# Optimizing Gamut Mapping: Lightness and Hue Adjustments

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## Abstract

This study evaluates gamut mapping algorithms with different mapping types and mapping directions. Among these are the method of mapping colors towards a focal point as well as the newly developed relative lightness change (RLC) technique. The latter maps colors along curved lines and enables the direct use of cylindrical coordinates lightness, chroma, and hue for the mapping, regardless of the mapping direction. Additionally, hue adjustments are applied.

The paper discusses issues of gamut mapping such as the mapping space, the coordinate system within the space, and gamut boundary description. Psychophysical experiments are described which were conducted to evaluate the reproduction of monitor images on a device with a clearly smaller color gamut. All images were viewed on the monitor. The algorithms were dependent on the image gamuts.

The experiments show that the RLC method performs superior over the centroid mapping. Moreover, the optimum mapping direction was RLC50 which means a slight adaptation of lightness. The best mapping type was pure clipping, regardless of the mapping direction. These results help understanding the mechanisms of gamut mapping and support further developments and research in color image reproduction.

## 1. Introduction

Gamut mapping is an important step in color image reproduction in order to conserve as much of the appearance of an original image as possible. Due to technical limitations, variations between color rendering processes, and differences in viewing conditions, a perfect match of a reproduced image to the original can rarely be achieved. The task of a well-designed gamut mapping algorithm is to get the best possible pleasing results.

While the measurement and specification of color in general is not trivial, the evaluation of the appearance of an image or of its closeness to an original is even more critical. Such evaluations can only be based on psycho-physical experiments and consecutive statistical evaluation.

The aim of this study is to achieve a better understanding of the mechanisms of gamut mapping rather than to directly develop an algorithm that is meant to be more or less applicable to arbitrary cases. The particular focus is on the modification of lightness and hue in order to preserve higher chroma. The results will be essential for the design of new techniques in the future.

## 2. Parameters of Gamut Mapping

### 2.1. Direction versus Type of Mapping

There are two basic parameters that can be used for classifying gamut mapping algorithms: the *direction of mapping* and the *type of mapping*. It is very important to understand that both influence each other rather strongly.

It is well-known that the structure of an image is mainly contained in the lightness/brightness information and not in the chroma channels. Otherwise, applications such as black-and-white photography or the established data compression algorithms of JPEG or TV broadcast systems would not work. The type of mapping can usually vary between clipping and linear compression. Clipping results in a loss of structure (blocking artifacts), and the degree of visibility of this loss in an image depends highly on the direction of mapping.

If, for example, lightness is kept constant, we can expect that the loss due to clipping is less visible compared to the case where chroma is kept constant and lightness is varied. This means that the optimum mapping type depends on the mapping direction.

On the other hand, if the mapping type is specified to be “clipping”, then it is expected that the loss of structure due to clipping is more visible in lightness, and an observer will attribute more importance to lightness than to chroma. This means that the optimum direction of mapping in turn depends on the specified type of mapping.

These considerations should be extended to include the modification of the hue-angle. Though it is known that hue-shifts should be treated very carefully and be limited, in some cases modified hues help to conserve larger chroma which in turn leads to more pleasing images.

### 2.2. Color Spaces and Gamut Boundary Description

A question often discussed is in which color space the mapping should be carried out. The mapping space should be approximately based on human perception. Candidates are e. g. CIELAB, LIELUV, and CIECAM97s. We consider it most important that the mapping space has correlates of perceived lightness, chroma, and hue, and less important that it represents an overall uniform distribution. For instance, it is known that the hue-angle $h_{ab}$ in CIELAB has some weaknesses in this regard.[1,2] Particularly in the blues, colors with the same *perceived* hue do not lie on lines of constant hue-*angle*.

While being aware of its weaknesses, we chose CIELAB as the mapping space throughout this study, due to its common use and the possibility to process CIELAB images with standard color imaging software. CIECAM97s may be better suited if different media are involved, which is not the case in this study.

A further important question is the coordinate system to choose within the color space. Basically, we have the choice between cartesian, cylindrical, and spherical coordinates. Based on the knowledge that the hue of colors should be conserved, only the latter two are relevant since they contain a hue-correlate in form of the hue-angle. However, the question which of these two better fits the needs, cannot be answered in general. It depends largely on the chosen direction of mapping.

E. g. if lightness is held constant (in addition to the hue-angle being constant), then cylindrical coordinates $L^*C^*h^*$ will be the first choice, since the mapping can be carried out one-dimensionally along one of the coordinate axes (chroma). However, an often used method is mapping towards a focal point on the lightness axis. Here, a spherical coordinate system with the origin at the focal point would allow the simplest mapping, namely along the spherical radius.

However, we felt that none of the two mentioned mapping directions are optimal. One of the purposes of this study was to find the optimum direction of mapping, dependent on the location in color space, relative to the boundaries of the reproduction as well as the image gamut. Since the direction is no longer fixed, the choice of the coordinate system seems to be more a matter of taste, at this time.

On the other hand, there are further aspects to consider which are related to the description of the gamut boundaries. While the color gamuts of reproduction devices (monitors and printers) are usually well-behaved, determining the gamut boundaries of images is a critical task. Image gamuts are usually calculated by scanning all the image pixels and finding the maximum chroma for a given lightness-hue pair (or analogously in spherical coordinates). The problem starts at the question which hue and lightness subsampling should be chosen. In this study, the lightness and hue sampling was 100 and 360 steps, respectively. Furthermore, after scanning the image, there are rather many holes in the boundary, partly because some colors do not exist in the image, and partly because the usual 8-bit quantization of L*a*b* leads to large hue-jumps at the low chromas. Hence, in order to be utilized, the image gamut boundary must be smoothened first.

Here, we must make sure that every entry of maximum chroma in the $(L^*, h^*)$-table is included in the smoothened gamut surface, so that some kind of maximum operator with a certain width/height must be applied. If the smoothing is too narrow, the mapped image will often look grainy; if the smoothing is to wide, some colors may be mapped (“compressed”) stronger than necessary. After some experiments we chose an operator that gives the maximum of all neighbors, weighted in dependence of their distance from the location under consideration. The maximum operator has a plateau of 5 degrees and 4 $L^*$ units and linear ramps of 7 degrees and 6 $L^*$ units.

Moreover, the form of the gamut boundary, according to the maximum operator, depends essentially on the direction to which the maximum is referred. E. g. looking for the maximum chroma leads to different results than looking for the maximum spherical radius. Here again the method must be adapted to the direction of the gamut mapping. Note that the focal point is often located at the lightness of the cusp (i. e. the point of maximum chroma at a given hue-angle). This means that a spherical coordinate system is different for each hue-angle.

## 3. Gamut Mapping Methods

From an earlier study, it is known that if the mapping direction is specified to keep lightness and hue constant, the best mapping type is simple clipping.[3] The general goal of gamut mapping should be to conserve as much of the original chroma as possible. However, in order to achieve this, it is often necessary to modify lightness and/or hue.

Another concern is the degree of soft-clipping. One class of mapping type that performed well in ref. 3 is plotted in Fig. 1. We use the parameter $\lambda$ to yield a continuous transition between linear compression ($\lambda = 0$) and clipping ($\lambda = 1$). Fig. 1 shows the class of possible mapping types in relative coordinates $c$ which may be identified as chroma as well as the spherical radius, depending on the mapping direction.

### 3.1. Mapping Towards a Focal Point

A very popular mapping method, due to its simplicity, is to clip all out-of-gamut colors towards a focal point on the lightness axis. This mapping direction often leads to lightness modifications that are considered unacceptably large by observers. Hence, our idea was to move the focal point of mapping towards negative chroma (see Figure 2).

The chroma of the focal point is the parameter to vary the direction of mapping from centroid mapping ($C^*_{focus} = 0$) to

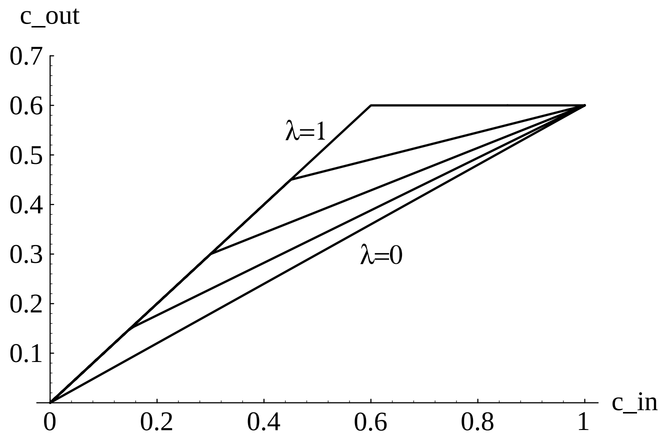


*Figure 1*: *Class of mapping types along the cylindrical/spherical radius for a maximum reproduction radius of 0.6. The degree of soft-clipping is dependent on the parameter λ*

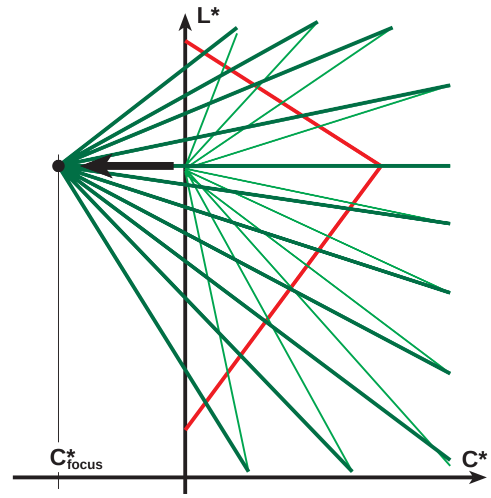


*Figure 2*: *To achieve a mapping direction between centroid mapping and mapping with constant lightness, the focal point is moved towards negative chroma.*

mapping with constant lightness ($C^*_{focus} = -\infty$). Here, the focal point depends on the hue-angle and is located at the lightness of the cusp (i. e. the point of maximum chroma) at a given hue-angle.

This kind of mapping has some drawbacks. In general, for every color to be mapped, the cross-sections between each of the two gamut boundaries (image and reproduction) and the vector of mapping, must be found. To simplify this process, the image gamut can be stored in fitting coordinates since it is calculated in real-time. However, the reproduction device gamut is usually calculated off-line. Hence, it is given in coordinates not suited for the mapping since the optimal coordinates depend on the mapping direction which are not known at the time the device gamut is determined. This necessitates time-consuming iterative searches to be carried out in real-time. An alternative may be to recalculate the device gamut in the suitable coordinates, related to the focal point which may be located at negative chroma.

Fig. 3 shows the curves of equal lightness after the mapping towards the focal point at $C^* = 0$ and $L^* = L^*_{cusp}$ with $\lambda = 1$ (clipping).

### 3.2. Relative Lightness Change Mapping

To overcome the limitations of the gamut boundary description, we developed a new technique that allows mapping in varying directions from constant lightness to strong lightness changes. The algorithm is straight-forward and avoids any iteration. Moreover, the coordinate system of the gamut boundaries needs not to be adapted to each specific case. All gamuts are simply stored in the convenient coordinates lightness, chroma and hue-angle.

The method is based on a lightness change, relative to the $L^*$-distance from the cusp and relative to the $C^*$-distance from the gamut boundary, followed by a simple chroma mapping with constant lightness. Therefore it is called *Relative Lightness Change* method. The algorithm is as follows:

If $(C^* < \lambda\hat{C}_{out}(L^*,h^*))$ or $(\hat{C}_{in}(L^*,h^*) < \hat{C}_{out}(L^*,h^*))$,
do nothing,
else

$$\Delta L^* = \frac{\alpha}{100}\frac{(L^*_{cusp}(h^*) - L^*)\cdot(C^* - \lambda\hat{C}_{out}(L^*,h^*))}{C_{ref} - \lambda\hat{C}_{out}(L^*,h^*)} \quad (1)$$

$$L^*_{mod} = L^* + \Delta L \quad (2)$$

$$C^*_{mod} = \lambda\hat{C}_{out}(L^*_{mod},h^*) + \quad (3)$$

$$+ (1-\lambda)\hat{C}_{out}(L^*_{mod},h^*)\frac{C^* - \lambda\hat{C}_{out}(L^*_{mod},h^*)}{\hat{C}_{in}(L^*,h^*) - \lambda\hat{C}_{out}(L^*_{mod},h^*)}$$

where $\hat{C}_{in}(L^*,h^*)$ and $\hat{C}_{out}(L^*,h^*)$ are the boundaries of the image and the reproduction gamut, respectively; $L^*_{cusp}(h^*)$ is the lightness of the cusp at a given hue-angle. $C_{ref}$ is a parameter that influences the curvature of the mapping direction. It must be greater than the largest possible image chroma, and in this study we chose $C_{ref} = \sqrt{2}\cdot 128$. α gives the degree of lightness change and varies from 0 (no change) to 100% (maximum lightness change). Finally, λ gives the degree of soft clipping, varying from 0 (linear compression) to 1 (clipping).

It should be noted that the relative lightness change method does not exactly map colors along rays originating at the focal point. In fact, there is no evidence that such straight lines should be adhered to. Equation (1) rather provides the potential to optimize mapping curvatures, e. g. by modifying $C_{ref}$ or by replacing the terms in $L^*$ and/or $C^*$ with higher-order polynomials. The mapping direction also slightly depends on the curvature of the gamut boundary.

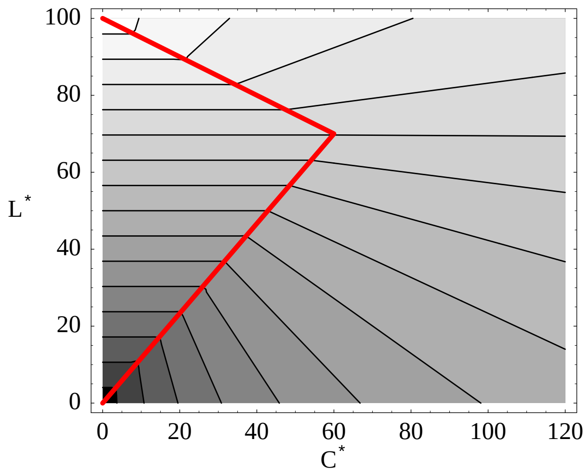


*Figure 3*: *Contour lines of equal lightness after clipping out-of-gamut colors towards the focal point at* $C^* = 0$ *and* $L^* = L^*_{cusp}$.

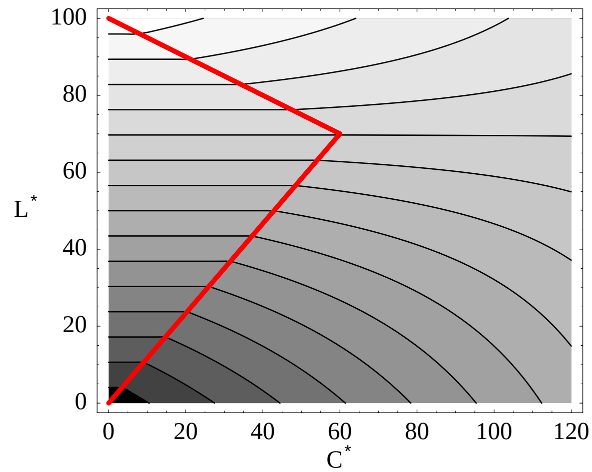


*Figure 4*: *Contour lines of equal lightness after clipping out-of-gamut colors with relative lightness change and* $\alpha = 100\%$

Fig. 4 shows a cross-section of CIELAB with constant hue. It displays the curves of equal lightness after the mapping with relative lightness change and $\alpha = 100\%$, $\lambda = 1$ (clipping). Compare the curvature with that of Fig. 3.

## 4. Experiments

### 4.1. Paired Comparison

We conducted psychophysical experiments to get closer to the "optimum" gamut mapping algorithm. Observers had to judge, which of a given pair of reproduced images was *more similar* to the original, viewed at the same time. Since we wanted to exclude effects from media changes between original and reproduction, all images were viewed on a calibrated Barco monitor. The original images were taken from the Kodak PhotoCD sampler ("creek", "girl", "windows", "parrots", "rafting") and from the Kodak web site ("colorballs", "pig") and were slightly modified in order to be completely displayable on the screen. These images were then mapped to the reduced color gamut of a dye diffusion thermal transfer printer.

The images were viewed in a dark surround, hence the screen's lightness ranged from 0 to 100. In order to avoid effects from the different lightness ranges, viewed on the same medium, the lightness of the reproduction gamut was linearly scaled to fit the range of the monitor (0–100). To make differences between the reproductions more clear, the chroma of the reproduction gamut was scaled to 50%. From previous experiments it was known that larger reproduction gamuts are less critical and that gamut mapping algorithms performing well for small gamuts also perform well with large gamuts.

From several studies it is known that image dependent methods perform better, hence all algorithms (except for the clipping methods) were related to the image gamuts rather than to the gamut of the original medium.

All reproduction methods were compared against each other for a number of test images. The sorting of the combinations and also the positions on the screen (left/right) was changed randomly. The observers were asked to choose the image that was most similar to the given original. They were allowed to make "don't know" decisions if a preference could not be found. The given time to view each combination was not limited but the subjects were advised not to take essentially longer than 30 seconds for each image pair. All subjects were tested for normal color vision.

From the merits of the observers, psychophysical scales were calculated using Thurstone's law of comparative judgment.[4] Here it was assumed that the variances were constant for each method under comparison, so that Thurstone's case number 5 could be applied.[5,6]

### 4.2. Experiment 1

Our first experiment investigated the optimum mapping direction for a given mapping type. The mapping type was clipping, i. e. reproducible colors were left untouched and the out-of-gamut colors were mapped to the gamut boundary. The directions tested were mapping with constant lightness (dL0), mapping towards a focal point at the lightness of the cusp with $C^*_F = 0$ (F0), $C^*_F = -20$ (F-20), $C^*_F = -50$ (F-50), and $C^*_F = -100$ (F-100), and the relative lightness change method with $\alpha = 25\%$ (RLC25), $\alpha = 50\%$ (RLC50), and $\alpha = 100\%$ (RLC100).

The images were "creek", "girl", "windows", "colorballs", "parrots", "pig" and "rafting", judged by eight observers. Fig. 5 shows the results, averaged over all images, together with the 95% confidence intervals. It can be observed that of the

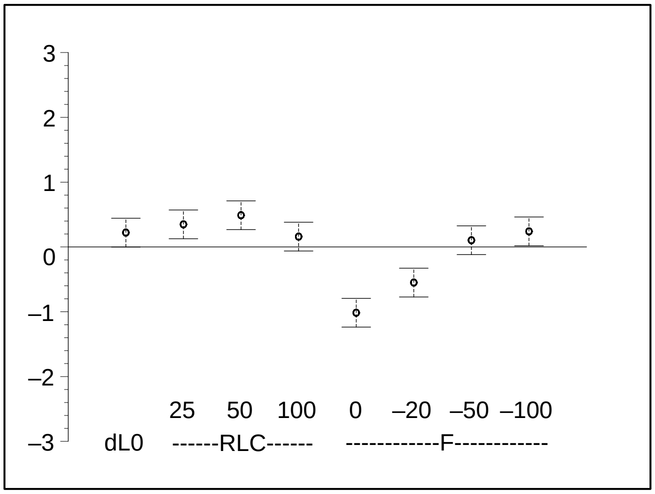


*Figure 5*: *Ratings of the eight tested methods of experiment 1 on a psychophysical scale, averaged over eight observers and all images. Algorithms are dL0, RLC25, RLC50, RLC100, F0, F-20, F-50, F-100, all with* $\lambda = 1$ *(clipping).*

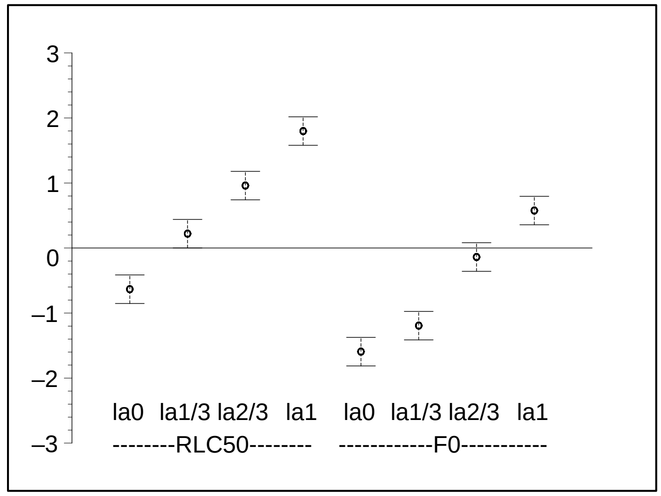


*Figure 6*: *Ratings of the eight tested methods of experiment 2 on a psychophysical scale for the accuracy of four test images. Algorithms are: RLC50la0, RLC50la1/3, RLC50la2/3, RLC50la1, F0la0, F0la1/3, F0la2/3, F0la1, where "la2/3" means* $\lambda = 2/3$*.*

tested methods mapping towards a focal point, the results get better, the more the focal point is moved towards negative chroma. F-100 performed virtually identical to dL0 which would be identical with F-$\infty$. The group of RLC methods performed better than the F-xx group and has a maximum of preference at $\alpha = 50\%$ (RLC50), though not statistically different from RLC25, but significantly better than dL0.

Hence, it can be concluded that given, clipping out-of-gamut colors to the gamut boundary of the reproduction process is to be used, the relative lightness compression method with $\alpha = 50\%$ (RLC50) leads to the best results of the methods tested.

### 4.3. Experiment 2

Based on the results from experiment 1, it was then desired to optimize the mapping *type* for given mapping directions. As mapping directions we chose the best of exp. 1 (RLC50) and F0 which performed best in other studies (F0 with linear compression is the same as the CUSP/GCUSP algorithm published by Morovic[7]; if the original and the reproduction device have the same lightness range, CUSP and GCUSP are identical). The mapping type ranged from linear compression ($\lambda = 0$) through $\lambda = 1/3$ and $\lambda = 2/3$ to clipping ($\lambda = 1$). Of the images of experiment 1, we chose those which produced the most distinct preferences ("creek", "girl", "windows", "parrots") and presented them to 10 observers.

Fig. 6 shows the results, averaged over all images, together with the 95% confidence intervals. It can be seen that for each of the two mapping directions, the ratings increase with increasing $\lambda$, i. e. the more a method approaches clipping, the better it performs. Moreover, it is again shown that the relative lightness change method (RLC50) performs better than mapping towards a focal point on the lightness axis.

Note that the F0la0 method, which is identical to the GCUSP algorithm proposed by Morovic,[7] performed worst in our experiment. A reason for the bad performance of GCUSP here may be the comparatively large difference in volume between the original and reproduction gamut. Moreover, Morovic used images with partly more complex content than ours. In fact, we did not use the source code provided by Morovic in this study, so that some uncertainty of identity may still remain.

### 4.4. Experiment 3

In our third experiment, we evaluated the usefulness of hue-modifications in order to preserve higher chroma. As Figure 7 shows, output gamuts often display sharp shapes, particularly in the bright yellows and in the dark blues. The algorithm is designed such that, given an image color, the hue of this color is modified up to a certain limit (e. g. $\pm 10°$) and the possible chroma gain is evaluated.

Results indicate that hue-modifications of this kind indeed can improve the appearance of reproduced images, especially in the said color regions. The tolerance of hue-shift seems to be at approximately $\pm 5°$, but may vary with hue. However, some artifacts were observed if the hue-shifts are applied independently for each pixel. It was observed that image areas with colors of a certain hue mostly span a considerable lightness range (e. g. from 60 to 90). In the yellow hues, the chroma gain due to hue shifts is significant for high lightnesses, while this is not the case at the lower lightnesses. This results in color seams, where the border between shifted

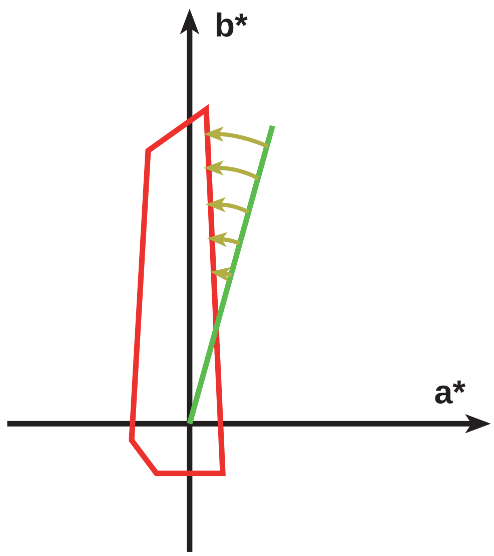


*Figure 7*: *Hue modifications provide a means to retain higher chroma in reproduced images.*

and not-shifted colors is well noticeable.

To overcome these artifacts, the shifting of hues must include complete regions in color space and cannot be applied to the color pixels independently. Hence, some kind of smoothing must be applied to the map of hue modification vectors.

We implemented several algorithms. All of them begin with testing if changing the hue by $\pm 1°$ moves a given color to a location where the reproduction gamut boundary lies at a higher chroma. If so, hue is modified one step further etc. until the given limit is reached. The differences between the algorithms were how the hue modification vectors are further processed.

The simplest case is no further processing. However, this can result in two colors that were initially at the same hue but at different lightnesses, being mapped to clearly distinct hues. The visual effect is the already mentioned color seams which are rather disturbing. A solution for this is to make the modification vector the same for all colors of the same hue. This indeed removes the seams but on the other hand modifies some of the colors more than optimal. This in turn can even diminish chroma rather than enlarging it.

Hence, it is necessary to evaluate the chroma gain of each single color when shifting hue, as well as the chroma loss when the shift is not carried out optimally due to smoothing. We did not reach a point where the results were really satisfactory, yet, but we believe that such an algorithm can be found.

It can be said that although hue-modifications can improve mapped images due to the fact that higher chromas are available, a very careful design of this technique is essential. Moreover, observers often found it difficult to judge the accuracy of a reproduction with modified hues, contrary to the pleasantness. In an auxiliary experiment, the subjects were presented with pairs of reproductions without the original image and were asked to chose the most pleasing image. Here, they often chose an image where hue was modified more than in the accuracy experiment. Hence we can assume that the results of hue modification experiments are dependent on how the experiment is conducted, i. e. if an observer is asked for pleasantness or accuracy. Another study[8] states that there are no differences between accuracy and pleasantness decisions as long as the original image is pleasant. Hence one can conclude that either our test images were not pleasant enough or the statement does no longer hold if hues are modified.

## 5. Discussion

From previous experiments it was known that clipping out-of-gamut colors to the output gamut boundary clearly is the best mapping type if the lightness is kept constant. On the other hand, lightness sometimes must be altered to enable higher output chroma. The purpose of this study was to investigate these effects.

Because of clipping being best when lightness is held constant, in the first experiment clipping was applied as the only mapping type. The experiment compared constant lightness clipping with three parameterizations of the relative lightness change method (RLC) and four of the centroid method. For the centroid method, moving the focal point to a chroma of $-100$ produced the best results, and this is virtually identical with keeping lightness constant. The basic result that the strong lightness changes of methods such as F0 ($C^*_{focus} = 0$) are undesirable, is confirmed by the RLC class. However, RLC50 performed significantly better than every of the focal mappings and significantly better than RLC100 and dL0 (constant lightness). Obviously, the curve form of the mapping direction of RLC is preferable over the straight lines of the centroid mapping.

The second experiment was designed to find the optimum degree of soft clipping for a given mapping direction. Here RLC50 (optimum in exp. 1) and F0 was chosen. Fig. 6 clearly demonstrates that pure clipping is best for both mapping classes. Again, RLC performed superior over F0.

Although it was expected that the best mapping type would not be too far from clipping, the clear preference of hard-clipping is somewhat surprising. When keeping lightness constant, the blocking artifact is usually not noticeable with clipping, but here lightness is modified partly considerably. We can learn from this that the already reproducible colors are very important and they should not lose any chroma. The strong lightness changes of some of the methods seem never be tolerable for two reasons: First, an image that incorporates strong lightness deviations from the original is not considered very similar to the original at all. Second, the blocking artifacts are well noticeable and considered disturbing. But even then, blocking (clipping) is favorable over too strong lightness changes. It seems that both items are minimized when choosing a mapping direction that only slightly modifies lightness.

It is an open question why the GCUSP algorithm proposed by Morovic performs such badly in our study. One reason may be the different conditions under which the experiments are conducted. While we viewed all images on the same media, Morovic compared monitor originals with printed reproductions. Possibly, the differences in viewing conditions between monitor and reflective image had influence on his optimum algorithm. Furthermore, the images chosen by Morovic partly had more complex scenes, and finally, the reproduction gamut of our study had a low volume, compared with the monitor original.

While the results must be verified under more standardized conditions, it is interesting to compare the results with those of Katoh and Ito[9,10] and Wei et al.[11] These authors use a modified color difference formula optimized for gamut mapping to find the optimum replacement colors for out-of-gamut colors. This algorithm is only applicable if the mapping type is clipping. If we know that clipping is preferred regardless of the mapping direction, such a metric may solve many problems.

## 6. Conclusions

In this study, we evaluated gamut mapping algorithms with different mapping types and mapping directions. Among these were the known method of mapping colors towards a focal point as well as the newly developed relative lightness change (RLC) technique. The latter maps colors along curved lines and enables the use of cylindrical coordinates lightness, chroma, and hue for the mapping, regardless of the mapping direction.

It was shown that the RLC method performs superior over the centroid mapping. Moreover, the optimum mapping direction was RLC50 which means a slight adaptation of lightness. The best mapping type was pure clipping, regardless of the mapping direction. These results help understanding the mechanisms of gamut mapping and support further developments and research in color image reproduction.

## 7. Acknowledgments

We are indebted to our observers who patiently did their best to make thorough decisions.

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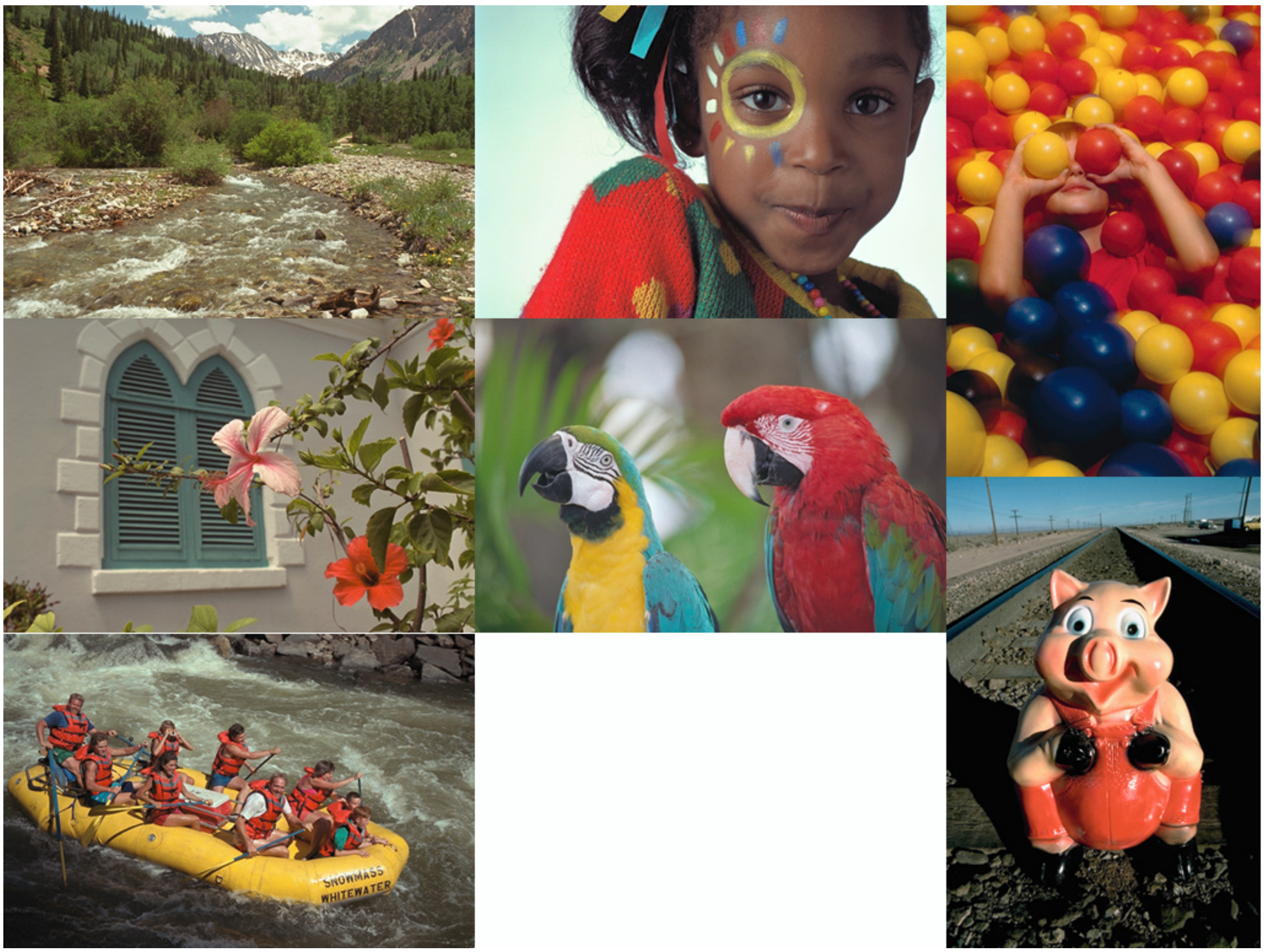
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