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gamutHeatMap: Visualizing the Colour Shift of Rendering Intent Transformations

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Abstract

When a photograph is printed, its original colours are converted to those of the output medium using a rendering intent transformation. This process takes into consideration the colour properties of the paper and the printer used. gamutHeatMaps *are a visualization that highlights the perceptual difference between a soft-proof of a photograph in the intended output medium, and its original. They can be used to compare different output media to determine the one that most accurately renders the colours of a given photograph.*

Original *Soft-proof* gamutHeatMap

1. Introduction

Choosing the right paper to print a photograph is an aesthetic decision that depends upon several factors such as the physical characteristics of the paper (its thickness, its surface finish, the material it is made, etc.) and its colour rendition capabilities (which are dependent on its reflectance, ink absorption, DMax–the measure of the maximum black it can render–, the inks and printer used, etc). Knowing how a photograph will print in a given combination of paper and printer is not trivial.

One of the most frustrating aspects of digital photography is to discover that usually the image printed on paper does not look like the same image in the screen. Even more frustrating for the digital photographer is that, even when proper colour-management workflow is used, the same photo might look different when printed into two different papers (e.g. the colours of a print in matte paper will look different than those in a glossy paper). This is not surprising. The colours that any medium can render are restricted by its physical properties (the gamut of the output medium). A glossy paper will, in general, have a larger gamut than matte paper.

Printing software will take into consideration the colour gamut of the output paper (this information is encoded in what is known as the colour profile of the paper). A transformation is performed such as, for every pixel in the image, its colours printed are as close as possible to those in the original image (this process is described by Stone et al. [SCB88]). Some colours will be accurately rendered, but others will be shifted. These shifted colours are what determine if a printed photo looks *similar* to those of the displayed photo (the photographic software will do a similar transformation to convert the colours in the image file to those presented by the display, and some colours might be shifted by the screen too). Photographers rely on a combination of test-printing, experience, and soft-proofing (described below) to visually spot the differences between the image printed on paper, and the one on screen. This is time and cost consuming.

In this paper we propose *gamutHeatMap*, a visualization that represents the magnitude of perceptual colour change that occurs when a destination colour profile and rendering intent are applied to an image. It provides an overview of the regions of the image that have their colour shifted, and by how much.

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2. Background and Related Work

The gamut characteristics of an output device (including paper) is encoded in a colour profile and they are standardized by the International Color Consortium (ICC) [Int04]. The colour profile of a paper is typically dependent on the paper itself, and the combination of printer and ink used. When an image is printed or displayed, each of its pixels are converted from its original colour space (such as sRGB or AdobeRGB) into the output device colour space as defined by its colour profile. Papers cannot render every possible colour stored in a photograph (their gamuts are smaller than the colours that can be stored in an image) hence it is necessary to remap some of the colours of the source image to different colours to be printed in the paper (this problem is known as gamut mapping–see the survey by Morovic and Luo [J. 01] for a comprehensive discussion of the topic). ICC defines four methods to do gamut mapping (known as rendering intent transformations): perceptual, saturation, relative colorimetric, and absolute colorimetric [Int04]. Each differs in the way it chooses to remap a colour. For example, in colorimetric, if a colour is outside the gamut of the destination medium the colour is “clipped” to the closest (this might result in posterization). In contrast, perceptual remaps the source colours to destination ones in such a way that it preserves their relationship to each other; in some cases, large sections of an image might show a subtle, but discernible colour shift between the original image and the printed one. (For more information see [FMB03]).


(a) (b) (c)

Figure 1: *Photograph (a), its soft-proof (b) and out-of-gamut view (c) if this photo was printed in non-photographic plain paper, which has a small gamut. The gray areas in the out-of-gamut view show regions of the original photograph with colours that cannot be rendered in the destination medium, hence are shifted.*

Soft proofing gives the photographer the ability to simulate the output medium colour rendering features (this includes paper tone and achievable black) based on a specified rendering intent. A soft proof is an image that has been rendered in the output device (such as if was printed on a given paper and then rescanned). Substantial research has been conducted regarding gamut rendering algorithms. For example, Nakauchi et al. [NHU99] describe a model of the perceptual image difference for a given pair of images, which takes the human’s contrast sensitivity into account and applies the model to a gamut mapping for generating a reproduction with minimum perceptual image difference; Yifeng et al. [YPX08] propose a new approach for image-dependent gamut mapping via image fusion. Montag and Fairchild [MF97] describes a experiment using humans to compare various gamut mapping algorithms. Based on various gamut mapping algorithms, soft proofing functionality is provided by a variety of commercial software such as Adobe Photoshop[†] and GIMP[‡]. With the simulation created by soft proofing, the photographer then makes print specific edits to optimize the simulation to their liking. Figure 1 shows a photograph (a) and its equivalent soft-proof that emulates non-photographic plain paper (b).

Out-of-gamut warning is one technique to show areas that are outside the colour gamut of the destination medium. Out-of-gamut warning will compare all the colours in an image with the gamut boundary of the destination colour space and show the colours that fall out of gamut. There are many algorithms that can determine the boundary of the colour space. For example, Cholewo and Loave [CL99] present a solution that can find the boundary of the gamut of a colour printing device or of a colour image by using alpha shapes. This is typically visualized by showing the areas of the photo that are out-of-gamut using a gray layer. Figure 1 shows a photo (a) and its out-of-gamut equivalent (c) if this photo was printed using non-photographic paper (which has a very small gamut). This is the mainstream technique supported by most image processing platforms such as Adobe Photoshop, GIMP, and SILKYPIX Developer Studio [§]. This approach is effective in showing which areas of a specific photo are within or outside of the gamut in the destination colour space, but tells nothing as to the distance between the out-of-gamut colours and the gamut boundary. It does not show the colours within-gamut that have been shifted.

Another approach, which is proposed by Farup et al. in [FHBR02] and implemented in [Nor11], displays the image colours in a 3D space visualization (the typical visualization of a colour space) where the out of gamut colours lie in regards to the destination gamut. This approach communicates the distance of out-of-gamut colours to the gamut boundary, and users are even able to interactively manipulate the image to adjust the out-of-gamut colours. However, there is a disconnection between the pixels in the photo and the out-of-gamut colours depicted in the 3D visualization. Two other tools present a similar visualization to those presented herein: Gamutvision Color pro [¶], and ColorThink Pro Chromix [‖].

[†] `www.adobe.com`

[‡] `www.gimp.org`

[§] `http://www.isl.co.jp/SILKYPIX/english/`

[¶] http://www.gamutvision.com/

[‖] http://www.chromix.com/

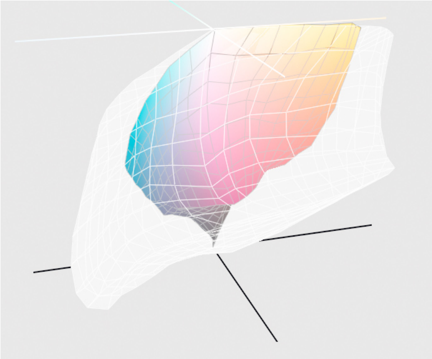


Figure 2: *Comparison of two ICC profiles. The one inside is non-photographic plain paper, while the one outside is Canon Heavyweight Satin, both printed using the Canon IPF5000.*

A common method for a photographer to compare the colour rendition of a paper is to compare the gamuts of the devices using a 3D visualization, such as the one provided by ColorSync (see Figure 2). Unfortunately this compares the profiles but says nothing about the way a photo will be affected by them.

3. Model

When a photo is rendered in an output media, each of its pixels might suffer a color shift. Whether this shift is perceptible it will depend on how big a shift is (for the pixel and its surroundings). One method of quantifying this difference is using ΔE^*_{ab}, defined by CIE [Com86] as the Euclidean distance between two colours in the CIE 1976 L*a*b colour space. ΔE^*_{uv} is similarly defined in the LUV colour space (instead of L*a*b). As described in [F. 01] many other metrics have been created over the years, including $\Delta E(Mc)^2$, ΔE_{JPC79}, ΔE^*_{94}, ΔE_{2000}, and ΔE_K. Each of these is trying to better quantify the perceptual difference between two colors.

Our visualization is constructed by comparing the pixels of the original image to those of its soft-proof using ΔE^*_{ab} (but it can be easily adapted to other color difference metrics). More precisely, I is an input image. The colours of I are encoded using a colour space C_s (the source colour space, such as sRGB, PhotoRGB, or AdobeRBG). The characteristics of the destination media colour rendering are described using its color profile C_d (the destination colour profile of the output media). The image I is converted to its equivalent soft proof S by mapping it from C_s to C_d according to the desired rendering intent transformation.

Let p_0 be a pixel of I at coordinates (x,y), and p_1 a pixel of S. Both p_0 and p_1 are encoded using CIE 1976 L*a*b colour space:

$$p_0 = (l_0, a_0, b_0) \qquad p_1 = (l_1, a_1, b_1)$$

We compute d as the Euclidean distance between p_0 and p_1:

$$d_{p_0 p_1} = \sqrt{(l_1 - l_0)^2 + (a_1 - a_0)^2 + (b_1 - b_0)^2}$$

The heatmap H is an image of the same dimensions as I where the color of each of its pixels p_h is computed as a heatmap based upon d. We use a modified version of the hot colormap algorithm used in Matlab: a distance zero is rendered as light grey (RGB values 0.7,0.7,0.7), and it uses m as the number of different levels in the heatmap. m is a parameter to our visualization and defaults to 50. If the distance d is greater than m, it results in clipping, but if m is too large it will result in a poor visualization (most out-of-gamut pixels will appear to be very close to light grey). Let $n = \lfloor \frac{3 \cdot m}{8} \rfloor$,

$$red(p_h) = \begin{cases} d = 0 & 0.7 \\ d \le n & \frac{d}{n} \\ d > n & 1 \end{cases} \qquad green(p_h) = \begin{cases} d = 0 & 0.7 \\ d \le n & 0 \\ n < d \le 2n & \frac{d-n}{n} \\ d > 2n & 1 \end{cases}$$

$$blue(p_h) = \begin{cases} d = 0 & 0.7 \\ d \le 2n & 0 \\ 2n < d \le m & \frac{d-2n}{m-2n} \\ d > m & 1 \end{cases}$$

The heatmap scale ranges from dark red (low values) to light yellow (large values), monotonically increasing in values. The two colour scale provides for a quick and easy distinction between high and low values, and separates low values from those that are not shifted (light grey colour).

Figure 3 shows the steps of the creation of the *gamutHeatMap* visualization.

4. Implementation

We have implemented *gamutHeatMap* with a GUI interface to assist the photographer in choosing a paper to print. We call this tool *GamutVis*. The main goal of *GamutVis* is to be able to compare an image in the context of different destination ICC profiles (i.e. profiles associated with a specific paper and printer). An input image is given, and the user selects multiple destination profiles and a specific rendering intent. For each profile, a *gamutHeatMap* version of the image is created, representing the colour shift that has occurred due to the application of the destination profile. These *gamutHeatMaps* are then shown side-by-side in our interface, so that the user can easily make general comparisons. We also give the option to select two specific *gamutHeatMaps* for closer inspection. The selections will appear in adjacent windows at 100 percent resolution, and the user may navigate to specific areas of the image for a more detailed comparison of colour change in those areas. Figure 4 shows the main window of *GamutVis*.

GamutVis can also rank the profiles by the total colour

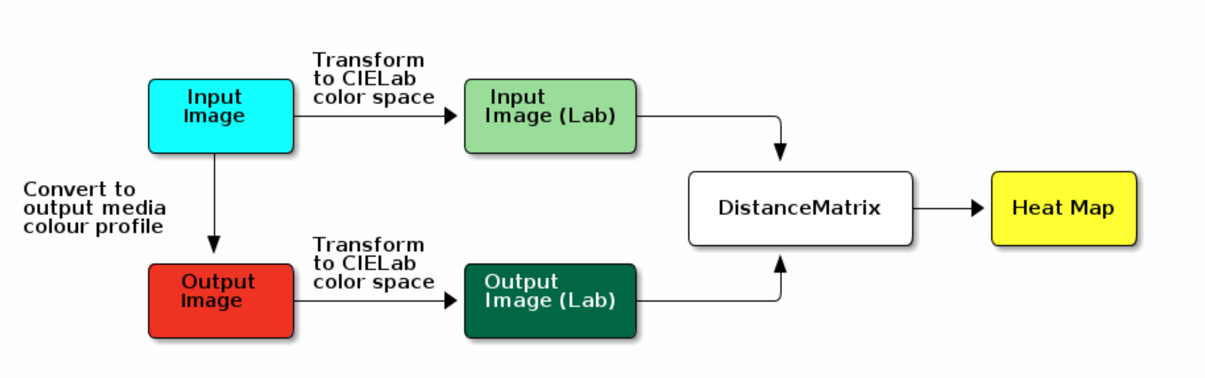
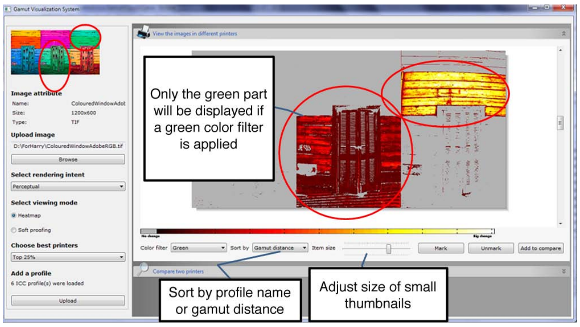


Figure 3: *Major steps to create the* gamutHeatMap *visualization.*

shift. That is, a pixel in a *gamutHeatMap* is associated with a colour change distance. These distances can be summed over the entire *gamutHeatMap*, representing the cumulative distance. This value is used to rank the *gamutHeatMaps* in ascending order, where a lower value is associated with less change.

Since a user may be more concerned with how the output device handles specific colours, we have also implemented a function to filter the areas of interest based on colour and luminance. *GamutVis* provides 11 filters, including red, blue, green, yellow, cyan, magenta, highlights (areas of high intensity), shadows (areas of low intensity), luminance, a*, and b*. As shown in Figure 5, if the user is interested in which device renders the green colour of the input image most accurately, they can select the green filter option. Pixels in the *gamutHeatMap* that are not associated with the green hue will be set to grey. Finally, we also give the user the option to change from the *gamutHeatMap* view to a soft proofing view: each *gamutHeatMap* in the interface is replaced with its corresponding soft proof. To the best of our knowledge, no other application provides this functionality.

We invite the reader to view the videos of *GamutVis* in the addendum.



Name: ColouredWindowAdot
Size: 1200x600
Type: TIF
Upload image: D:\ForHarry\ColouredWindowAdobeRGB.tif
Select rendering intent: Perceptual
Select viewing mode: ● Heatmap ○ Soft proofing
Choose best printers: Top 25%
Add a profile: 6 ICC profile(s) were loaded
Color filter: Green
Sort by: Gamut distance

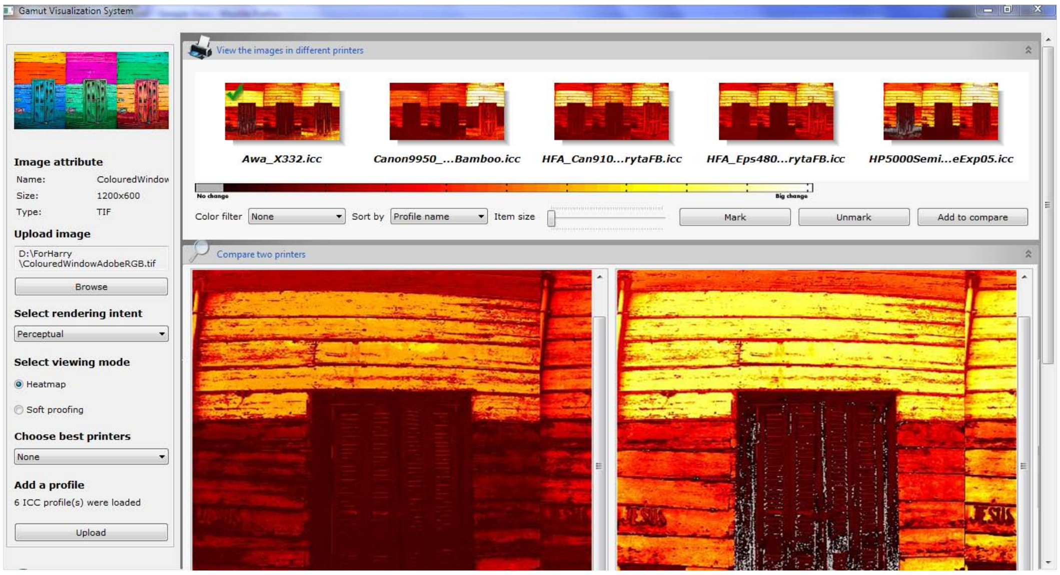
Figure 5: *The user can narrow the view to selected colours in the user interface of* GamutVis. *In this example, the user has chosen the green filter and only areas with green are shown.*

5. Evaluation

To evaluate our *GamutVis* we selected a set of photographs that span a range of scenes and colours. These are depicted in Figure 6. Each of them stresses different aspects of colour: saturation, tonality, detail in shadows, and transitions within a single colour.

Ideally, to evaluate whether the colours of a print have been shifted one would require to print the desired photograph, and compare it to other prints, and the view on screen. This, however, creates several potential confounds. For example, the quality of the printing process might add some variability to the printed colours. Similarly, the actual physical properties of the paper (such as its texture) and the light under which it is viewed might affect how a person perceives the colours of a print. These factors should be taken into consideration to minimize the potential threats to validity of such study.

For this reason we restrict our comparison to soft proofs. The soft proofs are created using MatLab and they are used as a baseline for comparison. We invite the reader to browse the images (provided as an electronic addendum to this paper) on a colour-calibrated display. The objective of our evaluation is to demonstrate that the *gamutHeatMap* are capable of describing differences between different colour-rendered versions of the same image when printed to different media. For this reason we selected various ICC profiles for various papers. An ICC profile determines how a paper/printer/ink combination renders colours, and hence, it is unique for a given paper and printer model (it is assumed that the printer uses the manufacturer's recommended inks). We selected a wide range of papers/printers, and in some cases, the ICC profile of one paper in different printers–it is expected that two different printers would render colours differently on the same paper. In general we selected printers



Name: ColouredWindow
Size: 1200x600
Type: TIF
D:\ForHarry \ColouredWindowAdobeRGB.tif
Select rendering intent: Perceptual
Select viewing mode: ● Heatmap ○ Soft proofing
Choose best printers: None
6 ICC profile(s) were loaded
Color filter: None
Sort by: Profile name
Item size

Figure 4: *Main window of* GamutVis*, our implementation of the* gamutHeatMap *visualization. The top section of the window shows the* gamutHeatMap *for each desired colour profile. The bottom section allows the user to compare two different profiles.*


Saturation Skin Tone Landscape Single Colour

Figure 6: *Test images used in our evaluation. Saturation: the original photo (left side) has been triplicated, its hue shifted and its saturation increased. Skin Tone: this photograph shows a traditional portrait with a near-black background. Landscape: a good balance of shadows and highlights. Single colour: an image with subtle transitions among tones of the same colour.*

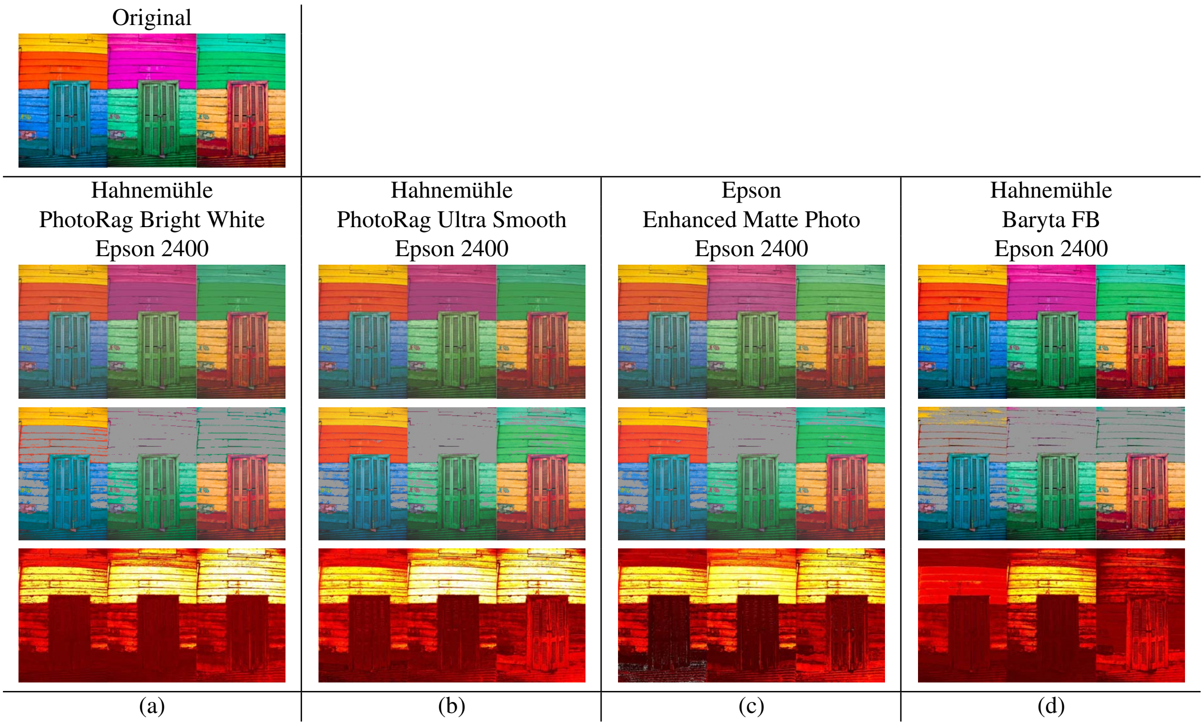
and papers profiles for fine-art papers, with different finishes (matte, glossy). We downloaded the ICC profiles from the paper's manufacturer's web sites. In addition, we created an ICC Profile for non-photographic plain paper (for a Canon IPF5000 printer). We expect that this paper will serve as an example of a paper that, due to its lack of coating, poorly renders the original colours (and hence shifts them significantly). This profile is included in the addendum. [**]

For our evaluation we have chosen to present the original photograph, and a sequence of soft-proofs for various papers. Due to space limitation we present only few examples for each photo. In all cases, the soft-proofs were done with perceptual rendering (the recommended by ICC for photographic material).

Manufacturer	Name	Finish
Hahnemühle	PhotoRag Bright White	Matte
	PhotoRag Ultra Smooth	Matte
	Baryta FB	Glossy
Epson	Enhanced Matte Photo	Matte
Ilford	Gold Fiber Silk	Glossy
Unknown	Non-photographic Plain	Matte

Table 1: *Paper ICC Profiles used in our evaluation. We downloaded these profiles from the paper manufacturer's web site (except the last which was created by one of the authors).*

[**] Unfortunately, due to copyright restrictions, we cannot include the ICC profiles of the other papers, but we invite the reader to download them from the manufacturer's web sites



(a) (b) (c) (d)

Figure 7: *Saturation test. The first row shows the soft proof, followed by the out-of-gamut warning. The last row is the* gamutHeatMap. *In all three matte papers (a,b and c), the upper part of the image is shifted the most (saturated purples are the most difficult to render, followed by the saturated oranges); while the doors are the ones with the least shifting. The glossy paper (d) is the one that handles the saturated colours best. Notice how the out-of-gamut view is not very useful.*

Figure 7 shows the *Saturation* test photograph. It includes the soft-proofs for each paper, the out-of-gamut warning, and the *gamutHeatMaps*. We have chosen profiles for the same printer: Epson2400. The soft-proofs, show how, in the first 3 papers, the top colours (orange, magenta and bright green) are muted by the papers (as expected, since all are matte). This effect is clearly visible in the *gamutHeatMaps*, while the out-of-gamut views are inconsistent and not very helpful. It is not surprising that the glossy paper (Baryta FB) is capable of rendering the saturated colours more accurately.

Notice how the Baryta FB paper is the best at rendering the magenta section, at the expense of shifting in other areas. This is where the filter and ranking function of *GamutVis* would be useful. A variety of paper profiles could be loaded. The purple filter is then applied, then the *gamutHeatMaps* are ranked. In the filtered ranking, Baryta is the best.

If we compare the 3 *gamutHeatMaps* of the matte papers (not including Baryta FB), it is clear that the Epson paper has the least shift in colour (interestingly enough, this paper is the cheapest of the group). Furthermore, areas that are clearly out of gamut in all images (the magenta area) show different levels of intensity in the *gamutHeatMap*, indicating that some papers react worse than others. This is confirmed by the soft-proofs, although these distinctions are much more difficult to make in the soft proof versions. While the differences might only be marginal, what they do tell us is that the more expensive paper won't reproduce the original colours any better.

The *Skin Tone* test is shown in Figure 8. In this case we have chosen a wide variety of papers and printers and including the non-photographic paper, which we expected to do poorly, and the *gamutHeatMap* confirms it. One can see that the lips colour has shifted from red to purplish, and the *gamutHeatMap* shows that indeed, the lips is the area with a significant shifting. Notice how the same paper renders colours slightly different in two printers (the Baryta FB). The Ilford paper (also a baryta-type paper) shows slightly less shifting that the others.

Figure 9 shows the *Landscape* test. The scene contains attributes that are often difficult to reproduce in print: dark shadows, bright highlight, and saturated colours. We've created *gamutHeatMaps* for 3 different profile types. Two of the profiles are the Hahnemüehle Baryta FB paper, but have been created for two different printers: the Epson 2400 and the Canon 9100 plus the non-photographic paper. First let us consider the soft proofs. It is immediately clear that the cheaper paper produces a poorer reproduction. This claim is

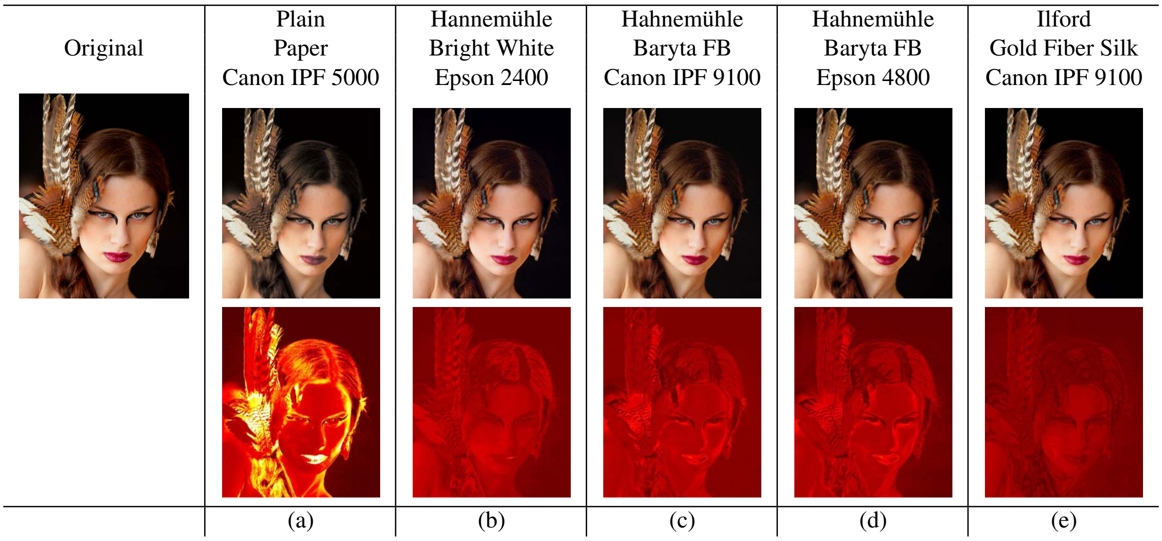


Figure 8: *Skin test. Unsurprisingly, the first paper, non-photographic plain paper (a), performs the worst. Nonetheless it is useful to know that the largest shift occurs in the lips (the paper renders the red as purplish). The rest of the papers are closer to the original image, but all of them show shifting (albeit small). The most colour-accurate paper is the Ilford paper (e).*

supported by the *gamutHeatMap* image; there is clearly less gray area and the colours appear to be lighter (which represent greater magnitude shifts). Now consider the profiles associated with the more expensive paper. These clearly will do a better job. However, by examining the soft proofs it is difficult to clearly identify which printer will do a better job. With the *gamutHeatMaps* though, it is fairly clear that the Epson 4800 printer will do a slightly better job. Compare these *gamutHeatMaps* with those of Figures 8 and 7. It is interesting to see that in this image a large proportion of the image can be rendered without shifting.

Finally, Figure 10 shows the results of the *Single Colour* test. One can see the transition areas between the different tones show significant differences among the papers (and among the same paper in different printers). The Ilford paper is clearly the most accurate. Hannemühle Baryta FP was simulated in a Canon and Epson printer, showing how one printer is more accurate in highly-saturated blues (Canon) while the other is with more subtle blues (Epson).

6. Discussion

We cannot claim that the *gamutHeatMap* can be the determining factor in choosing a given paper to render a photo. It can, however, be used to inform the photographer on which areas can be particularly difficult to render, and where to expect colour shifting.

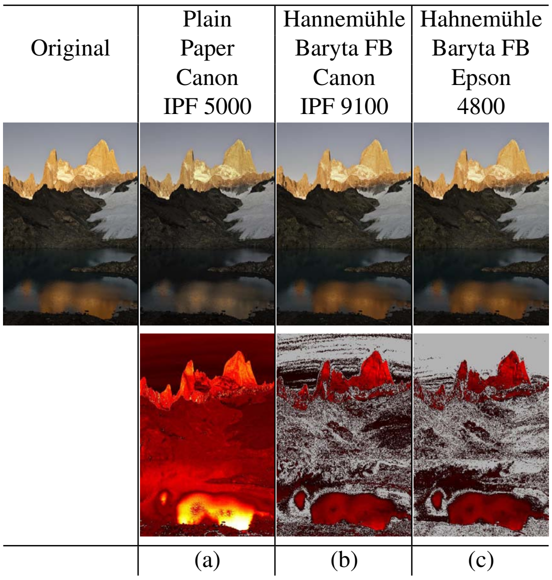
We found that the *gamutHeatMap* is also a useful tool to learn the subtleties of colour rendering, and the advantages and disadvantages of different types of paper finishes (glossy papers can display more saturated colours, but matte papers can be more accurate with non-saturated colours). We believe that with *gamutHeatMaps* photographers can get a better understanding of the process of colour rendering intent transformations.

Colour printing is an art. The photographer will make aesthetic decisions that go beyond colour accuracy. In fact, an artist might take advantage of the colour shifting capabilities of a medium to materialize her vision. As such, the *gamutHeatMaps* are simply one more tool in their palette.

The work presented herein needs to be evaluated within the context of the printing process used by photographers. Future work should include an evaluation by those who print photographs, both professionals and amateurs. Such a study would determine if, and how these visualizations are useful. Similarly, different color difference metrics should be evaluated to determine which ones are more useful, and under which circumstances (for example, some metrics might be more useful for landscapes, while others for portraits, or black and white photographs).

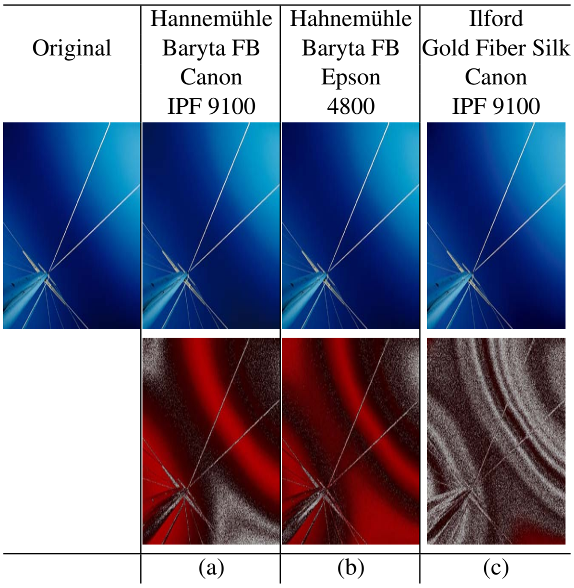
7. Conclusions

We have created a visualization called *gamutHeatMap* that aids the user in identifying the most accurate output device (paper and printer) for colour reproduction, and implemented a tool called *GamutVis* to apply to digital photographs. The information given in the *gamutHeatMaps* is related to the perceptual change in colour, and thus gives the photographer some quantitative information to base his or her decision. It also provides a connection between colour change and spatial location, allowing photographers to eas-



(a) (b) (c)

Figure 9: *Landscape test. The worst colour rendering corresponds to the non-photographic plain paper, which shows significant shifting. Both (b) and (c) correspond to the same paper, but different printer. As expected, the renderings are similar, yet, have subtle differences; it is also interesting to see how the shadows are rendered accurately (light-grey areas). In all cases the golden tones of the mountains are the most difficult to render.*



(a) (b) (c)

Figure 10: *Single Colour test. We have chosen only baryta-type papers for this test. Notice how the same paper renders blue differently in different printers, with the Canon showing less shifting. The Ilford paper shows significantly less colour shifting than the Hannemühle. And the Canon printer is more accurate in the saturated areas, but less than the Epson in the others.*

ily identify where the colour shift occur, and if it is important to the final print.

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