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Gamut Mapping: Evaluation of Chroma Clipping Techniques for Three Destination Gamuts

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Abstract

A psychophysical experiment was carried out to evaluate 5 chroma clipping techniques for gamut mapping. Three different destination gamuts were used in order to determine how the shape of the destination gamut would influence performance of the different mapping techniques. The test images consisted of 7 colored computer-rendered textured spheres and one image which contained all 7 objects. Therefore the effect of hue on the preferred technique could be gauged. Although straight chroma-clipping, keeping lightness constant, was overall the best technique, there were notable exceptions. The results indicate that trade-offs between global trends and specific exceptions to these trends may need to be implemented based on local gamut shape and object hue in the image.

Introduction

One strategy in color gamut mapping research is to discover algorithms which may be implemented in a "universal" gamut mapping strategy. However, common experience tells us that a gamut mapping algorithm that produces pleasing results for one image may not work well for another image. This is true for pictorial images as well as business graphics and computer generated images.

One of the goals of our research involving gamut mapping is to simplify the problem in order to determine whether there are some general rules that can be applied to gamut mapping. We have done this in a number of ways. The gamut of the CRT is taken as the original image gamut and the destination gamut is simulated on the CRT in order to eliminate issues involving cross media reproduction. The images used to test the gamut mapping algorithms are simple computer rendered objects that are of one color in order to test hue dependency in gamut mapping.

In addition, we use CIELAB as our color space for gamut mapping although hue nonlinearities are known to exist.[1] Although CIELAB was not designed as a color appearance space, it has shown utility for such purposes.[2-4] The prevalence of CIELAB as well as its usefulness in determining color differences make it useful as a starting point for defining and manipulating color gamuts.

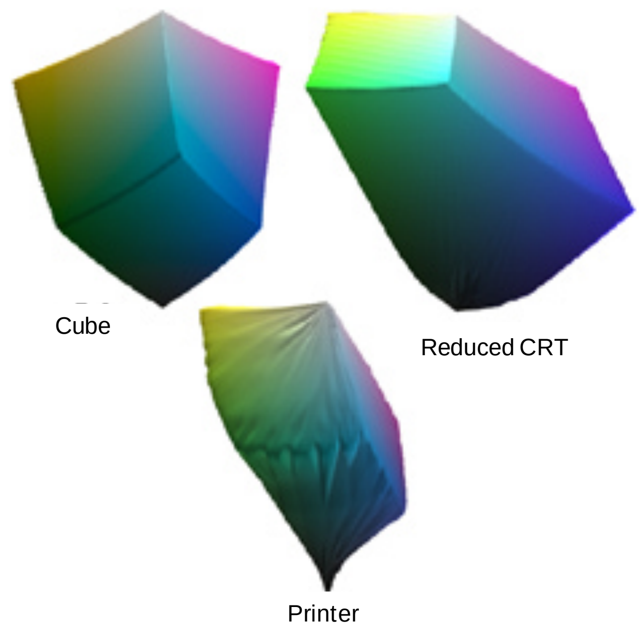

Figure 1. Destination gamuts

In our previous research,[5] arbitrary gamut boundaries were set in order to test gamut mapping in three different cases: lightness mapping, at both low and high values of L*, and chroma mapping when C^*_{ab} is limited. The results from these experiments indicated that for lightness mapping at the top of the gamut, a soft-clipping or knee-function with a particular rate of compression for the majority of the L* range produced the best results for the algorithms tested. In addition, when mapping lightness at the top of the gamut, reducing chroma to preserve the original saturation produced the best results. For lightness mapping to gamuts limited at the bottom, algorithms that clipped or compressed just the darker regions of the image performed best. For chroma mapping we tested a variety of scaling and soft-clipping techniques as well as straight clipping (clipping chroma to the destination gamut while keeping lightness constant) and a clipping technique in which lightness varies in order to preserve the analog of saturation (C^*_{ab}/L^*).

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Straight clipping was overwhelmingly the preferred chroma mapping technique except for those images in which hue nonlinearities in CIELAB created hue artifacts. Gentile, et al.[6] also found that straight clipping was preferred over other compression methods.

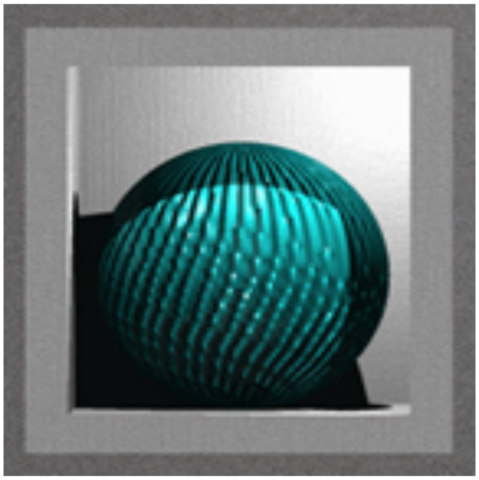

Figure 2. Sample Image

In the experiments described here, a variety of chroma clipping techniques were tested. Different destination gamuts were used in order to determine how the shape of the gamut influenced the performance of the different clipping techniques.

Experimental

The three destination gamuts used in the experiment are shown in figure 1. The Cube Gamut is an arbitrary gamut based on a distorted cube. The Reduced CRT Gamut is based on the gamut of a CRT which is scaled down by approximately 80%. The Printer Gamut is based on measurements of the gamut of an ink-jet printer. All three gamuts range from L* = 10 to L* = 90. Although shown in L*,a*,b* coordinates in figure 1, we have found that representing the gamut in a L*, h_{ab}, C^*_{ab} mountain range facilitates gamut manipulation. The printer gamut was the smallest with a volume of 2.25 x10^5 cubic color difference units. The reduced CRT and deformed cube gamuts were each approximately 4.25×10^5 units. In comparison, the original CRT gamut was 8.36×10^5 cubic units in volume.

The images were created using a 3D rendering program. The images consisted of simple textured spheres each of a unique color: red, green, blue, cyan, magenta, yellow and skin. In addition an image that consisted of all seven spheres was tested. The images used in this experiment contained more texture and shadow content than our previous images. An example image is shown in figure 2.

The mapping was performed sequentially in an order that was indicated by the previous results. First lightness was mapped in order to bring the image into gamut at the top of the gamut (L*=90) following equation 1:

$$L_{temp} = \begin{cases} L_{in}\left(\frac{2}{3}\left(\frac{90}{L_{MAX}}\right)+\frac{1}{3}\right), & 0 \le L_{in} \le 90, \\ 90\left(L_{in}\left(\frac{2/3}{L_{MAX}}\right)+\frac{1}{3}\right), & 90 \le L_{in} \le L_{MAX}, \end{cases} \tag{1}$$

where L_{in} is the L* value of the original image color, L_{temp} is the interim L* value (before the next mapping step) and L_{MAX} is the maximum L* value in the original image. This equation is adapted from Gentile et al.[6]

Then lightness was mapped to bring the image into gamut at the bottom of the gamut (L*=10) following equation 2:

$$L_{out} = \begin{cases} 10, & 0 \le L_{temp} \le \frac{(L_{temp}^{MAX}+10)}{2}, \\ \dfrac{\left(\frac{(L_{temp}^{MAX}+10)}{2}-10\right)\left(L_{temp}-\frac{(L_{temp}^{MIN}+10)}{2}\right)}{(L_{temp}^{MAX}+10)/2-(L_{temp}^{MIN}+10)/2}+10, & \frac{(L_{temp}^{MAX}+10)}{2} \le L_{temp} \le \frac{(L_{temp}^{MIN}+10)}{2}, \\ L_{temp}, & \frac{(L_{temp}^{MIN}+10)}{2} \le L_{temp} \le 100. \end{cases} \tag{2}$$

where L_{temp} is the input L* value of each image color after the first gamut mapping step in equation 1, and L_{temp}^{MIN} and L_{temp}^{MAX} are the L* values of the pixels in the image with the minimum and maximum values, respectively. For all colors in the image that have a reduced L* values in the destination gamut compared to the original, the C^*_{ab} values were adjusted so that the original "saturation" (C^*_{ab}/L*) is preserved.

Five chroma clipping techniques were used on each image for mapping the images (after lightness mapping) into the three destination gamuts. Table one lists the five techniques with their reference numbers which will be used to summarize the results.

Table 1. Chroma Clipping Techniques:

Technique Number	Technique Name
1	Straight Clipping
2	Closest Lab clipping
3	Closest Lab Clipping with Constant Hue
4	Node Clipping
5	Cusp Clipping

Examples of Straight Clipping, Node Clipping, and Cusp clipping are shown in figure 3. In Straight Clipping, L* is preserved and all out of gamut color are mapped to the destination gamut boundary. Node Clipping maps the out of gamut colors to the destination gamut in the direction connecting the color to the achromatic axis at L*=50. Cusp clipping maps each out of gamut color to the destination gamut surface towards the achromatic axis at the value of maximum C^*_{ab} for each hue angle (which were quantized in steps of 1°). For Closest Lab clipping, each out of gamut color was mapped to the gamut surface in order to minimize ΔE^*_{ab}. The gamut surface was quantized in steps of 1° in hue angle and 1 L* unit in lightness. The ΔE^*_{ab} distance of the out-of-gamut point to each surface node was calculated and the minimum value determined the location of the new mapped location. For Closest Lab Clipping with Constant Hue, the same procedure was followed except that only the hue leaf closest to the hue of the out-of-gamut color was used.

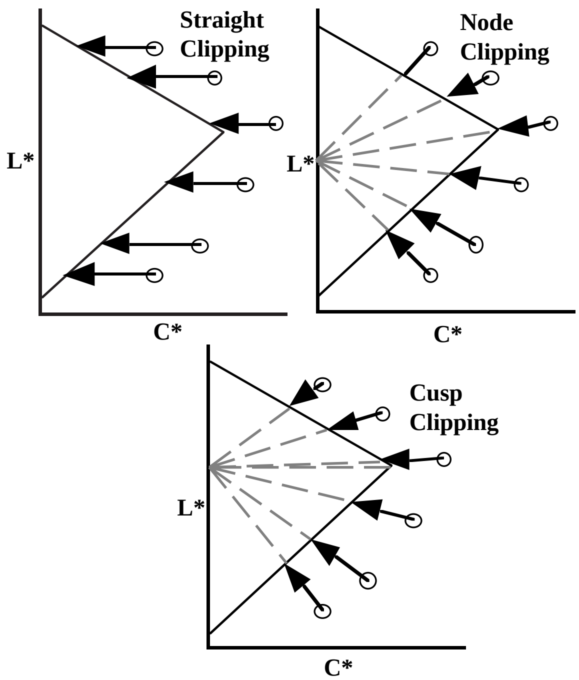

Figure 3. Chroma Clipping Techniques

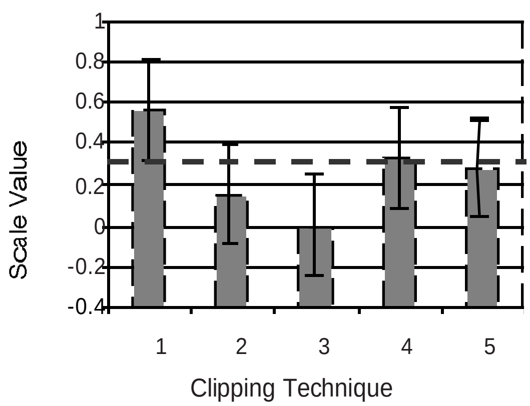

Figure 4. Cyan image results for Printer Gamut.

The monitor was calibrated according to Berns[7] and CIELAB space was used for image processing. For each of the 8 images and gamuts, a paired comparison experiment was run in which 20 subjects judged each possible pair twice (counterbalanced for screen position) against the original image and chose the one that was the more veridical reproduction. Therefore there were 24 paired comparison experiments that were run intermixed. Using Thurstone's Law of Comparative Judgement[8] the results were converted to an interval scale and 95% confidence intervals were calculated for each of the experiments.[9,10] In addition the overall rank orders across images and gamuts were determined.

Results and Discussion

The results of one of the analyses, for the Cyan image using the Printer Gamut, is shown in figure 4.

Table 2: Paired Comparison Results:

Cube	rCRT	Printer	Cube	rCRT	Printer
All7			Blue		
1	4	2	1	1	1
5	5	4	4	4	4
4	1	5	5	2	2
2	2	1	3	5	5
3	3	3	2	3	3
Cyan			Green		
1	4	1	5	1	1
2	5	4	4	2	4
3	2	5	2	3	5
5	1	2	3	4	2
4	3	3	1	5	3
Magenta			Red		
1	1	3	1	1	4
4	4	1	2	4	5
5	5	4	3	5	1
2	3	2	4	2	2
3	2	5	5	3	3
Skin			Yellow		
1	1	1	1	1	2
3	4	4	4	2	1
5	5	5	5	3	3
2	2	3	2	4	4
4	3	2	3	5	5

For the cyan image, Straight Clipping had the best performance although it was not significantly better than Node Clipping. In Table 2, the results from all the experiments are shown. The clipping techniques are listed in order from best to worst and the double line indicates the level at which the best technique is significantly better than the rest.

Based on the rank order of results, collapsed over destination gamut and image, the Straight Clipping technique is overall the technique that shows the best performance. This is also true if rank order is determined across gamut. Technique 3, Closest Lab Clipping with Constant Hue was the worst performer overall. This is summarized in Table 3. In general Node and Cusp Clipping performed better than either Closest Lab technique.

Table 3. Summary of Rank Order

	Clipping Technique Ranking			
	Overall	Cube Gamut	Reduced CRT	Printer
Best	1	1	1	1
↑	4	5	4	4
	5	4	5	2
	2	2	2	5
Worst	3	3	3	3

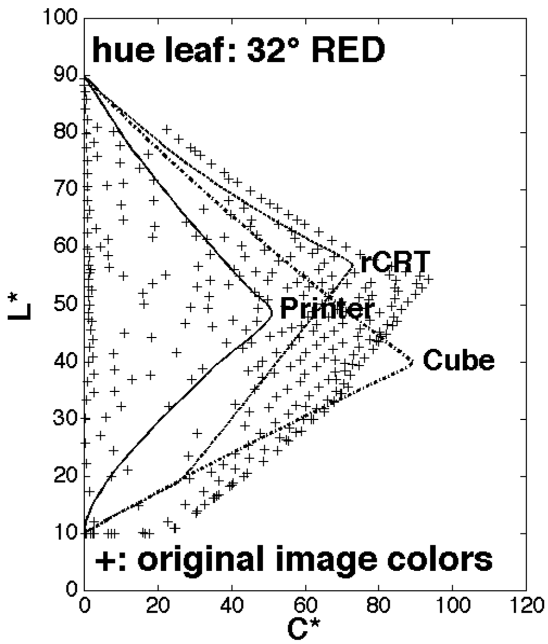

Figure 5. Image colors and gamut boundaries for red image.

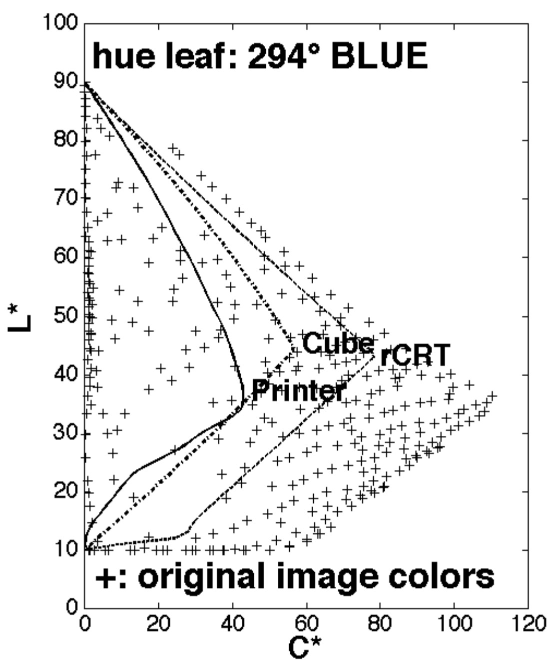

Figure 6. Image colors and gamut boundaries for blue image.

These results would indicate that preserving image lightness is of primary importance in mapping an image into a limited gamut. This is evident *ad extremum*, when rendering a colored image in black and white. Despite these overall trends, there were notable exceptions that indicate that the overall best technique may not be the optimal one. For example, for the Printer Gamut, Closest Lab Clipping worked best for the yellow image. Closest Lab Clipping with Constant Hue was best for the magenta image, and Node Clipping outperformed the others for the red image. In the image containing all seven colored spheres, Closest Lab Clipping was significantly better than Straight Clipping.

One reason why the number of exceptions is greatest for the Printer Gamut is because it has the greatest mismatch between the original and mapped images. An example of this is shown in figure 5. Here we show the location of the image colors and the boundaries of the three destination gamuts for the median hue in the image. The area of the Printer Gamut is only 42% of the area covered by the image colors. In comparison, the mismatch between the Reduced CRT and the image is 72% and between the Cube Gamut and the image is 70%.

However, the mismatch is not the overriding factor behind the difference in results. If we look at the same plot for the blue image (figure 6) we see a large gamut mismatch although Straight Clipping performed the best.

There does not appear to be a simple metric that can explain why one particular technique performs better than another based on gamut mismatch or color differences. What seems to make a difference is how the trade-off between lightness fidelity and loss of chroma affect the image appearance for a particular image.

The results from the image with all 7 colored spheres also does not follow the general rule of preserving lightness for the Reduced CRT Gamut and the Printer Gamut. It appears that those segments of the image that are mapped best by techniques other than straight clipping influence which technique is chosen in a way that forces a compromise.

Conclusion

There are a number of implications for gamut mapping based on the results of these experiments. One implication is that a global chroma clipping mapping strategy that does not take into account the distribution of colors in an image, the particular hue of the segment of the image being mapped, and the shape of the destination gamut, may not be tenable. It may be necessary to segment the image by object or hue and apply different techniques to the various segments.

Another implication is that it may be possible for a pair of gamuts, the original and destination gamut, to use a set of sample images, such as the ones used here, to quickly determine for particular hues, which techniques are best. For example, after connecting a printer, a user may print out a series of images containing simple colored objects. Based on the appearance of these, a gamut mapping profile can be created that is suited for that particular pair of input and output devices.

Only chroma clipping techniques were tested in these experiments. It may be the case that more complicated scaling and soft clipping techniques may produce better results. However, the results found here may have implications on the development and testing of more complicated algorithms. If one clipping technique cannot be used globally, then it is likely the case that a more complicated global chroma mapping technique may not work either.

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