Lightness filtering in color images with respect to the gamut

Judith Dijk[1] ***and Piet W. Verbeek***[2]
[1] ***TNO Defense, Security and Safety, The Hague, the Netherlands***
[2] ***Delft University of Technology, Delft, the Netherlands***
email: `judith.dijk@tno.nl, p.w.verbeek@tnw.tudelft.nl`

Abstract

When image processing operations are performed on color images, it is normal that the production of out-of-gamut pixels is not prevented. The gamut mapping may reduce the effect of the image processing algorithm. In this paper we propose a generic method that allows grey image processing for lightness processing on color images without exceeding the limits of the gamut of the technique or device.

In the proposed method the lightness processing is a function of the color of the pixel in question, the desired lightness change and a maximum and minimum lightness change per pixel. This maximum and minimum depend on the position of the pixel in the gamut of the output device and the relation between the lightness change and the chroma change. The hue of all pixels is kept constant. The monotonic character of the lightness correction guarantees that all points that were different before the lightness correction, remain different.

The results of the proposed method are shown for two grey-value image processing algorithms: 1) sharpening and 2) contrast improvement using gamma manipulation.

For these two applications the gamut-limiting process is only advisable when the limiting is applied to the lightness dimension, rather than the chroma dimension.

Introduction

For a long time, image processing research has concentrated on grey-value images, but with the advance of digital color reproduction, more and more image processing algorithms for color images are being developed [**1**]. A difference with grey value images is that the range of colors, that can be visualized or rendered, is not a simple scale between black and white, but a 3D body in color space, the gamut of the rendering technique or device. When image processing operations are performed on color images, it is normal that the production of out-of-gamut pixels is not prevented. Colors that were inside the gamut of the displaying technique or device before the image processing may unwantedly be converted to colors outside this gamut. So, in order to fully render the image, some *gamut mapping* algorithm has to be used to bring out-of-gamut colors into the gamut. In these algorithms neither the color before processing, nor the kind of processing are taken into account, and thus they may reduce the effect of the image processing operation. In this paper we propose a generic method that applies grey image processing on the luminance of color images without exceeding the limits of the output gamut [**2**].

The generic method

Image processing of color images typically focuses on hue, chroma or saturation, and lightness. Many processing algorithms only deal with the achromatic variables (like in a grey image). We propose a generic method for converting *grey* image processing into lightness or luminance processing for *color* images. This method assumes that the colors of the input image are located within the gamut of the rendering device. If the original image contains out-of-gamut pixels, gamut mapping should be performed *before* the image processing. In this paper we define colors as points in the CIELAB space, but other colorspaces could be used as well.

For a given color point an algorithm for grey-value image processing defines an "ideal" lightness correction. At the same time, however, the gamut defines, for the given hue, a limited "acceptability" area of lightness and chroma. The ideal correction may cause the point to exceed that area.

We propose a method to adjust the "ideal" lightness correction in such a way that the colors stay inside the gamut (or "acceptability area") The monotonic character of the lightness correction guarantees that the color relations within the image remain undisrupted. That is, all points that were different before the lightness correction, remain different. Note that this difference might be smaller than the Just Noticeable Difference, so it is possible that colors that appeared different before the lightness correction can appear the same after the lightness correction.

The desired lightness correction causes the original color point to travel along a fixed path in a constant hue plane. This path is defined by the color of the original point, its position in the gamut and the specified relation between the lightness and chroma change. The relation between lightness and chroma change is referred to as the recipe. The hue of the point is always kept constant, because this is the attribute that we can distinguish with the highest precision (the same reason why hue is kept constant in the gamut mapping).

An obvious choice for the recipe is to keep the same chroma before and after the image processing, so that the colorfulness of the image stays more or less the same. This is illustrated in figure 1, which shows how a point within a given plane of constant hue can be moved within that plane, depending on the path. Another choice can be to change the lightness and chroma over paths to the whitepoint and blackpoint of the gamut, so that the maximum lightness change can be achieved without leaving the gamut.

Some grey value manipulations, such as sharpening, affect the high frequencies of the grey values but leave the low frequency information constant. For such lightness manipulations, we want to keep this feature. When using sharpening, for instance, we may assume that color changes can only be seen in the low frequencies. The goal of the manipulation is to sharpen the image while trying to keep the color information of the low frequencies the same. To achieve this with the proposed method for the lightness, we must add the constraint that not only the shift for a desired lightness correction will stay in the gamut, but also the shift for the same lightness correction in the opposite direction. For the total image this will lead to equal size lightness corrections in the positive and negative direction.

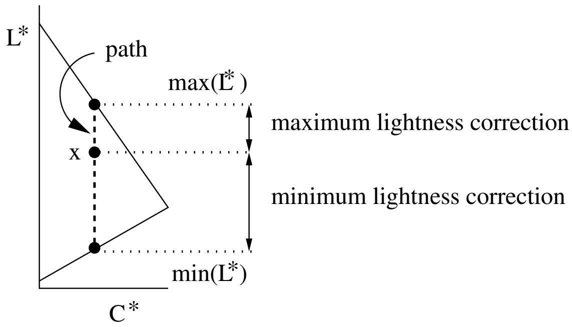


Figure 1. Illustration of a path for a given point x with chroma constant. The intersection of the gamut boundary with a constant hue plane is visualized as a triangle. The maximum and minimum lightness correction are determined by the intersections with the gamut boundary.

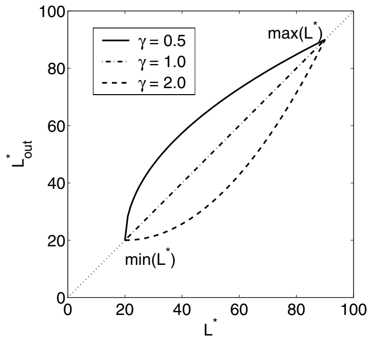


Figure 2. Gamma manipulation. The result of equation 1 is given for three different gamma values. It can be seen that for $\gamma < 1$ the lightness of the image (L^*_{out}) is always higher than for the original image (L^*_{in}), and that darker colors have more contrast. For $\gamma > 1$ the opposite holds true.

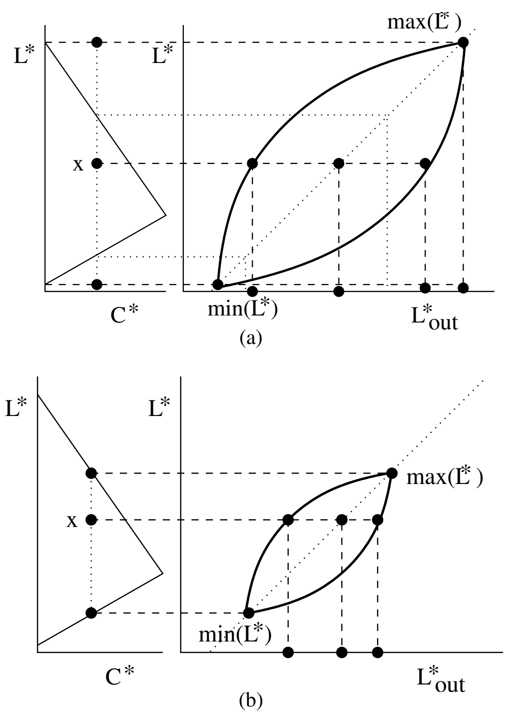


Figure 3. Gamma manipulation, while keeping chroma constant. The original color point is indicated by x. Note that axes in the graphs in the right part of the figure are unusual; the graphs are tilted versions of figure 2. In (a) the normal, not gamut-limited, gamma manipulation is shown. It can be seen that one of the resulting points is indeed out-of-gamut. In (b) the gamma manipulation as defined in equation 1 is shown. The intersections with the gamut for constant chroma are the maximum and minimum used in the gamma manipulation.

Gamma manipulation

The proposed method can be used to apply a variety of grey value algorithms on color images. In this section we show the results for contrast improvement using gamma manipulation.

The effect of a gamma manipulation is that the lightness values are distributed nonlinearly over the range that is used [**3**]. This may increase the contrast in one or more regions of the lightness range, at the cost of decreasing the contrast in other regions. In figure 2 the most common form of gamma manipulation is shown, mathematically described by:

$$L^*_{out} = L^*_{min} + (L^*_{max} - L^*_{min}) * \left(\frac{L^* - L^*_{min}}{L^*_{max} - L^*_{min}} \right)^{\gamma}. \qquad (1)$$

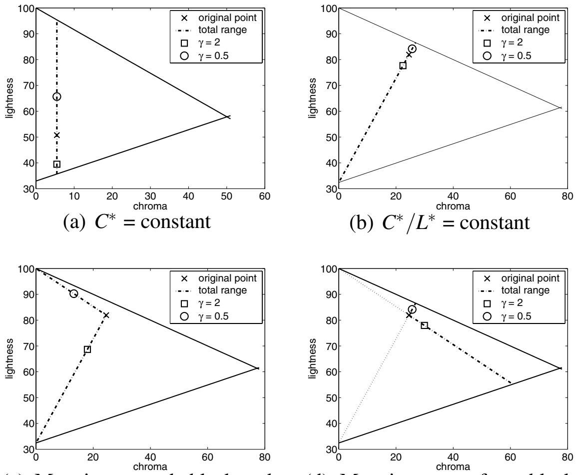
L^* and L^*_{out} are the input and output lightness and L^*_{min} and L^*_{max} are the minimum and maximum of the lightness range. When this manipulation is used with $\gamma > 1$, the higher (lighter) lightness range gains more contrast, at the expense of the contrast of the darker colors. At the same time the mean lightness is decreased, i.e. all new colors are darker than the original colors. When $\gamma < 1$, the opposite occurs (more contrast in the darker colors, less contrast in the lighter colors, and mean lightness increases).

In figure 3 is shown how the original color point, x, can travel over the path indicated by the dotted line in the constant hue plane. This path has the property that chroma (C^*) is constant. In figure 3 (a) the normal, not gamut-limited, gamma manipulation is shown. It can be seen that points can indeed be out-of-gamut. In figure 3 (b) the gamma manipulation defined by equation 1 is used. In the right hand part of this figure the limits, $\max(L^*)$ and $\min(L^*)$ of the lightness range are shown. These are dictated by the available gamut, so whatever the value of L^*_{in}, it will always be such that the lightness of point x will stay within the available gamut.

Recipes for gamut-limited gamma manipulation

In this section we discuss possible recipes for gamut-limited manipulations. The results are shown in the next section.

- **(a) C^* = constant** The lightness is manipulated while keeping the chroma C^* constant. The maximum and minimum value are the maximum and minimum lightness L^* for this particular C^* value. The effect of this recipe has already been shown in figure 3.
- **(b) C^*/L^* = constant** The lightness is manipulated while keeping the ratio C^*/L^* constant. The minimum value is per definition 0, the maximum value is the lightness value for which the line C^*/L^* intersects the gamut boundary.
- **(c) Mapping towards black and white** The lightness is manipulated in such a way that the point in the chroma/lightness space moves towards black for a lightness decrease and towards white for a lightness increase.
- **(d) Mapping away from black and white** The lightness is manipulated in such a way that the point in the chroma/lightness space moves away from black for a lightness increase and away from white for a lightness decrease. The maximum and minimum lightness are given by the intersections of both lines with the gamut boundary. This recipe is the opposite of the previous recipe.



(a) C^* = constant
(b) C^*/L^* = constant
(c) Mapping towards black and white
(d) Mapping away from black and white

Figure 4. Paths along which a color point may move within the constant hue plane, when applying different recipes for gamma manipulations. For each recipe for an original point, x, the range for lightness changes is given, along with the result for $\gamma = 2$ and $\gamma = 0.5$. More details about the paths are given in the text.

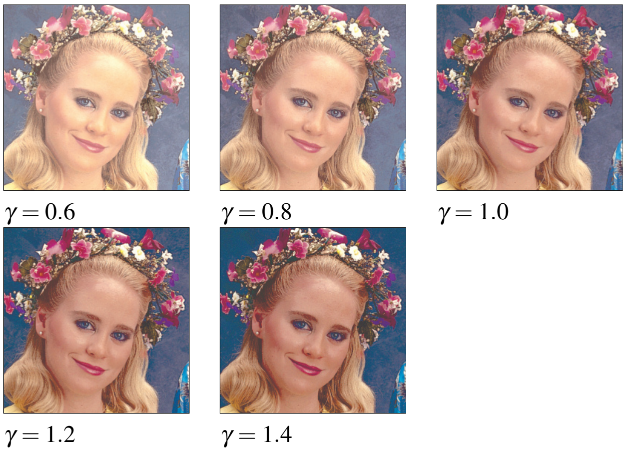


Figure 5. The result for normal gamma manipulation, without taking the gamut into account.

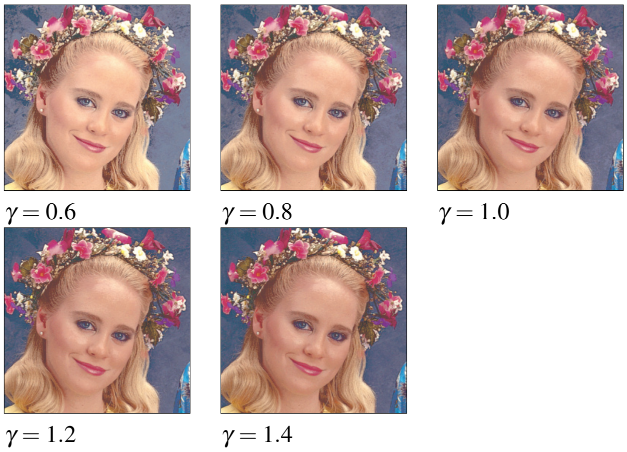


Figure 6. *The results for the* C^* = constant *recipe.*

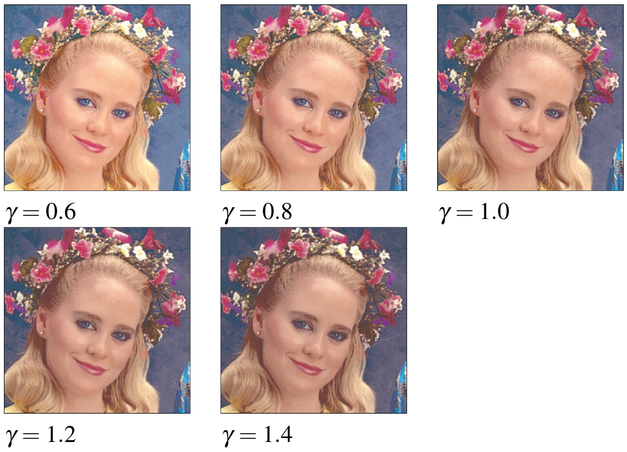


Figure 7. *The results for the* C^*/L^* = constant *recipe.*

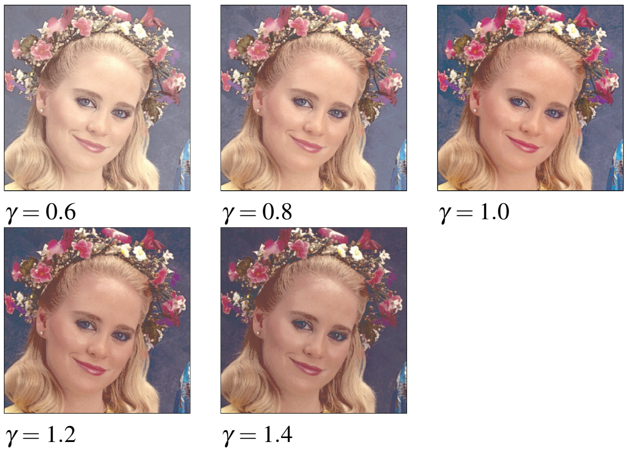


Figure 8. *The results for the* mapping towards black *recipe.*

Figure 9. *The results for the* away from black *recipe.*

The different paths in the constant hue plane that result when applying the above recipes are illustrated in figure **4**.

On these paths the two positions of the color point are indicated that result for $\gamma = 2$ and $\gamma = 0.5$. We would not expect the recipe *Mapping away from black and white* (d) to give nice results, because it adds chroma to almost all points. This will introduce colors that are too colorful for the luminance, as if they are self luminant. However, it can be instructive to see the results of this manipulation.

Results for gamut-limited gamma manipulation

The visual results for the different recipes are given in figure **5** - **9**. In each image five different gamma settings are given. The image for which $\gamma = 1$ is for all recipes the same as the original image. The results are shown for an image of a blond girl, which is part of an ISO standard image (n7a from the cdrom 12640:1997).

In figure **5** the results for the normal gamma manipulation are shown, where out-of-gamut pixels are not prevented. Out-of-gamut pixels are mapped onto the gamut with orthogonal clipping. This results, for low gamma values, in a skin color that is too yellow.

In figure **6** the results for the $C^* = constant$ recipe are shown. It can be seen that the effect of the gamma manipulation is smaller, because the mean lightness change is smaller. The results are better in that here the skin tones are more natural than the results with the normal, not gamut-limited, gamma manipulation (shown in figure **5**).

In figure **7** C^*/L^* is kept constant, instead of C^*. The effect is that images with $\gamma < 1$ gain chroma, whereas images with $\gamma > 1$ loose chroma. Therefore, the quality of these images is somewhat less than the images in figure **6**.

As could be expected, the results with the *mapping towards black and white* recipe, shown in figure **8**, cause a loss of chroma. All colors are mixed with either black (for $\gamma > 1$) or white (for $\gamma < 1$). The resulting images are less vivid, and therefore the quality is less than that of other recipes. The results for the *mapping away from black and white* recipe (shown in figure **9**), do not differ very much from each other. This is due to the fact that the size of the path in this recipe is much smaller than the paths in other recipes.

Gamut limited sharpening

In image processing the use of sharpening can change the lightness of a point rather drastically. If sharpening is applied to the lightness of color images, some of the resulting colors may be out-of-gamut, because the lightness exceeds the (vertical) limits set by the lightness (and chroma) of the constant hue plane. To avoid this, the lightness correction should depend on the available "gamut space", just as in the case of gamma manipulation. Sharpening is usually achieved by adding a high frequency filtered version of the image to the original image [**4**, **5**]. In these experiments we use unsharp masking, where the high frequency filtered version is found by subtracting a Gaussian-smoothed image:

$$\tilde{I}_{high} = (1 - \tilde{G}(I, \sigma))\tilde{I} = \tilde{F}_{high}\tilde{I} \quad (2)$$

where ˜ denotes the Fourier transform. The unsharp masking sharpening filter is defined as

$$\tilde{F}_R(\alpha)\tilde{I} = \tilde{I} + \alpha \cdot \tilde{I}_{high} \quad (3)$$

We also used inverse unsharp masking to blur the input image. This filter is defined as

$$\tilde{F}_b(\alpha_{inverse})\tilde{I} = \frac{\tilde{I}}{\tilde{I} + \alpha_{inverse} \cdot \tilde{I}_{high}} = \frac{1}{\tilde{F}_R(\alpha_{inverse})}\tilde{I} \quad (4)$$

The width of the edges that are amplified by the unsharp masking is determined by σ, and the amount of sharpening, that is, the size of the lightness change, is controlled by the parameter α. In some recipes α can be changed by the user, but in other recipes the amount of sharpening is determined by the maximum and minimum lightness difference and the distance of the point to the gamut. To avoid that the results are largely influenced by outliers, I_{high} is clipped between the 5^{th} and 95^{th} percentile. An undesired effect of unsharp masking is that not only the edges are enhanced, but that also the (high frequency) noise is amplified.

Since the sharpening should only work on high frequency parts of the image, we use the property of images [**6**] that the pixels that make up lines and edges are outnumbered by the pixels in homogeneous areas. Further, we assume that the chroma changes are only seen in the low frequencies, so that we can change the chroma of the line and edge pixels without changing much of the color impression.

Recipes for gamut-limited sharpening

When using gamut-limited sharpening, there are a number of approaches to be considered. We tested the following recipes:

(a) Sharpening within the gamut For each point the maximum and minimum sharpening should be within the gamut. If this is not the case, the chroma C^* is reduced to obtain a larger lightness range[1].

(b) Gamut limited sharpening For each point the desired lightness difference is adjusted so that the maximum lightness difference (either up or down) just fits within the gamut, without changing the chroma. This is achieved by adjusting the value of α so that the maximum lightness change fits exactly in the gamut.

(c) Mapping towards black and white The lightness is manipulated in such a way that the point in the chroma/lightness space moves towards black for a lightness decrease and towards white for a lightness increase. In other words, the new point lies on the line through the original point and white ($\Delta L^* > 0$) or black ($\Delta L^* < 0$). Note that this has the effect that the chroma of all points is reduced.

(d) Mapping halfway towards black and white The points are again mapped over lines toward black and white. For each point the lightness difference is scaled in such a way that the maximum lightness difference is halfway to the minimum distance to black or white. If, for instance, the original lightness difference is 10, the distance from the original point to black and white is 40 and 60, respectively, and the maximum lightness difference is 30, then the effective lightness difference is (0.5 * 40/30) * 10. The chroma is adjusted so that the new point lies on the line through the original point and black or white. The size of α is optimized by the recipe.

(e) Mapping away from black and white The new point is located on the line through the original point and black (for $\Delta L^* > 0$) or white ($\Delta L^* < 0$). The maximum lightness difference is the distance to the upper and lower boundary, respectively. All points gain chroma. This is the opposite from the *mapping towards black and white* recipe.

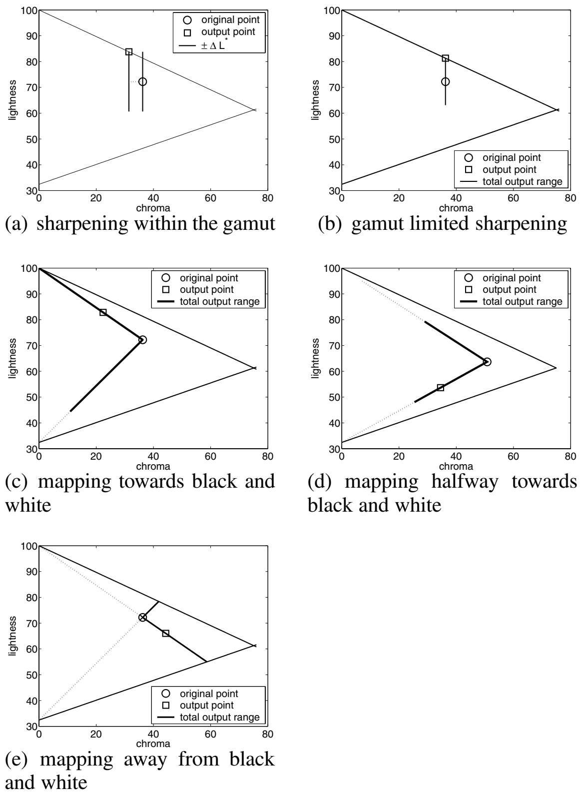
The different paths in the constant hue plane that result when applying the above recipes are illustrated in figure **10**. On these paths, the original point and the output point for a given lightness correction are indicated. For some recipes the total output range can be defined, for some recipes only the (positive and negative) lightness change for the given point is shown.

Results for gamut-limited sharpening

The results for the different recipes are shown in figure **11** for the `blond` image. The original image is blurred with inverse unsharp masking to obtain a test image that can be improved. The two images on the top row are given for comparison. These are the test image, and the image which is filtered using "normal" sharpening, where the gamut is not taken into account. If the original image is located in the gamut and if α is equal to $\alpha_{inverse}$, the latter equals the original. Pixels that are out-of-gamut are clipped onto the gamut using orthogonal clipping.

The rest of figure **11** shows the images, that are changed using the new method for several recipes. For all recipes the values of σ and α are chosen 1.0 and 0.6, respectively. It can be

[1] Note that this does not entirely comply to the described method. There is no fixed path for each point, but the path is moved along the x-axis until the lightness range between the maximum and minimum sharpening fits into the gamut.



(a) sharpening within the gamut
(b) gamut limited sharpening
(c) mapping towards black and white
(d) mapping halfway towards black and white
(e) mapping away from black and white

Figure 10. Different paths for sharpening manipulations. The triangles are the intersection of the gamut with a constant hue plane. More details about the paths are given in the text.

Test image
Normal sharpening
(a) sharpening within the gamut
(b) gamut limited sharpening
(c) mapping towards black and white
(d) mapping halfway towards black and white
(e) mapping away from black and white

Figure 11. The result for the different recipes (a-e). The original image is smoothed with inverse unsharp masking with $\alpha_{inverse}$ = 0.6. The sharpening algorithm is unsharp masking with σ = 1 and α = 0.6.

seen that the result for *gamut limited sharpness* (b) and *mapping halfway towards black and white* (d) are the sharpest. This can for instance be seen on the location of the eyes and the mouth. This effect is probably due to the fact that for these two recipes α is optimized with respect to the gamut instead of set by the user. The difference between the two results is that the image produced by *gamut limited sharpening* (b) is more colorful than the image produced by *mapping halfway towards black and white* (d). This suggests that the chroma change in the low frequency for the *mapping halfway towards black and white* (d) recipe are quite visible, despite the fact that the chroma change is not large for most points.

The *mapping away from black and white* (e) recipe adds chroma on places where the lightness is changed. The colors in the resulting image will therefore be more colorful than the colors in the original image. This can be best seen in figure **11** in the colors of the mouth of the woman.

The *sharpening within the gamut* (a) and *mapping towards black and white* (c) recipe are comparable to the normal sharpening procedure. Because for these recipes the size of α is adjusted by the user, we need to compare the results for different α's. This is done in figure **12** for *sharpening within the gamut* (a) and in figure **13** for *mapping towards black and white* (c). For both recipes the results tend to become somewhat "greyish" for $\alpha > 0.6$. For *sharpening within the gamut* (a) the chroma reduction is due to the fact that the points are shifted towards the achromatic axis until the sharpening fits within the gamut, and for larger α these shifts will be larger. In the *mapping towards black and white* (c) recipe all points are shifted towards black and white, also causing a chroma reduction.

We conclude that the results of the original ("normal") sharpening method can be improved upon by taking the gamut into account. *Gamut limited sharpening* (b) is the best recipe for the `blond` image, because the chroma is not reduced and because the value of α is optimized by the recipe. Other recipes may also give somewhat better results than normal sharpening.

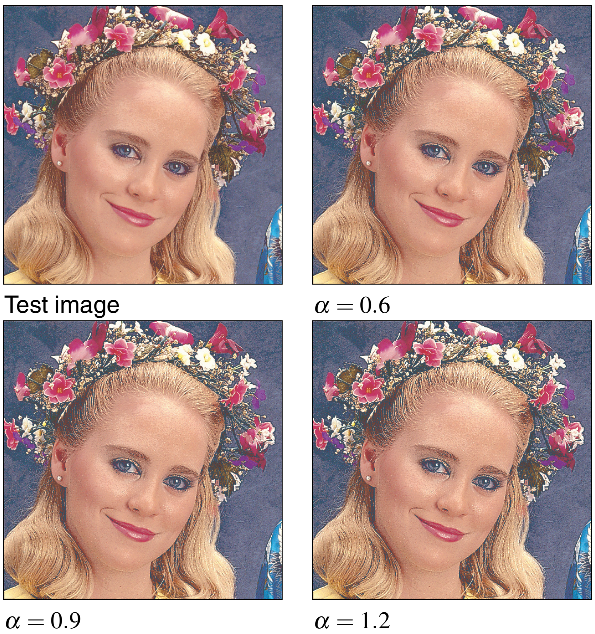


Figure 12. The result for sharpening within the gamut *(a) for different values of α, with σ = 1. The original image is smoothed with inverse unsharp masking with $\alpha_{inverse}$ = 0.6. masking.*

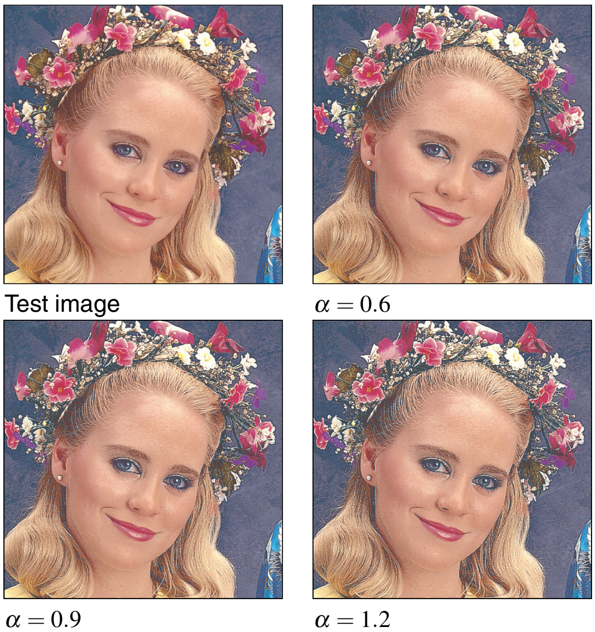


Figure 13. The result for mapping towards black and white *(c) for different values of α, with σ = 1. The original image is smoothed with inverse unsharp masking with $\alpha_{inverse}$ = 0.6.*

Conclusions

In this paper we have proposed a generic method that allows grey image processing for lightness processing on color images without affecting color rendering, that is, staying within the gamut of the apparatus in question.

In the proposed method the lightness correction is a function of

- the particular lightness and chroma of the original point in question.
- the desired lightness change, as implemented by the grey value image processing algorithm (like gamma manipulation or sharpening)
- the choice of recipe to perform the lightness change. For each point, a path is determined, which is specified by the recipe. The lightness and chroma changes depend on the maximum and minimum of this path.

The monotonic character of the lightness correction guarantees that the color relations within the image remain undisrupted. That is, all points that were different before the lightness correction, remain different.

The results of the proposed method are shown for two grey-value image processing algorithms: 1) sharpening and 2) contrast improvement using gamma manipulation.

The processed images for which the gamut is taken into account result in more natural images. For gamma manipulation, the lightness of all pixels changes. Therefore, *mapping towards black and white*, where the chroma reduction is proportional to the lightness difference, results in greyish images, whereas *mapping away from black and white*, where the chroma increase is proportional to the lightness difference, results in images that are too colorful.

For sharpening method, the lightness correction is small for most points, since most pixels do not belong to lines or edges. Therefore, it is to be expected that the chroma can be changed proportionally to the lightness. However, when the chroma is changed, this small correction is perceptually quite visible. For sharpening also paths with constant chroma give the best results.

A sharpening procedure that improves most images can be implemented easily. It might be hard, however, to automatically find the optimal settings for each image.

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Author Biography

Judith Dijk has received her Masters Degree (1998) and her PhD (2004) in Applied Physics at Delft University of Technology. Since 2003 Judith has worked at the TNO Institute for Defense, Safety and Security as a research scientist. Her work has focused on color image processing.