The Effect of Gamma and Chroma on the Perception of Color Images

Judith Dijk [1, 2], Piet W. Verbeek[1], Jan Walraven[2] and Ian T. Young[1]
[1]Delft University of Technology, Delft, The Netherlands
[2]TNO Human Factors, Soesterberg, The Netherlands

Abstract

We present the results of experiments in which we manipulated color images in the CIELAB space by first applying a scaling factor on chroma (C^*). After this we applied a gamma transformation (an exponent relating the input to the output) to the luminance (Y) in XYZ space, while keeping the chromaticity values (x, y) constant. The aim of the experiments was to test the subjective preference for a particular gamma and chroma scaling factor.

Two natural images (standard ISO images) were transformed with 4 different values of gamma and 4 different scaling factors for chroma. The images were viewed on a CRT monitor.

We found that the preference depends on the gamma, on the chroma scaling factor and on both variables combined. However, increasing or decreasing one or both variables does not improve the preference for the images that are used.

The results were not significantly different for the two different images.

1. Introduction

When reproducing an image, for instance on a monitor, the colors of the reproduced image affect the quality of this image. In this study we investigated two variables that influences the color reproductions, i.e. the gamma of the luminance distribution and the scaling of the chroma. The first manipulation we investigated was scaling the chroma C^* of each point

$$C^*_{out} = sf_{chroma} C^*_{in} , \tag{1}$$

in which sf_{chroma} is the chroma scaling factor. The subscripts *in* and *out* denote the variables before and after the manipulation, respectively. Experiments with this manipulation in the CIELUV color space have been done by Fedorovskaya et.al.[1] They found that when chroma varies, the colorfulness of an image is the main perceptual attribute underlying image quality. They also found that, in general, the subjects preferred slightly more colorful images to the original ones.

The second manipulation we investigated was the gamma transformation of the luminance Y, given by

$$Y_{out} = kY_{in}^{\gamma} \tag{2}$$

where k is a constant for keeping the output range constant. The exponent γ, gamma determines the compression or expansion of the luminance steps. The color coordinates x and y are kept constant.

The effect of a gamma transformation was studied by Roufs et.al.[2,3,4] for grey scale images. They found, that the optimal gamma for their images was always larger than 1 and, also, that this optimal gamma differs for the different scenes that are displayed. They identified global brightness contrast as the underlying perceptual attribute.

In the past we have done experiments with images in which this gamma was varied in printed color images.[5] In these experiments we scaled the chroma of each point with a value of 0.85 to reduce the out-of-gamut colors. The conclusions of these experiments were that for one of the images the preferred gamma was 1 and for the other image the preferred gamma was 1.1 or 1.2.

We describe in the present paper experiments in which we investigated how gamma affects the perception of color images, but now for images displayed on a monitor. In contrast with the previous experiment we also varied the scaling factor that was used in the previous experiment to reduce the out-of-gamut colors, to see if this influences the choice for the optimal gamma. To be able to compare these results with the previous experiments, we used the gamut of the printer for gamut mapping.

2. The Relation Between Gamma and Chroma

In the experiment we first scaled the chroma C^* in the CIELAB space. In this space we also have the variables a^*, b^*, L^*, and h^*. After this we applied a gamma transformation (an exponent relating the input to the output) to the luminance (Y) in XYZ space, while keeping the chromaticity values (x, y) constant.

In this section we derive the theoretical relation between a gamma transformation and the chroma, and also the role of h^*. First we look how the chroma changes from C_1^* to C_2^* due to a change in Y from Y_1 to Y_2. We keep (x, y, z) constant, so

$$x_1 = x_2 \text{ and } y_1 = y_2 \text{ and } z_1 = z_2 , \tag{3}$$

where subscript *1* and *2* denote the values before and after the change, respectively.

This gives

$$\frac{X_1}{e} = \frac{X_2}{f}$$
$$\frac{Y_1}{e} = \frac{Y_2}{f} \qquad (4)$$
$$\frac{Z_1}{e} = \frac{Z_2}{f}$$

with (X, Y, Z) the tristimulus values of the point,

$$e = X_1 + Y_1 + Z_1 \text{ and } f = X_2 + Y_2 + Z_2 \qquad (5)$$

After eliminating e and f we find

$$X_2 = X_1 \frac{Y_2}{Y_1} \text{ and } Z_2 = Z_1 \frac{Y_2}{Y_1} \qquad (6)$$

We define

$$\begin{aligned} X_{rel} &= X_1 / X_0 \\ Y_{rel} &= Y_1 / Y_0 \\ Z_{rel} &= Z_1 / Z_0 \\ Y_{ratio} &= Y_2 / Y_1 \end{aligned} \qquad (7)$$

with $(X_0\ Y_0\ Z_0)$ the tristimulus values of reference white.

In approximation, a_1* and a_2* are given by

$$\begin{aligned} a_1* &= 500\left(X_{rel}{}^{1/3} - Y_{rel}{}^{1/3}\right) \\ a_2* &= 500\left(X_{rel}{}^{1/3} Y_{ratio}{}^{1/3} - Y_{rel}{}^{1/3} Y_{ratio}{}^{1/3}\right) \\ a_2* &= Y_{ratio}{}^{1/3} a_1* \end{aligned} \qquad (8)$$

and b_1* and b_2* by

$$\begin{aligned} b_1* &= 200\left(Y_{rel}{}^{1/3} - Z_{rel}{}^{1/3}\right) \\ b_2* &= 200\left(Y_{rel}{}^{1/3} Y_{ratio}{}^{1/3} - Z_{rel}{}^{1/3} Y_{ratio}{}^{1/3}\right) \\ b_2* &= Y_{ratio}{}^{1/3} b_1* \end{aligned} \qquad (9)$$

This approximation holds for $X>0.008856X_0$, $Y>0.008856Y_0$ and $Z>0.008856\ Z_0$. With these equations we can determine $C*$

$$\begin{aligned} C_1* &= \sqrt{a_1*^2 + b_1*^2} \\ C_2* &= \sqrt{a_2*^2 + b_2*^2} \\ C_2* &= \sqrt{a_1*^2\, Y_{ratio}{}^{2/3} + b_1*^2\, Y_{ratio}{}^{2/3}} \\ C_2* &= Y_{ratio}{}^{1/3} C_1* \end{aligned} \qquad (10)$$

and $h*$

$$\begin{aligned} h_1* &= \arctan(b_1* / a_1*) \\ h_2* &= \arctan(b_2* / a_2*) \\ h_2* &= \arctan(b_1* Y_{ratio}{}^{1/3} / a_1* Y_{ratio}{}^{1/3}) \\ h_2* &= h_1* \end{aligned} \qquad (11)$$

So we found that if $Y_2 > Y_1$, Y_{ratio} is larger than 1 and $C_2* > C_1*$. The hue $h*$ does not change for any changes of Y.

(a) *bicycle* (b) *musicians*

Figure 1. The two stimuli

Now we look at a gamma transformation applied to the luminance Y of the image. The transformation is given by

$$Y_2 = k_1 Y_1^{\gamma} - k_2 \qquad (12)$$

in which k_1 and k_2 are constants, which are used to keep the maximum and minimum luminance of the image constant. Combining equations 10 and 12, we obtain

$$\begin{aligned} Y_{ratio} &= \frac{Y_2}{Y_1} = \frac{k_1 Y_1^{\gamma} - k_2}{Y_1} = k_1 Y_1^{\gamma-1} - k_2 / Y_1 \\ C_2* &= \left(k_1 Y_1^{\gamma-1} - k_2 / Y_1\right)^{1/3} C_1* \end{aligned} \quad . \qquad (13)$$

We interpret the effect of the gamma transformation on the chroma as a new scaling factor. For gammas larger than 1, this scaling factor is smaller than 1 for all luminance values (this can be seen by the fact that Y_2 is always smaller than Y_1 for a gamma larger than 1). For gammas smaller than 1 this scaling factor is larger than 1 for all luminance values. So, the larger the gamma, the smaller the chroma of each point.

3. Method

The Images

The stimulus set consisted of two different images (figure 1). These images are the ISO standard images (from the CD-ROM ISO 12640:1997), 'bicycle' and 'musicians'. Since we were interested in the question whether image content plays a role, we chose two test images that were quite different in this respect.

These images are given in CMYK format. Although this is a device dependent color space, we chose to use these images because we also used them in the previous experiments.

With the methods described in appendix A, we transformed the images to the device independent color space XYZ.

The original white point of the paper (X_o, Y_o, Z_o) was transformed to the reference white of the printer gamut (X_p, Y_p, Z_p), using[6]

$$\begin{aligned} X_{out} &= X_{in} X_p / X_o \\ Y_{out} &= Y_{in} Y_p / Y_o \\ Z_{out} &= Z_{in} Z_p / Z_o \end{aligned} \qquad (14)$$

in which (X_{in}, Y_{in}, Z_{in}) and (X_{out}, Y_{out}, Z_{out}) were the tristimulus values of the point before and after the transformation, respectively.

Next we changed the C^* (in CIELAB) of each point by

$$C_{new}{}^* = C_{old} * sf_{chroma} \tag{15}$$

where sf_{chroma} is the chroma scaling factor. Note that this transformation is often used with a scale factor smaller than 1, to perform a gamut mapping.[7]

The luminance values of the stimuli were changed using

$$Y_2 = k_1 Y_1^{\gamma} - k_2 \tag{16}$$

The constants k_1 and k_2 were adjusted so as to hold the minimum and the maximum luminance in the image constant.

Before the transformation from XYZ to RGB, a gamut clipping on the gamut of the printer was done in which the out-of-gamut colors were clipped to the closest boundary points in the CIELAB color space. Note that in this manipulation the hue h^* is not changed.[7] Also note that the higher the sf_{chroma} the more pixels have to be clipped.

The images were converted from XYZ to RGB using[8]

$$\begin{pmatrix} Y_R \\ Y_G \\ Y_B \end{pmatrix} = \begin{pmatrix} x_R / y_R & x_G / y_G & x_B / y_B \\ 1 & 1 & 1 \\ z_R / y_R & z_G / y_G & z_B / y_B \end{pmatrix} \tag{17}$$

and

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} \left(\left(Y_R / Y_{R,\max} \right)^{1/\gamma_R} - 1 + k_R \right) / k_R \\ \left(\left(Y_G / Y_{G,\max} \right)^{1/\gamma_G} - 1 + k_G \right) / k_G \\ \left(\left(Y_B / Y_{B,\max} \right)^{1/\gamma_B} - 1 + k_B \right) / k_B \end{pmatrix} \tag{18}$$

where x, y and z are the 1931 CIE chromaticity coordinates for the phosphors R, G and B. Y_R, Y_G and Y_B are the luminances that are generated by these phosphors. $\gamma_{\{R,\,G,\,B\}}$ and $k_{\{R,\,G,\,B\}}$ are values that represent the relation between $\{R, G, B\}$ and $\{Y_R, Y_G, Y_B\}$.

Pixels that were still out of the gamut of the monitor were clipped onto the boundary of the monitor's gamut. Still, the clipping was sufficiently small that it is not likely that it will have effected the results.

Setup of Experiment A

In this experiment the subjective preference for a particular gamma was tested for different (constant) values of the chroma scaling factor sf_{chroma}. Two images were displayed on the monitor, and the subject had to choose which image was preferred over the other. Four series of images were used, with scaling factors 0.7, 0.85, 1.0 and 1.15. In each series γ varied from 0.7 to 1.4 in steps of 0.1. Each pair of images was presented in both permutations. This resulted in 56 pairs of images per series. The background surrounding the images was either white or grey.

Setup of Experiment B

In this experiment the subjective preference for a particular chroma scaling factor was tested for different (constant) values of gamma. Two images were displayed on the monitor, and the subject had to choose which image was preferred over the other. Four series of images were used, with gamma 0.8, 1.0, 1.2 and 1.4. In each series sf_{chroma} varied from 0.7 to 1.15 in steps of 0.075. Each pair of images was presented in both permutations. This resulted in 42 pairs of images per series. The background surrounding the images was either white or grey.

Setup of Experiment C

In this experiment the subjective preference for a particular gamma and chroma scaling factor was tested. Two images were displayed on the monitor, and the subject had to choose which image was preferred over the other. The gamma values used were 0.8, 1.0, 1.2 and 1.4 and the chroma scaling factors that were used were 0.7, 0.85, 1.0 and 1.15. Each pair of images was presented in both permutations. This resulted in 240 pairs of images. The background surrounding the images was either white or gray.

The Experimental Environment

The monitor used for presenting the images was an IIYAMA Vision Master 501 (21"). The room in which the images were presented was dark (no background illumination). The error in the color of the displayed values is 3.0 ± 4.0 $\Delta E_{L^*a^*b^*}$ for the white background, and 1.6 ± 1.3 $\Delta E_{L^*a^*b^*}$ for the gray background. The smallest mean values of $\Delta E_{L^*a^*b^*}$ between two images was 1.5 ± 1.4 and 3.2 ± 2.8 for the musicians image and 1.0 ± 1.7 and 2.0 ± 3.0 for bicycle. Although these values could be smaller than the error in the display, they are not in a random direction. The subjects could see the differences between the images. Four naive subjects took part in the experiments.

4. Results

The preference values of the subjects were obtained using the "Law of comparative judgment".[9] These values can only be compared within each separate experiment and only for each image separately. The reason for that is, that for each experiment and image the unit of measurement and the offset is chosen differently, which makes it hard to compare between the different experiments and images. In order to obtain scales that can be better compared, they were transformed according to

$$z' = \frac{mean(s') - s'}{std(s')} \quad , \tag{19}$$

in which s' is the value of the old scale and z' is the value of the new scale. The mean of this scale is 0 and the unit of the scale is 1 standard deviation. The maximum value of the scale refers to the score of the best image.

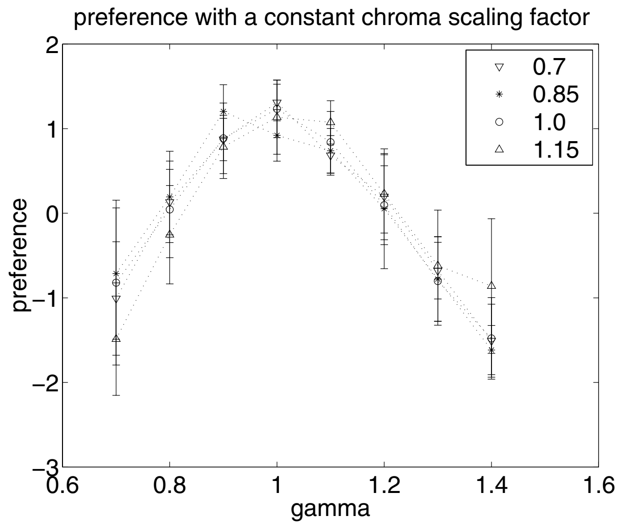


Figure 2. The results of experiment A: the preference for a gamma when the chroma scaling factor is constant

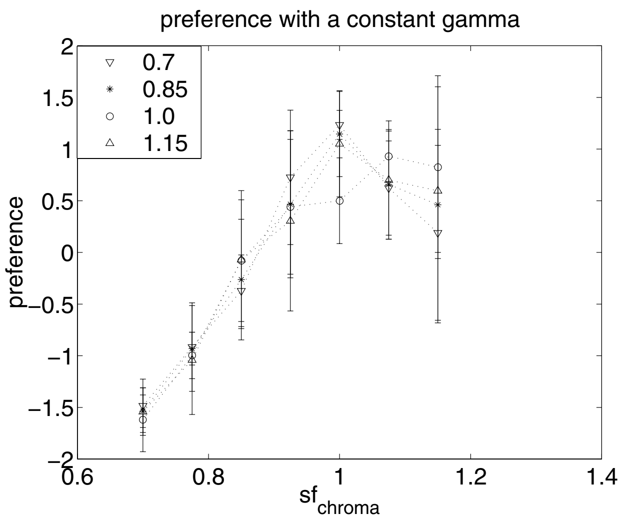
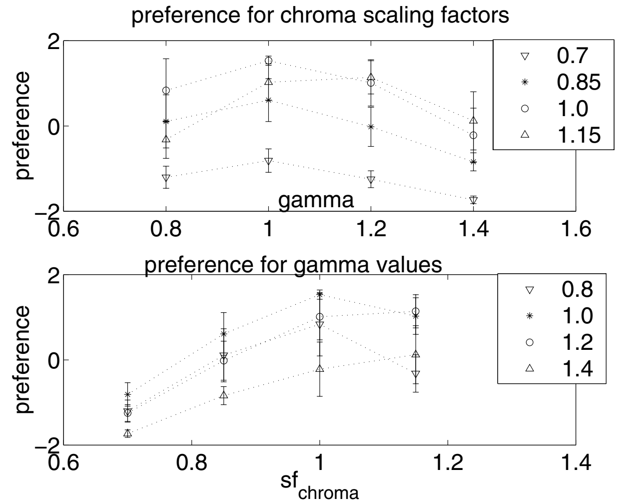


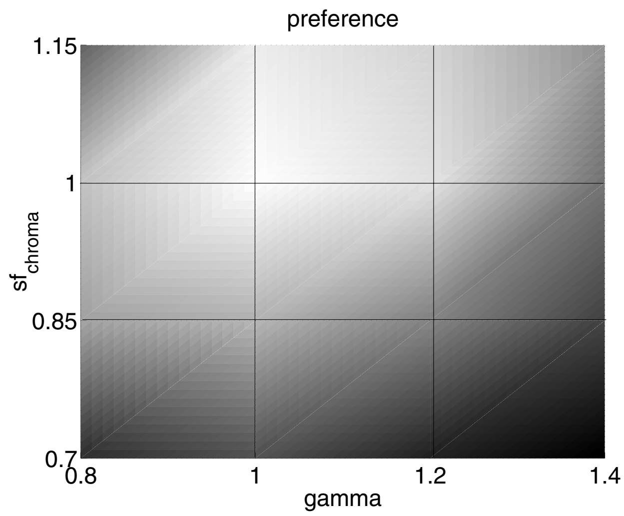
Figure 3. The results of experiment B: the preference for a chroma scaling factor when gamma is constant

To obtain confidence intervals we used bootstrapping. The idea of bootstrapping is that we take *n* random draws (with replacement) out of the responses of *n* subjects. If we determine the preference of their inputs with the Law of comparative judgment,[9] we obtain one realization of the preference. If we average *j* realizations, we obtain an estimation of the real preference values. The size of the 95% confidence interval is given by the standard deviation over the realizations, multiplied by the *student t* factor with *(j-1)* degrees of freedom.

In order to say something about the significance of effects and points we used an Analysis of Variance (ANOVA),[10] in combination with the Newman-Keuls test.[11]



(a)



(b)

Figure 4. The results of experiment C. In these graphs the preferences for 16 images are given. In (a) the preferences relate to a constant γ or sfchroma. In (b) the same preferences are given, but now plotted against γ and sf_{chroma}. The lighter the point, the higher the preference. The areas between the points have been obtained by linear interpolation.

Results of Experiment A

The results of experiment A, averaged over the subjects and images, are given in figure 2. It can be seen that for all values of the chroma scale factor, the preferred gamma (the maximum of the curves) is between 0.9 and 1.1 gamma. However, the maxima are not significantly different from neighboring points. We did a combined analysis over all chroma values, to see if we could find an effect for the chroma values of the images. Such an effect was not found.

In earlier experiments[5] we found that the preferred gamma for a chroma scaling factor of 0.85 was 1 for the musicians image and 1.1/1.2 for the bicycle image.

We found that the results of these experiments were corroborated by the results of the present experiment.

Results of Experiment B

The results of experiment B, averaged over subjects and images, are shown in figure 3. The data indicate that the maximum of the curves (the preferred image in each scale) is at values of sf_{chroma} between 0.925 and 1.075. However, these maximum values do not significantly differ from their neighbors. The changes in the curves that are due to different values of gamma are not significant either.

Results of Experiment C

The results of experiment C, averaged over the subjects and all conditions, are given in figure 4. The highest preference is observed for the point where γ and sf_{chroma} are both 1. With the ANOVA techniques we found that this point has a significantly higher preference than all other points. We also found that the preference was determined by the gamma, by the chroma scaling factor and by the interaction between gamma and chroma scaling factor. This was already expected, given the relation between gamma and chroma scaling factor in section 2.

We also looked at the preferences for the images separately. We did not find a main effect for the images, but we still found effects for gamma, chroma scaling factor and the interaction of these two. We did not find a significant main effect for the background of the images either.

It is not possible as yet to compare the results of experiment C to those of experiments A and B.

5. Conclusions and Discussion

In these experiments we measured the subjective preference for images that were scaled in chroma and then subjected to a gamma transform. We found that both factors have an effect on the subjective preference. The interaction of gamma and chroma scaling factor also has a main effect on the image preference.

We used two images and two backgrounds, but we did not find that this effected the results.

The preference for the original image (gamma = 1 and chroma scaling factor is 1) was significantly higher than the preference for the other images. This result is interesting because it means that for these images, both manipulations decrease the quality of the image. Put in another way, the best results are obtained if gamma and chroma scaling factor are both set at unity.

For the future, we plan to do the same experiments, but now with printed images. We also intend to derive an empirical function, which describes the relationship between gamma, chroma and the preference for an image.

Acknowledgments

This research is partly supported by Senter, Agency of the Ministry of Economic Affairs of the Netherlands

References

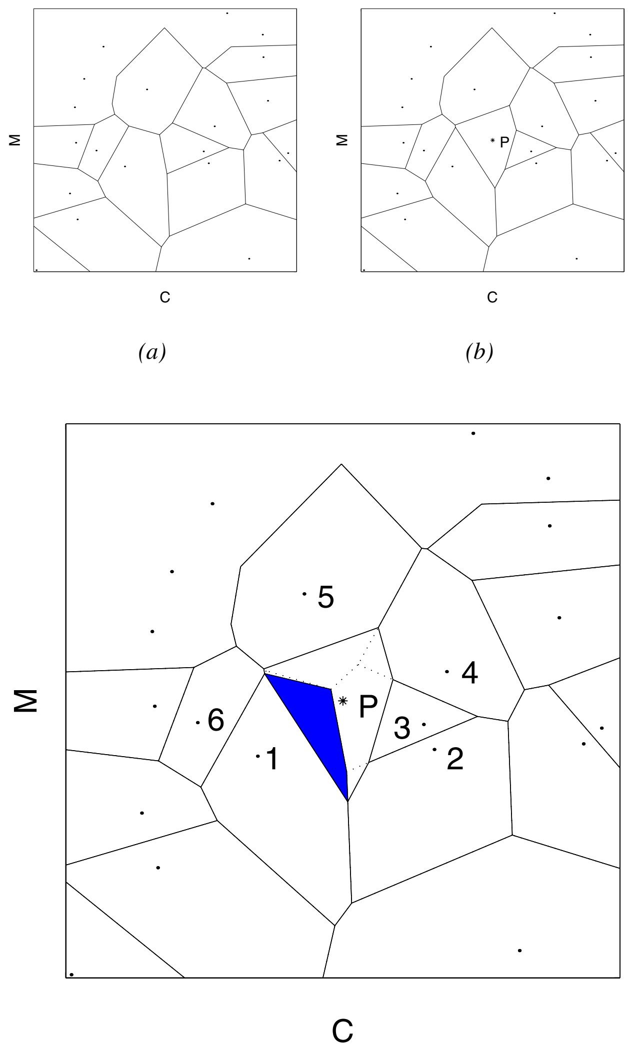
1. E.A. Fedorovskaya, H. de Ridder, F.J.J. Blommaert, Chroma variations and perceived quality of color images of natural scenes, Color Research and Application, vol 22, no 2, 96-110, 1997.
2. J.A.J. Roufs, Perceptual image quality: concept and measurement, Philips J. Res : 47, 35-63, 1992.
3. J.A.J. Roufs and A.M.J Goossens, Perceived quality and contrast as a function of gamma, IPO annual progress report 23, 1989.
4. J.A.J. Roufs, Brightness contrast and sharpness, interactive factors in perceptual image quality, SPIE vol. 1077, Human Vision, Visual Processing and Digital Display, 66-72, 1989.
5. J. Dijk, P.W. Verbeek, J. Walraven, and I.T. Young, The effect of gamma on the perception of printed color images. In Proc. First international conference on color in graphics and image processing}, pages 7-12, France, 2000. CGIP'2000.
6. J. Y. Hardeberg, F. Schmitt, H. Brettel, J-P. Crettez, and H. Maitre, Multispectral image acquisition and simulation of illuminant changes, chapter 8, pages 145-164. Wiley and Sons, 1999.
7. J. Morovic, The colour image processing handbook}, chapter Colour management for the graphic arts, pages 332-357. Chapman and Hall, London, UK, 1998.
8. M.P. Lucassen and J. Walraven. Evaluation of a simple model for color monitor recalibration. Color research and Application, 15:321-326, 1990.
9. W.S. Torgerson, Theory and methods of scaling. Wiley and sons, NY, 1958.
10. B.J Winer. Statistical priciples in experimental design, McGraw_Hill, London, UK, 1970.
11. Inc StatSoft. STATISTICA for Windows [Computer program manual] StatSoft, Inc, 2300 East 14th Street, Tulsa, 2000.
12. ANSI CGATS TR 001-1995. Graphic technology - color characterization data for type 1 printing. Technical report, NPES, 1995.
13. J.M. Sutyinszky, `http://home.earthlink.net/~janos1/vidpage/color_faq.html`, 1999.
14. R. Sibson, A brief description of natural neighbour interpolation, chapter 2, pages 21-36, Wiley and Sons, NY, USA, 1981.

Appendix A. Transforming the original images from CMYK to XYZ

In this appendix the transformation from CMYK to XYZ is described. The images that we used are standard ISO images (ISO 12640:1997) for the quality of printing, and are given in CMYK format. We want to change attributes in the XYZ color space, so we have to convert these images to XYZ. Therefore, we use a table with reference CMYK and corresponding XYZ values.[12] This table is specifically provided for this purpose.

We first transformed both the reference table and the images from CMYK to CMY using[13]

$$\begin{aligned} C' &= \min(1, C(1-K)+K) \\ M' &= \min(1, M(1-K)+K) \\ Y' &= \min(1, Y(1-K)+K) \end{aligned} \tag{20}$$



(a) *(b)*

(c)

Figure 5. An example of the natural neighborhood interpolation in 2D. In (a) the Voronoi tessellation of the reference points is seen. In (b) point P *that has to be interpolated is added, it can be seen that the tessellation changes locally. In (c) the natural neighbors of* P *are given the numbers 1-6. The area corresponding to the weight of reference point 1 is filled.*

The transformation from CMY to XYZ is achieved by the natural neighbor interpolation.[14] The advantage of this interpolation is that the reference points do not have to form a regular grid.

The image points have to be transformed from 3D CMY color space to 3D XYZ color space. We can divide the CMY color space into small volumes, in which all points in the volume are closest to a particular reference point. This technique is called Voronoi Tessellation.

The point *P* that we want to interpolate has values $\{C_P, M_P\ Y_P\}$. A new tessellation is obtained for the reference points and point *P*. This tessellation differs only locally from the original tessellation. Some volumes are divided into two. The natural neighbors of point *P* are the reference points whose volumes are divided into two parts.

The natural neighborhood weight λ_i of reference point *i* is defined as the size of the volume, which is closest to P, and second closest to *i*. Theoretically, $\lambda_i = 0$ for points that are not natural neighbors of the point. The weight is normalized by the size of the area or volume belonging to the extra point ($\sum\lambda_i = 1$).

The interpolated value at of X, Y, and Z for point *P* can be determined with

$$
\begin{aligned}
X_P &= \sum_i \lambda_i X_i \\
Y_P &= \sum_i \lambda_i Y_i \\
Z_P &= \sum_i \lambda_i Z_i
\end{aligned}
\tag{21}
$$

where $\{X_i, Y_i, Z_i\}$ are the tristimulus values of point i. So the interpolated value only depends on the values of the natural neighbors.

An example in 2D is given in figure 5. In figure 5 (a) the reference points are seen, as well as their Voronoi tessellation. In figure 5 (b) the point that we want to interpolate, point *P* is added. It can be seen that the Voronoi tessellation changes only locally. In figure 5 (c) it can be seen that the interpolated tristimulus values depend only on the tristimulus values in points 1 to 6. These are the natural neighbors. The λ_i's of 1, 3 and 5 are large, those of the other three points are small.

Biography

Judith Dijk studied applied physics at Delft University of Technology. She obtained her master’s degree in 1998. Currently she is a PhD student on the project “Image Quality Measures for the Perception of Printing”. This project is a collaboration between the Applied Physics Department in Delft and TNO Human Factors in Soesterberg.