images by GMA.

Finally, it is of interest to consider the grouping of GMAs for the five test images used here (Table XII.), as a good performance in this is of great practical importance for universal gamut mapping algorithms. It can be seen that the GCUSP and CARISMA algorithms are in the top two groups for each of the five test images, which is further evidence for their suitability as universal GMAs.

	BUS	**DOL**	**MUS**	**NAT**	**SKI**	**mean**
GCUSP	1	1	1	2	2	**1.4**
CARISMA	2	2	2	1	1	**1.6**
LCUSPH	3	2	1	3	2	**2.2**
UniGMA	2	2	2	2	2	**2.0**
LLIN	4	1	1	2	3	**2.2**

Table XII. Ranking of GMA groups for five test images.

Summary of Experiment 3

Based on this experiment, it can be said that the GCUSP and CARISMA algorithms performed best in terms of overall results as well as the results for individual test images and colour regions in them and that the GCUSP algorithms in particular had a low variance of accuracy scores. It was again shown that those algorithms which maintained relatively more chroma gave more accurate reproductions and that these algorithms also made smaller overall changes to the images' colours.

Further, the results suggested that the magnitude of original and reproduction gamut difference has a significant influence on the range of the GMAs' performances, which means that the choice of GMA for the reproduction of images between two media is more critical when there are larger differences between these.

CONCLUSIONS

The evolutionary approach to developing gamut mapping algorithms used in this study has clearly resulted in a new algorithm (GCUSP) which significantly and consistently outperforms the initial methods on which it is based. GCUSP achieved high accuracy scores for the vast majority of judgements made both in Experiment 2 (where it was first evaluated) and Experiment 3 (where it was verified). In addition to the good overall performance, the variance of its accuracy scores was also very small (it was lowest in Experiment 2 and lower than that of CARISMA in Experiment 3), which indicates a stable performance across the range of images used. Further, it was shown that this method performs well both in CIELAB and CIECAM97s, which is of particular practical interest and in another paper it was also shown that the reproductions made with this GMA are pleasant when the original images reproduced using it are pleasant.[6] All these features make GCUSP an excellent candidate for being a universal gamut mapping algorithm and its evaluation in other studies would be of great interest (Guidelines for implementing GCUSP are provided in Appendix C).

ACKNOWLEDGEMENTS

The authors would like to thank Prof. Tony Johnson and Dr. Peter Rhodes for their kind assistance.

APPENDIX A

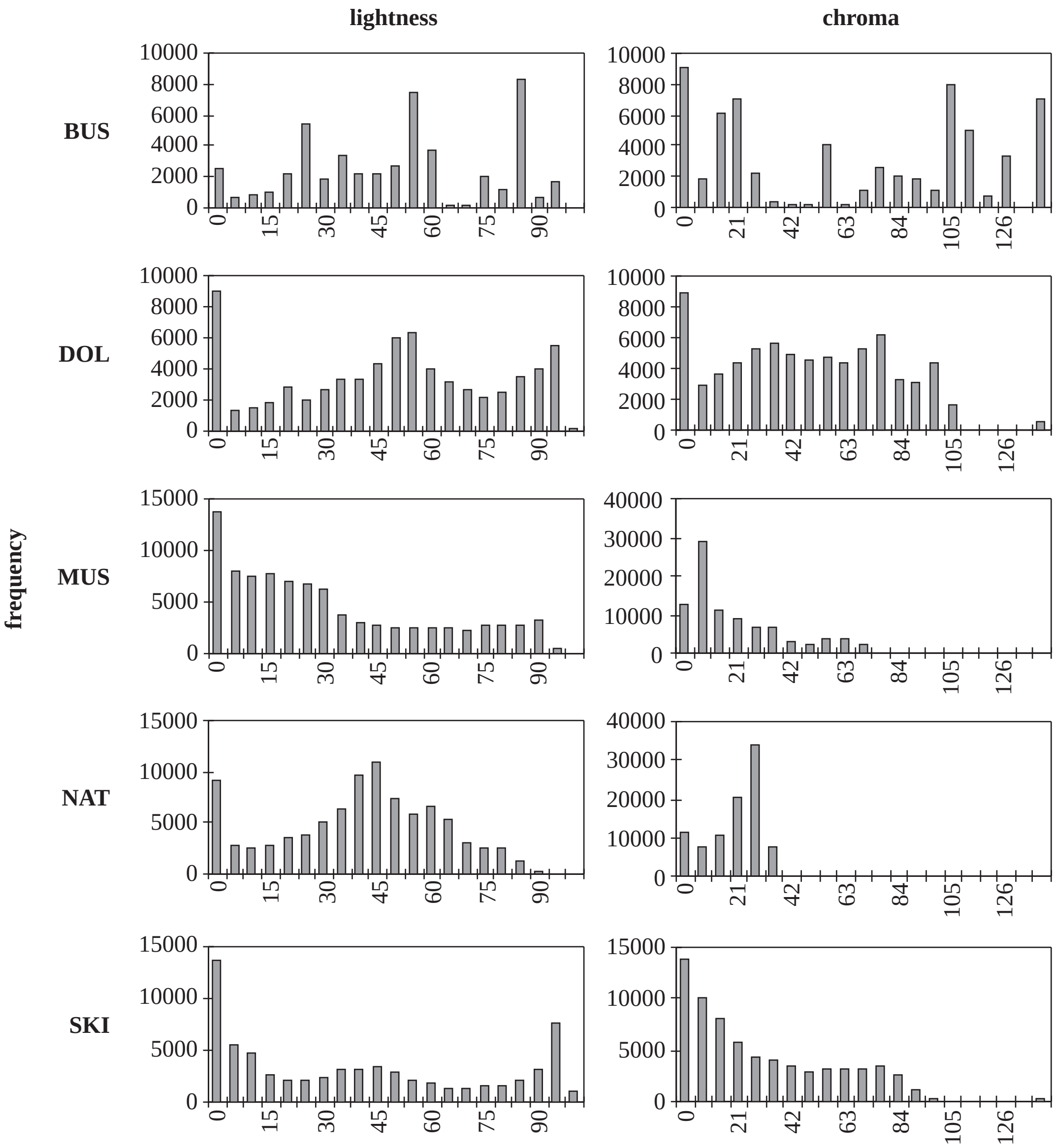


Fig. 24. CIELAB lightness and chroma histograms of test images.

APPENDIX B

The purpose of this appendix is to give a very brief overview of the gamut mapping algorithms evaluated in the present paper so as to make it easier to understand the nature of colour transformations they carried out. For the simple algorithms this will be done primarily by way of diagrams and for the complex ones by giving a brief outline of their structure. For a detailed description of the algorithms see Morovic and Luo.[4]

Throughout the following diagrams the *o* and *r* subscripts will refer to the original and reproduction respectively; the letters *g* and *s* will be used to label the gamut boundary and a arbitrarily–chosen sample colour respectively; where applicable, E will represent a centre–of–gravity; α will stand for hue angle and θ for a spherical angle in planes of constant hue.

First Generation GMAs

The **LLIN**, **LCLIP** and **LNLIN** (Fig. 25.) algorithms all start with a uniform linear lightness compression and are then followed by either linear compression, clipping or non–linear compression respectively along lines of constant lightness.

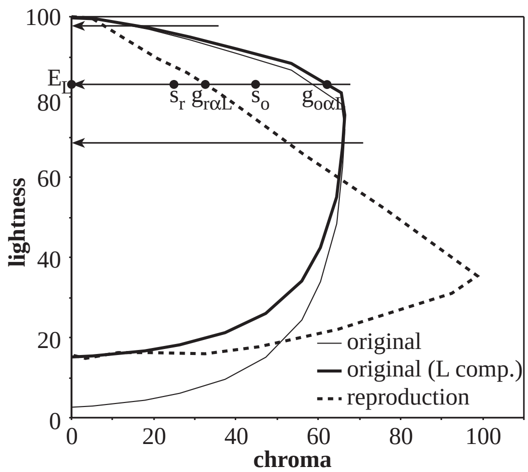


*Fig. 25. Overview of LCLIP, LLIN and LNLIN algorithms (*s *represents the original colour after lightness compression).*

SLIN (Fig. 26.) and **CUSP** (Fig. 27.) on the other had consist in a single step – i.e. linear compression towards a centre–of–gravity which for the former is the point on the lightness axis with a value of 50 and for the latter is the point on the lightness axis with the lightness of the cusp at the given hue. **LSLIN** is simply a combination of an initial uniform linear lightness compression with SLIN.

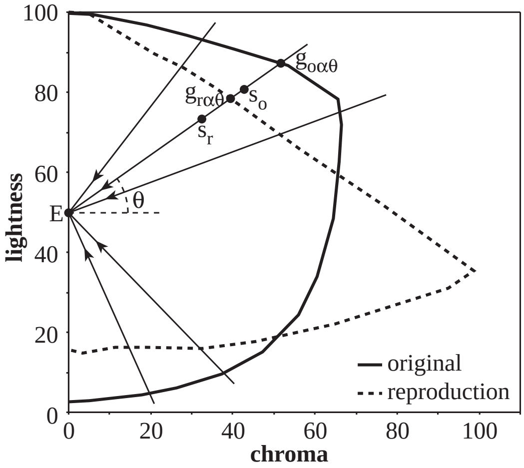


Fig. 26. Overview of SLIN algorithm.

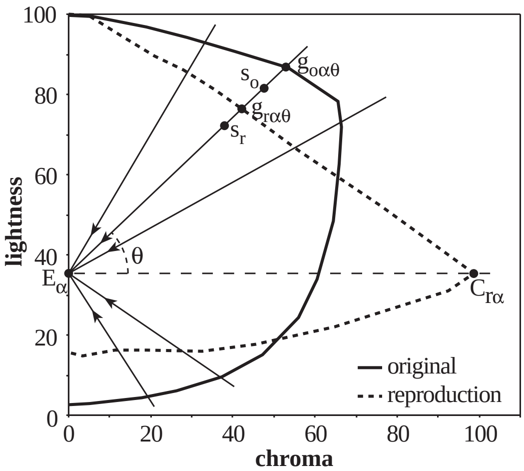
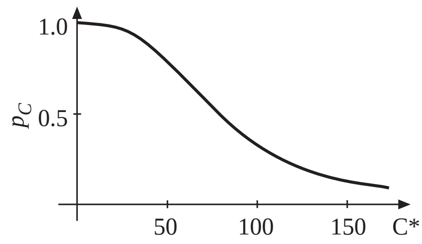


Fig. 27. Overview of CUSP algorithm.

Second Generation GMAs

GCUSP is a combination of an initial chroma–dependent lightness compression (Fig. 28) with CUSP.



$$p_C = 1 - \sqrt{\frac{C^{*3}}{C^{*3} + 5 \times 10^5}}$$

Fig. 28. Chroma–dependent Gaussian lightness compression used in GCUSP.

CLLIN (Fig. 29.) first compresses the chroma of a colour based on the original and reproduction cusps at its hue angle and then maps lightness ranges at a given chroma onto each other.

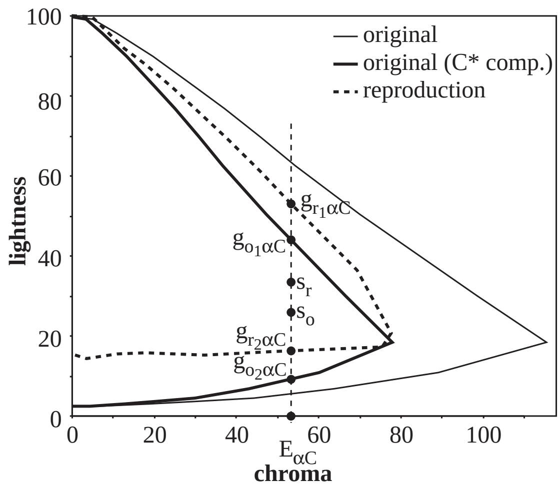


Fig. 29. Overview of CLLIN algorithm (s_o is original colour after chroma compression).

The **TRIA** algorithm (Fig. 30.) reduces a gamut boundary at a given hue angle to a triangle and then transforms the colour into the reproduction gamut triangle so that the relative position in the original gamut triangle is preserved after transforming it. Note that this transformation maps the original cusp onto the reproduction cusp and is monotonic.

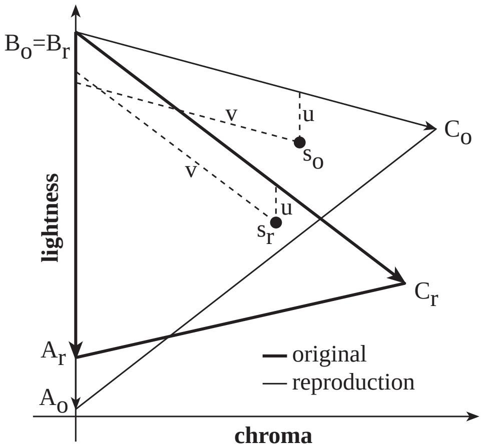


Fig. 30. Overview of TRIA algorithm.

The **CARISMA** algorithm consists of three stages. First a uniform linear lightness compression, second, a hue shift based on the hue angles of the primary and secondary hue angles of the original and reproduction medium and third, a simultaneous lightness–chroma compression in planes of constant hue angle dependent on the relative shape of the original and reproduction gamut boundaries. Three different compression techniques were used n this last step whereby the first of them was a compression towards the point on the lightness axis that resulted from its intersection with the line connecting the two cusps, the second was a compression towards the point on the chroma axis that had half the chroma of the reproduction cusp and the third was the CUSP algorithm.

Third Generation GMAs

UniGMA is a variation of CARISMA which differs from it by not having an initial uniform linear lightness compression, by using different criteria for evaluating the nature of the relationship between the original and reproduction gamut boundaries and applying different gamut mapping techniques. The lightness–chroma mappings used are CLLIN, GCUSP and CUSP preceded by uniform linear lightness compression.

LCUSPH is in effect one of the three possible mapping methods used in UniGMA which starts with a uniform linear lightness compression, the performs a CARISMA–type hue shift and finally uses the CUSP algorithm for mapping lightness and chroma simultaneously.

The hue shift used by CARISMA, UniGMA and LCUSPH is determined by the hue shifts at the primary and secondary hues of the original medium whereby these hues are shifted half–way towards the corresponding hues of the reproduction medium. Hues shifts for other hue angles are determined by interpolation from their nearest neighbouring primary and secondary hue. No optimisation of the hue shifting method was carried out though it is questionable whether this would result in significant improvement as the magnitude of hue shifts should be kept small and hence they contribute less significantly to the overall performance of a GMA than how lightness and chroma are treated.

It is strongly recommended that the previously–mentioned paper[4] containing details of all the algorithms is consulted for a better understanding of the material presented here.

APPENDIX B

The following C–based pseudo–code outlines a possible implementation of the GCUSP algorithm (variables are shown in italics).

Variables

o – original colour, *r* – reproduction colour, *rcusp* – reproduction cusp, *E* – centre of compression (structures contain lightness (*L*), chroma (*C*) and hue (*h*) data and the minimum and maximum lightness of their corresponding gamut) *ogb* – point on original gamut boundary, *rgb* – point on reproduction gamut boundary (structures containing *L* and *C* data and distance (*d*) along line determined by *E* and *o*, whereby *o* always has distance of 1.0)

l – structure containing equations of a line

t – target distance along l for reproduction (unit is distance between E and o), *p* – chroma–dependent compression factor

GCUSP

{

1. keep hue unchanged

   r.h=*o.h*;

2. compress lightness

   2.1 first calculate chroma–dependent compression factor

   p=1-sqrt(pow(*o.C*,3.0)/(pow(*o.C*,3.0)+500000.0));

   2.2 apply compression

   r.L=((1-*p*)**o.L* + *p**(*r.maxL* - (*o.maxL* – *o.L*)*(*r.maxL*-*r.minL*)/(*o.maxL*-*o.minL*)));

3. find reproduction cusp at *r.h* – *rcusp*

4. determine centre of compression *E*

   E.C=0.0;

E.L=*rcusp.L*;

5. calculate equation of line *l* connecting *E* and *o*

6. intersect *l* and original gamut boundary to get *ogb*

7. intersect *l* and reproduction gamut boundary to get *rgb*

8. linearly compress *o* along *l* based on *ogb* and *rgb* only if *o* is out–of–gamut

if(*rgb.d*<1.0) *t*=*rgb.d* +(1.0-*ogb.d*)***rgb.d*/*ogb.d*;

9. calculate *o.L* and *o.C* on the basis of *l* and *t*.

}

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FIGURES

Fig. 14. Results for test images by image.

Fig. 15. Results for test images by GMA.

Fig. 16. Overall results of Experiment 3.

Fig. 17. Test colours used for investigating the changes made by GMAs in Experiment 3 (shown in CIECAM97s JC diagrams).

Fig. 18. Overall results for plain paper.

Fig. 19. Overall results for glossy substrate.

Fig. 20. Results for colour regions by colour region.

Fig. 21 . Results for colour regions by GMA.

Fig. 22. Results for test images by image.

Fig. 23. Results for test images by GMA.

Fig. 24. CIELAB lightness and chroma histograms of test images.

Fig. 25. Overview of LCLIP, LLIN and LNLIN algorithms (*s* represents the original colour after lightness compression).

Fig. 26. Overview of SLIN algorithm.

Fig. 27. Overview of CUSP algorithm.

Fig. 28. Chroma–dependent Gaussian lightness compression used in GCUSP.

Fig. 29. Overview of CLLIN algorithm (s_o is original colour after chroma compression).

Fig. 30. Overview of TRIA algorithm.

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