Wide Gamut Color Mapping and Image Enhancement using Image Segmentation

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Abstract
Most of today's image enhancement and gamut mapping algorithms are pixel based and can therefore suffer from severe clipping artifacts. We propose an algorithm that is based on super pixels, which is an (over-) segmentation of the input image. We tested various segmentation algorithms in combination with a number of gamut mapping algorithms and compared a selection of those in a perception experiment. The results show that for large enhancement the segmented approach is preferred, but for moderate enhancements this was not statistically significant. We also found that correcting for the Helmholtz-Kohlrausch effect did not improve the performance of the algorithm.

Introduction
New developments in color filters and backlight spectra for Liquid Cristal Displays (LCDs) have resulted in so called wide gamut displays. These displays have primaries that span a wider color gamut than the Rec. 709 standard primaries on which the input colors are coded. In order to make use of this wider gamut the input colors need to be increased in saturation.

There are various methods described in the literature to enhance an input image to a wider gamut [1,9]. Typically these algorithms increase chroma, while keeping lightness and hue angle constant. In some of these algorithms a two-step approach is taken. First the chroma is increased independent of the actual display gamut. Typically, the preferred amount of chroma increase is very viewer dependent. In the second step these enhanced colors are mapped to the display gamut.

In order to do a clean chroma increase, without affecting lightness and hue angle, it is important to work in a perceptually-uniform hue-constant color space for the color processing. IPT [5] is such a color space, which is similar to CIELAB, but without it's known hue problems. Also more advanced color spaces, such as CIECAM02 [7] have these properties. For very saturated colors near the boundary of the visual gamut it can also be important to correct for the Helmholtz-Kohlrausch effect [8]. This effect indicates that in the photopic range of vision the brightness of a perceived color increases with the purity of a color stimulus.

In order to map the enhanced colors to the display gamut, several gamut mapping techniques were proposed [1]. One technique, constant lightness clipping, preserves lightness and hue angle. Another technique, CUSP clipping, preserves only hue angle and is mapping towards the CUSP (the hue angle dependent lightness of maximum chroma of the output gamut) [10]. Note that in the case of relatively small differences between input and output gamut, clipping is known to give better results than compression [9]. For aggressive enhancements, however, the differences can become quite substantial and clipping can give annoying artifacts whereas compression counteracts with the strong enhancement.

In order to prevent clipping artifacts several so called spatial gamut mapping algorithms were proposed [12,13,14]. In [13] first a pixel based gamut mapping was performed and a luminance difference with the original was calculated. This difference image was then high-pass filtered and added back to the mapping image. In [14] a spatial frequency-based decomposition of the image was performed and gamut mapping was carried out differently per frequency band preserving the high frequency detail.

In this paper, we describe a different kind of spatial gamut mapping algorithm using image segmentation [2,3]. The image segments, also called superpixels, are enhanced as a group, such that the color differences between the pixels in a segment are preserved. For example, if the pixels in a segment have different saturations and are mapped to a single saturation after the image enhancement, the algorithm will limit the saturation increase to preserve saturation differences within the segment.

We describe how we segmented the images and applied the color gamut mapping and image enhancement. We also present the results of a perception study in which we compared our results with pixel based enhancement and we tested the effect of taking the Helmholtz-Kohlrausch effect into account.

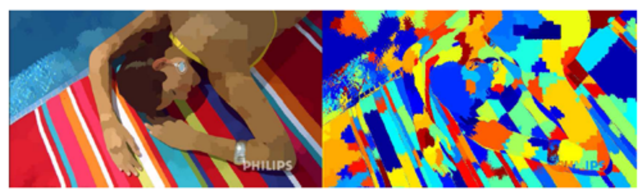

Figure 1: Illustration of automatic image segmentation. The left image shows the segments using the average color of pixels in a segment, the right image has a random color per segment.

Methods
Image segmentation
There exist many algorithms in the literature to segment an image [1,2]. For our purpose we tested several algorithms such as histogram-based segmentation [11], k-means [3], and mean shift [4]. The histogram-based segmentation did not give very good results. The k-means approach did give good segmentation results, but it requires a priori knowledge of the number of segments per image which made it unsuitable for automatic image enhancement. The mean shift approach gives good segmentation results within reasonable computation time and does not require a priori knowledge of the number of segments. For further details on the mean shift algorithm we refer to the literature [2,3,4].

Figure 1 shows the result of image segmentation using the mean shift approach. The left image shows the segments using the average color of pixels in a segment. It illustrates that the segments follow object boundaries in the image and that even small details, such as those in the earring, are preserved. The right image illustrates that the objects in the image are over-segmented;

there are more segments than objects. For example the right arm is segmented with more than 10 segments. The amount of segments is not predefined, but results from the algorithm. Typical images tested were segmented with around 500-1000 segments, but of course the number of segments highly depends on the amount of detail in the image.

Color enhancement

For the color enhancement we varied the chroma while keeping lightness and hue angle constant. We choose the IPT color space with and without Helmholtz-Kohlrausch correction. The IPT colors can be calculated from XYZ and vice versa using the following formula's assuming a D65 white point:

$$IPT = M_{IPT} f\left(M_{LMS} XYZ\right)$$

$$XYZ = M_{LMS}^{-1} f^{-1}\left(M_{IPT}^{-1} IPT\right)$$

where

$$f(t) = \begin{cases} t^{0.43} & t \geq 0 \\ -(-t)^{0.43} & t < 0 \end{cases}$$

and M_{LMS} is the XYZ to LMS conversion matrix and M_{IPT} the LMS to IPT conversion matrix (see [18] for details).

From the IPT coordinates we can calculate perceived lightness (J), perceived chroma (C), and hue angle (h) using:

$$J \approx I \quad C \approx \sqrt{P^2 + T^2} \quad h \approx \tan^{-1}\left(\frac{P}{T}\right)$$

The Helmholtz-Kohlrausch effect can be corrected for with a simple hue independent formula in IPT color space [5]:

$$J = I + 0.202C$$

For a natural color enhancement, it is required to apply only limited enhancement to skin tones, whereas non-skin tones can be enhanced much more. Therefore we applied two types of chroma enhancements, each with its own enhancement factor; one for skin tones and one for non-skin tones. Pixels were identified as skin when their chromaticity fell within a predefined skin region in the IPT color space.

Gamut mapping

Because the color enhancement algorithm is device independent it can result in out-of-gamut pixels when rendered on an actual display. In order to map these pixels inside the gamut we used an algorithm that combines pure chroma clipping with CUSP clipping. In case of pure chroma clipping (LC clipping) lightness and hue angle are kept constant, and the out-of-gamut pixel is clipped to the nearest chroma value (C_{LC}) within the gamut. In case of CUSP clipping the out-of-gamut pixel is clipped towards the CUSP, which is a hue angle dependent point on the gray axis (C=0) for which the output gamut has its maximum chroma. The result after clipping can differ both in chroma (C_{CUSP}) and in lightness (J_{CUSP}). In the combined algorithm CUSP clipping is used for pixels above the CUSP and LC clipping is used for pixels below the CUSP. Note that the hue angle is always preserved in the clipping.

$$J_{LC} = J$$

$$C_{LC} = \min(C, G_{LC}(J,h))$$

$$a = \tan^{-1}\left(\frac{J - CUSP(h)}{C}\right)$$

$$r = \sqrt{(J - CUSP(h))^2 + C^2}$$

$$J_{CUSP} = \sin(a)\min\left(r, G_{CUSP}(a,h)\right) + CUSP(h)$$

$$C_{CUSP} = \cos(a)\min\left(r, G_{CUSP}(a,h)\right)$$

where $G_{LC}(J,h)$ is the GBD for the LC mapping, $CUSP(h)$ is the hue-dependent CUSP lightness and $G_{CUSP}(a,h)$ is the GBD for the CUSP mapping.

Segmentation based enhancement and gamut mapping

In case of pixel based enhancement, the color of each pixel is enhanced and mapped to the display gamut independently. In case of segment based enhancement, the image is first segmented and then for each segment the following procedure is applied:

1. The average color of a segment is calculated.
2. The average segment color is identified as skin or non-skin
   a. In the case it is identified as skin, a moderate enhancement is applied that is equal for all colors in the segment.
   b. In case of non-skin, a stronger enhancement is applied to all segment pixels.
3. For the gamut mapping, it is first identified if any of the pixels in a segment are out-of-gamut.
   a. If all pixels are in-gamut, no gamut mapping is applied.
   b. If one or more pixels are out-of-gamut, we determine which pixel in the segment is the farthest away from the display gamut boundary. For that pixel we determine the decrease in chroma and lightness when it is clipped to the gamut boundary using the combined CUSP-LC clipping algorithm as described in the previous section. Finally, we apply this chroma and lightness decrease to all pixels in the segment.

Display calibration

In order to test our color enhancement and gamut mapping algorithms we used a calibrated wide gamut display. The wide gamut display consisted of a standard LC panel and a custom build RGB LED backlight. The gamut of the display (thick blue triangle) is shown in Figure 2 together with the EBU gamut (thin black triangle). Note that only the red and green primary are more saturated than EBU in wide gamut display. The wide gamut display was calibrated such that it reproduced colors well within one ΔE_{94} as was tested with the EBU standard set of test colors [6].

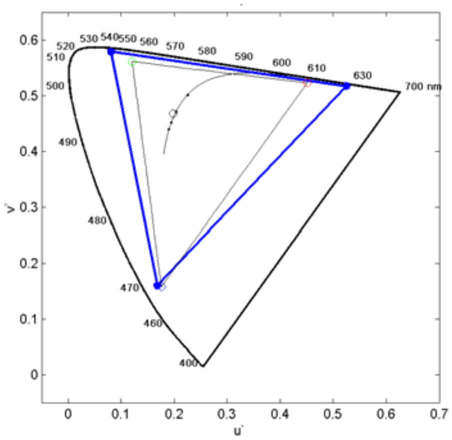

Figure 2: Plot of the wide gamut display gamut (blue thick triangle) and the EBU gamut (thin black triangle) in the 1976 u'v' chromaticity space.

Results

Segmentation based enhancement and gamut mapping

The results of our color rendering are difficult to visualize in this paper, because it should be rendered on a calibrated wide gamut display. What can be illustrated are color enhancement artifacts in the skin areas. In Figure 3 we show an image with pixel-based enhancement (left) and one with segmentation-based enhancement (right). Note the enhancement artifacts in the skin regions for the pixel-based enhancement, due to some pixels in the skin that are just outside the skin tone area.

Figure 3: Illustration of pixel-based (left) and segmentation-based (right) enhancement and gamut mapping. Note the enhancement artifacts in the skin regions (boy's arm) for the pixel-based mapping.

The results of the segmentation based enhancement clearly showed the added value of segmentation in case of large chroma enhancements. Typically pixel based enhancements showed clipping, whereas the segmentation based enhancement could fully prevent visible clipping artifacts.

Without specific measures the segmentation based enhancement would introduce visible boundaries between some segments. We applied a spatial smoothing procedure of the enhancement factor between neighboring segments. This could prevent visible boundary artifacts between segments in a large set of test images (n>25).

Altogether the results showed that segmentation based enhancement can be a very robust method for image enhancement.

Perceptual Validation

In order to test the performance of the segmentation based color enhancement, we performed a perception test using the calibrated wide gamut display in a room with 40 lx lighting. More details of the viewings conditions and display properties are shown in Table 1.

Table 1: Perception test viewing conditions

Measurement	Luminance [cd/m2]	Illuminance [lx]	x	y	CCT (K)
Wall behind display	9.4	32.7	0.44	0.40	2900
Table in front of display	7.7	41.4	0.48	0.41	2450
Display (off)	0.1	27.2	-	-	-
Display (off, white paper)	7.2	-	0.44	0.38	2750
Display (on, D75 white)	503.5	-	0.30	0.31	7550

In this test, 20 viewers compared 3 algorithms for 18 different images. These are the aloriithms:

1. Pixel based enhancement (PNLN)
2. Segmentation based enhancement (SNLN)
3. Segmentation based enhancement + Helmholtz-Kohlrausch compensation (HNLN)

And the images are shown in Figure 7.

For each algorithm and each image the viewers first tuned the enhancement to an optimal level (*the tuning task*). Then for each optimal setting, they compared the three different algorithms in a paired comparison test (*the paired comparison task*).

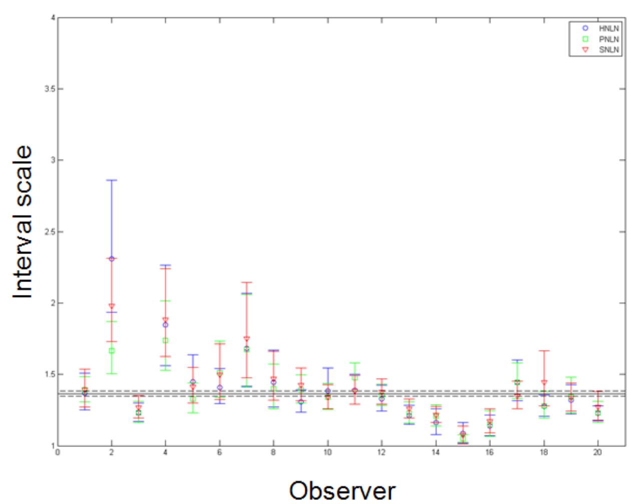

Figure 4: Results of the tuning task per observer (1…20) per color enhancement algorithm (o HNLN, □ PNLN, ▼ SNLN) and averaged across images.

The results of the tuning task indicate that typical images coded on sRGB primaries can be enhanced by a factor 1.4 in chroma when displayed on a wide gamut display. For some viewers enhancement above 1.5 is preferred, whereas a few others prefer very limited enhancement (just above 1) as is illustrated in Figure 4.

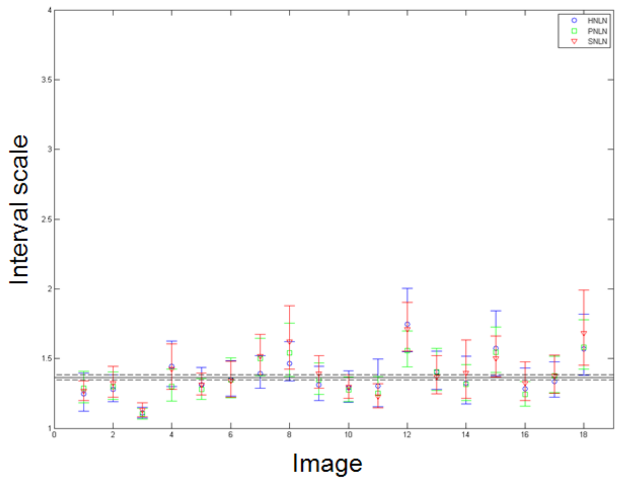

Figure 5: Results of the tuning task per image (1…18) per color enhancement algorithm (o HNLN, □ PNLN, ▼ SNLN) and averaged across viewers.

As is shown in Figure 5, preferred enhancements for most images were not significantly different from the average, with a few exceptions. For image 3, which showed two faces and very little saturated colors, the preferred enhancement is somewhat lower than the average. For images 12 and 18, both showing flowers, the preferred enhancement was somewhat higher than the average.

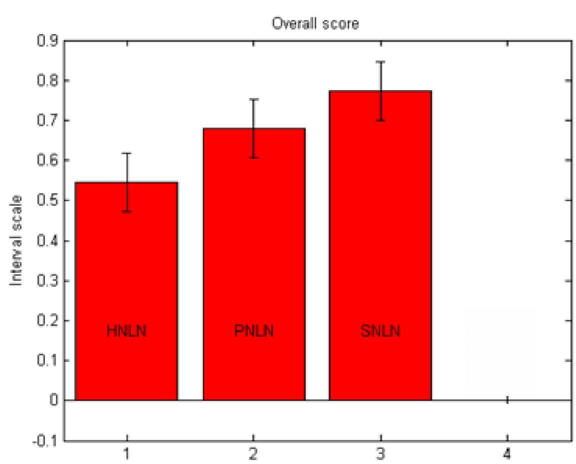

Figure 6: Result of the paired comparison task. Preference and 95% confidence interval of the mean for each color enhancement algorithm (see text for details) averaged across images and observers.

In the paired comparison task the segmentation based enhancement was most preferred, but it was not statistically significantly better than the pixel based enhancement (confidence intervals overlap). Close investigation of the tuned parameter setting per viewer per algorithm indicated that most viewers preferred moderate chroma enhancements for all three algorithms which resulted in very little clipping artifacts for the pixel based enhancement and as a result very little difference between pixel based and segmentation based enhancement.

One viewer preferred a much higher enhancement factor for the various algorithms, and for that viewer the segmentation based algorithms were much more preferred than the pixel based algorithm. It would be interesting to test if more viewers would prefer the segmentation based algorithms above the pixel based one if a fixed and high enhancement factor (i.e. >2) was used. In such an experiment it would also be interesting to test the difference with other spatial gamut mapping algorithms described in the literature [12,13,14] and the reference gamut mapping algorithms described by the CIE TC8-03 in the "Guidelines for the evaluation of Gamut Mapping Algorithms" as well as using the test images recommended by this committee [15].

In contrast to what we expected the Helmholtz-Kohlrausch compensation did not improve the enhancement. Interviews with the observers after the test taught us that most observers did not like the darker impression of the compensated images. They did also not observe that colors became "fluorescent" after enhancement. This indicates that the Helmholtz-Kohlrausch compensation as suggested in [5] needs further investigation before it can be applied in image enhancement.

Conclusions

We tested various segmentation algorithms in combination with a number of gamut mapping algorithms and compared a selection of those in a perception experiment. The results show that for large enhancement the segmented approach has clearly less clipping artifacts, but viewers in general prefer moderate enhancements for which the difference in preference was not statistically significant between both algorithms. We also found that correcting for the Helmholtz-Kohlrausch effect did not improve the performance of the enhancement algorithm in case of moderate enhancement settings.

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Figure 7: Images used in the perception test.