Color difference equations and the human eye

Martin Habekost*

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Abstract: Ever since colors could be measured, various color difference equations have been used to describe the difference between two colors. The numbers generated from the various equations were not interchangeable and each number had a different meaning depending on which difference equation was used.

The first internationally endorsed color difference equation was the CIE 1976 equation. This color difference equation deemed a difference or DE of 1.0 to be the smallest difference perceivable by the human eye. The DE76 formula was revised in 1994 and 2000 to adjust the numerical expression of difference to the way human observers perceive differences depending on the location of the color in color space and its intensity. An independent approach was done in 1984 by the CMC (Color Measurement Committee of the Society of Dyers and Colorists of Great Britain), which resulted in the DE_{CMC} formula. This formula also takes the various different color sensitivities of the human visual system into consideration.

Now there are 4 color difference equations available. The fastest and easiest way to calculate color difference is the DE76 formula, but it has its drawbacks. Most widely used in the graphic arts field are probably the DE94 and/or DE_{CMC} formula.

Although DE2000 has been available for some time now not much evidence was found to suggest widespread use in industry.

Color standards and samples for this study were obtained through a color-managed press run. Overall 34 printed samples plus variations were printed. Volunteers were asked to rank the paired samples in the order of best match. All 17 volunteers had to undergo a color blindness test based on the Ishihara test charts. The obtained data was analyzed to correlate visual color difference with the various delta E equations mentioned above. Color management was used to create printed sample pairs that were equally distanced in color space.

*Ryerson University, School of Graphic Communications Management

This study wanted to evaluate which of the four main color difference equations correlate best with human color vision using test subjects with little or no experience in viewing color differences.

The main result of this study is, that the CIEDE 2000 and the DE_{CMC} formula relates quite well with the human perception of color differences in regards to Lightness, Chroma and Hue of the tested colors.

If a recommendation has to be given in regards to which equation should be used in everyday application the formula DE_{CMC} would be favored, followed very closely by the formula CIEDE 2000.

Introduction

Since the beginning of colorimetry researchers have attempted to express the visual difference with a numerical value. Various equations were developed and used, but it was not possible to compare these numbers, since these equations all calculated the difference in various ways and various color spaces were used as a basis (Luo, 2006).

In 1976 the CIE committee endorsed the CIE 1976 equation for color differencing. On this scale, a DE of 1.0 was deemed to be the smallest color difference perceivable by the human eye. It was soon discovered that the DE equation did not take into consideration that the human eye is more sensitive in some regions of the visible spectrum than in others. This means that a DE of 1.0 could be a small visible difference in one area of the visible spectrum (i.e. dark blue colors) and a large difference in another area (i.e. light pastel type colors). This arises due to the imperfections in the underlying CIE L*a*b* color model.
In 1976 the CIE introduced the L*a*b*- color notation with the intent to bring order to the various systems that were used (CIE, 1986). That year also saw the introduction of the DE_{ab} or DE 76 equation.

$$\Delta E_{ab} = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}}$$
$$\Delta L^{*} = L^{*}_{Batch} - L^{*}_{\text{Standard}}$$
$$\Delta a^{*} = a^{*}_{Batch} - a^{*}_{\text{Standard}}$$
$$\Delta b^{*} = b^{*}_{Batch} - b^{*}_{\text{Standard}}$$

This equation was soon established as the standard equation to express color differences and for the first time color scientists were able to exchange color difference data, since they were all speaking the same language. Criteria were established that classify the severity of numerical color differences (Heidelberg 1995).

Drawbacks of the DE_{ab} formula were soon discovered. For some colors the numerical difference was small, while there was a very visible difference, which would justify a larger color difference number.

In 1988 the Color Measurement Committee of the Society of Dyers and Colorists of Great Britain (Clarke, 1984) introduced the DE_{CMC} color differencing formula, which is based on the L*C*h*-color notation and contains weighting factors that change the size of allowable color difference and is thought to better model the way the human visual system perceives color differences. The DE_{CMC} formula was modeled to give the same visual difference in all regions of the color wheel with DE_{CMC}-value of 1.0. This was the first attempt to adjust a color difference formula to the actual perception of color differences.

$$dE_{CMC} = \sqrt{\left(\frac{dL^*}{lS_L}\right)^2 + \left(\frac{dC^*}{cS_C}\right)^2 + \left(\frac{dh^*}{S_h}\right)^2}$$

The S_L, S_C and S_h are the main weighting factors for lightness (S_L), chroma (S_C) and hue (S_H). The two other factors l and c are constant and are defined by the user and weight the importance of lightness and chroma relative to the hue of the measured color.

In 1994 the CIE introduced the DE_{94}-formula (CIE, 1995). This formula, like the DE_{CMC}-formula, contains weighting factors that adjust the size of the allowable color differences depending on the location of the color in color space. Although an improvement compared to the DE_{ab} formula, this formula had a weakness in the blue-violet region of the visible spectrum. This formula, like the DE_{CMC} formula, is also based on the L*C*h*-notation of color.

$$dE^*_{94} = \sqrt{\left(\frac{dL^*}{k_L S_L}\right)^2 + \left(\frac{dC^*}{k_C S_C}\right)^2 + \left(\frac{dh^*}{k_h S_h}\right)^2}$$

This equation has two sets of coefficients. The k-coefficients are also known as parametric factors and refer to effects influencing color-difference judgment. The s-coefficients account for CIELab's lack of visual uniformity (Billmeyer and Saltzman, 2000)

In 1995 the CIE introduced a color difference equation that is similar to the CMC equation and takes also into consideration the sensitivities of the human visual system. This equation also has its weak points, especially in the blue region, which lead to the introduction of the CIEDE2000 equation. CIEDE2000 takes also the varying sensitivity in regards to Lightness into consideration to determine the difference between two colors.

After extensive testing the CIE came up with a corrected version of the DE94-equation that contains a correction factor for the blue-violet region. This formula was published as the CIE DE2000 equation (CIE 2001). The formula looks as follows:

$$dE_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right) + \left(\frac{\Delta C'}{k_C S_C}\right) + \left(\frac{\Delta H'}{k_H S_H}\right) + R_T \left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)}$$

The observant reader notices that the equation does not use LCh anymore but L', C' and H'. This is a transformation of the LCh-color space. It was not the intention of this paper to go into the mathematical details on how the L*C*h* values are transformed into the L', C' and H' values. This has been done extensively at the Rochester Institute of Technology (Sharma, 2005). The DE2000 formula has five corrections to CIELab: A lightness weighting function ($k_L S_L$), a chroma weighting function ($k_C S_C$), a hue weighting function ($k_H S_H$) and an interactive term between chroma and hue differences for improving the performance for blue colors and a factor (R_T) for re-scaling the CIELAB a*-scale for improving performance for grey colors.

All these equations show the drawbacks of the L*a*b*-color space and introduce corrections to the non-uniform L*a*b*-color space. Attempts have been made in Germany to adapt the L*a*b*-color space by modifying each axis, so that the color difference formula from 1976 can be used and represents the true Euclidian difference between two points in color space (Buering, 2001).

It has to be mentioned that all DE equations are intended for small color differences and not for large DE values, like when comparing green and red for their numerical difference.

Experimental

Before the human test subjects could rank the existing color differences it was necessary to generate the test colors. This was done by generating 34 colors with 4 variations per color. These variations were made with a color difference DE_{ab} of 2, 5, 5.5 and 7. These DE-values were selected based on previously done research (Basemir, 1995). All colors samples were drawn in Adobe Photoshop CS2 using the L*a*b*-mode to enter the color information. The color patches were approximately 2 x 2 cm. The saved file contained no ICC-color profile information. This procedure was chosen so proper colors would be chosen that fell within the gamut of the printing device. This was more economical than running a printing press in this stage of the study.

An ICC-profile of an HP 5550 color laser printed was generated using an IT8.7/4 target, Monaco software and an X-Rite DTP70 measurement device. The profile was generated on the same paper stock that was used during the press run of the color patches.

After generating the ICC-profile for the proofing device this profile was applied to the test colors and proofs created. All L*a*b* values of the test patches were measured in five different spots with an X-Rite 530 instrument for each patch to minimize color variations that might occur within each patch. With the help of Chromix® ColorThink software it was verified that no colors were out of gamut. This can be seen in figure 1.

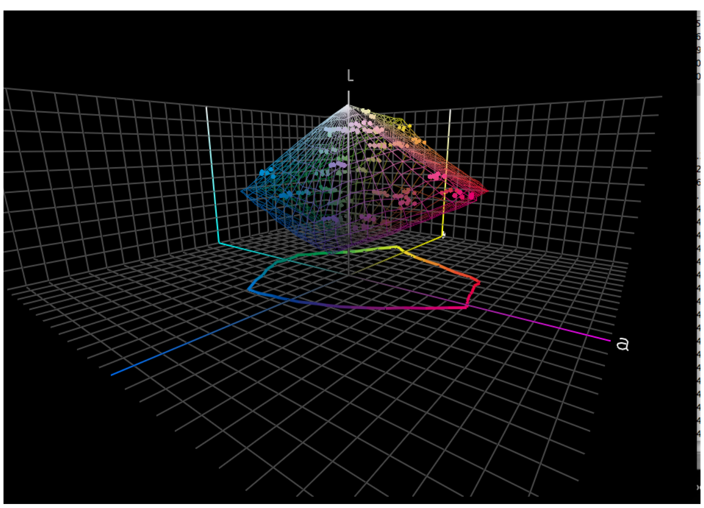

Figure 1 Proofer color space with test colors

The test colors are well distributed within the color space and cover also light and dark colors.

After the test colors had been established on the proofing device it was necessary to generate an ICC-profile for the four color offset press. An IT8.7/4 target was printed at the target densities for coated paper and an ICC-profile generated using an X-Rite DTP70 device and Monaco software. A comparison of the two profiles can be seen in figure 2.

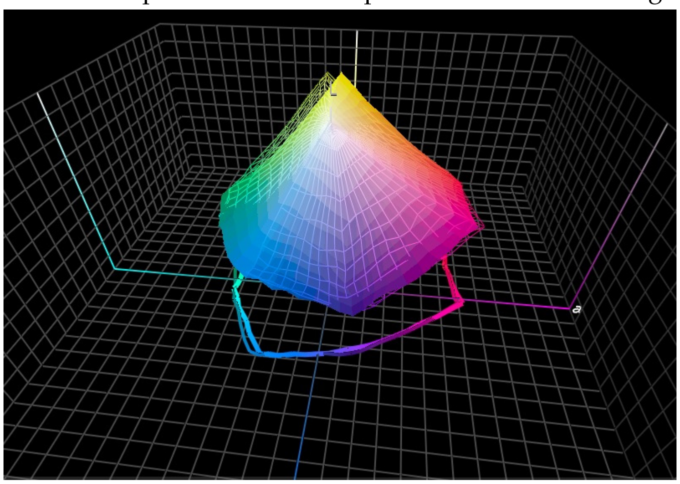

Figure 2 ICC-profile of the proofer (wire frame) and press (solid color)

Figure 2 clearly shows that ICC-profile of the proofing device and the press are quite similar. The largest deviation exists in the yellow region; otherwise the proofing device can reproduce a few more colors than the press. The difference between both devices is not very large; meaning the colors that will be used in this study did not need any modification since the colors are within the color space of each color reproduction device.

The following figure shows the distribution of the colors in the L*a*b*-color space to illustrate that saturated and also unsaturated color were used in this study.

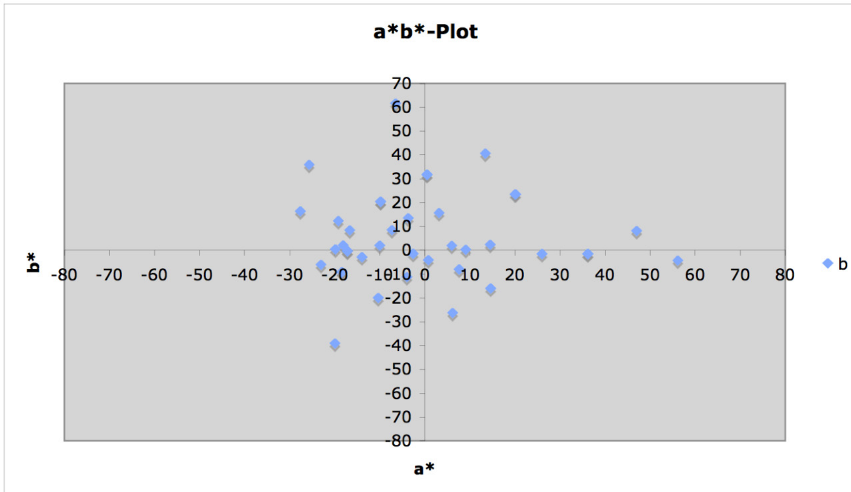

Figure 3 a*,b*-Plot of the colors used in this study

The viewing test took place in a GTI Color Viewing Station viewing booth. A GATF/RHEM indicator was used to ensure that the light source had a color temperature of 5000 K. The participants could arrange the color standard and the 4 variations for each color in any way or form and apply the rating scheme to them. Each participant was given the same rating scale:

- Match
- Slightly different
- Different
- More different
- Very different

These ratings were translated into numbers from 1 (Match) to 5 (Very different) and a ranking scheme was applied to weight the given responses. A typical ranking looked as shown in table 1:

	DE: 1.86	Ranking	DE: 5.85	Ranking	DE: 4.49	Ranking	DE: 8.27	Ranking
Match:	4	20	0	0	1	5	0	0
Slighly different	11	44	1	4	1	4	0	0
Different	2	6	5	15	8	24	2	6
More Different	0	0	5	10	3	6	4	8
Very Different	0	0	6	6	4	1	11	11
Total:		**70**		**35**		**40**		**25**

Table 1 Ratings and rankings of a color, DE_{ab}-values

These DE_{ab}-values were plotted against the total number and the r^2-value obtained. This was done for the DE-values from all four equations and all color samples used in this study. A typical plot of this can be seen in figure 4.

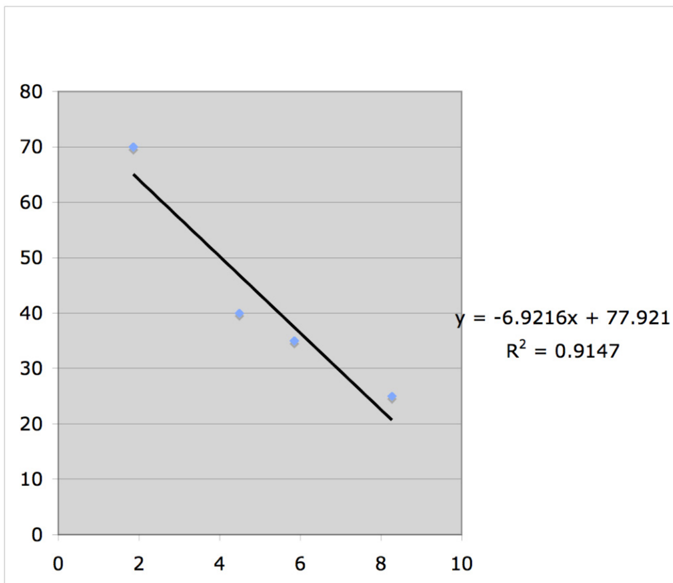

Figure 4 Example of a correlation between color difference DE_{ab} and rating

The r^2-values for this sample for the other equations were 0.96 for DE94, 0.94 for DE2000 and 0.96 for DE_{CMC}.

The r^2-values from all color samples and the various DE-equations were then plotted against the L, C and h values of all the colors evaluated in this study to see which color difference equation showed a linear correlation. From these graphs it was possible to conclude which color difference equation performs best within this study.

Results

Performance against Lightness

The first evaluation of the color difference equations was against the Lightness of the color samples. The graphs for all four difference equations can be seen in figure 5 – 8.

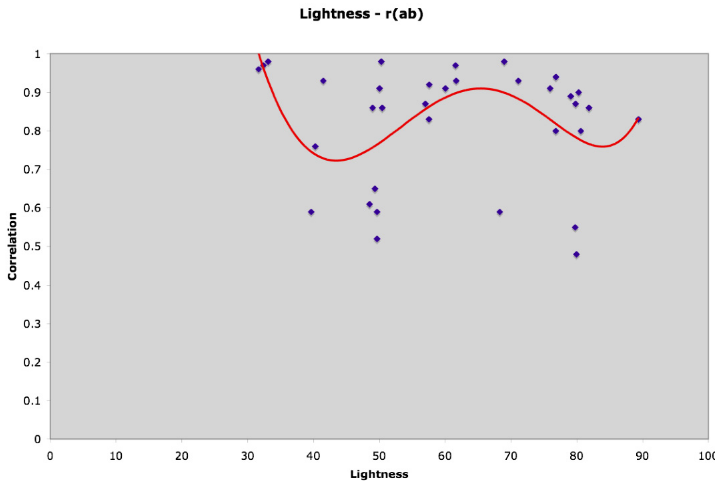

Figure 5 Performance of DE_{ab} vs. Lightness

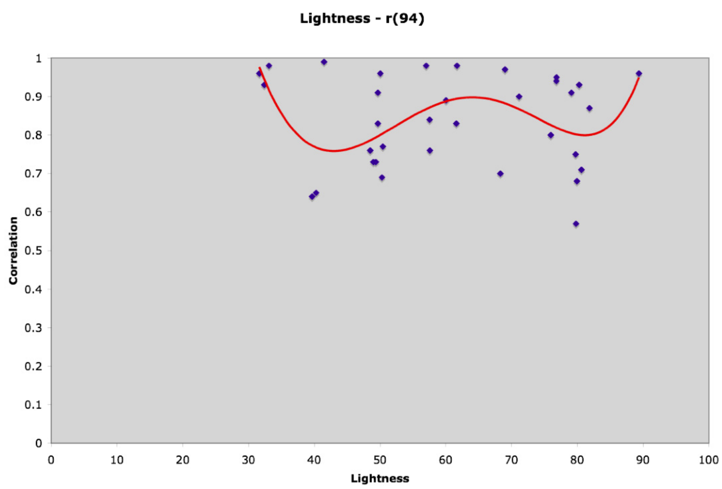

Figure 6 Performance DE94 vs. Lightness

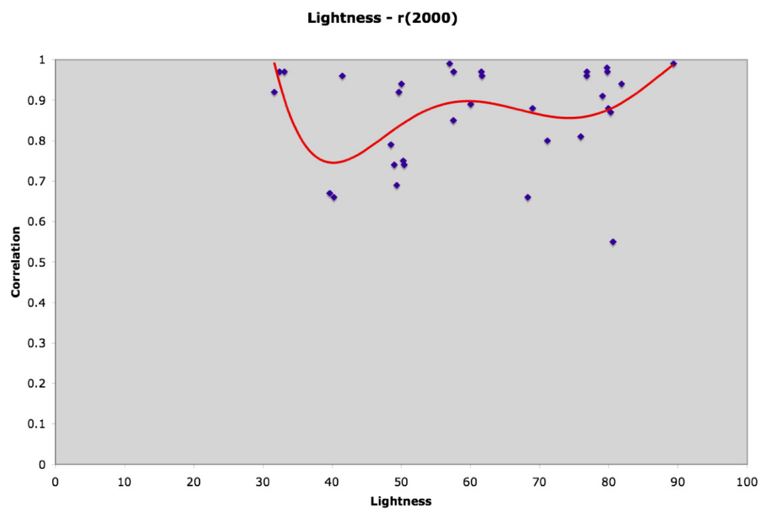

Figure 7 Performance DE2000 vs. Lightness

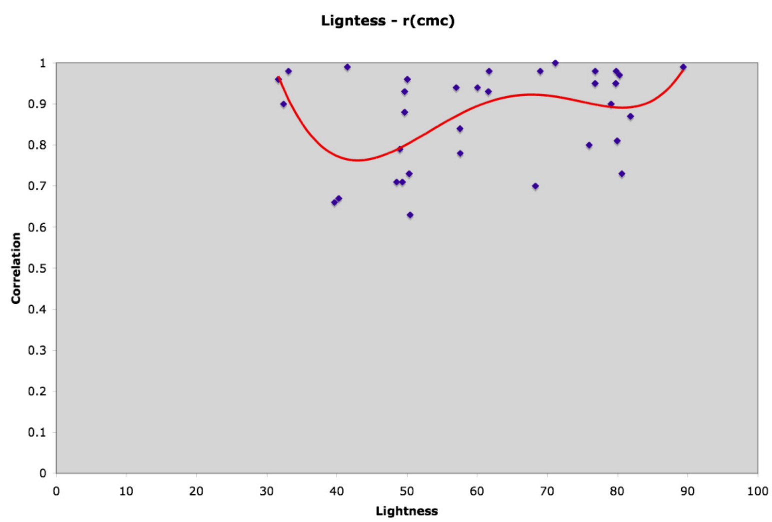

Figure 8 Performance DE_{CMC} vs. Lightness

These four figures demonstrate that DE200 and DE_{CMC} equations show similar behavior in regards to lightness. Both equations improve their correlation with increasing Lightness of the samples. This is important since small differences in lighter colors are more noticeable than the same difference among darker colors. The DE_{CMC} equation has a slight advantage over DE2000 showing more coherent data points and higher individual r^2-values at high lightness values.
The following table shows the average r^2-values for all four equations and the standard deviation of these values. The best r^2-values were with the DE2000 and the DE_{CMC}-equation

	r(ab)	r(94)	r(2000)	r(cmc)
Average r2-value	0.82	0.84	0.87	0.87
StdDev	0.15	0.12	0.12	0.12

Table 2 Average r2-values and standard deviation of all four color difference equations

Performance vs. Chroma

The second evaluation of the color difference equations was against the Chroma of the color samples. The graphs for this are shown in figure 9 - 12.

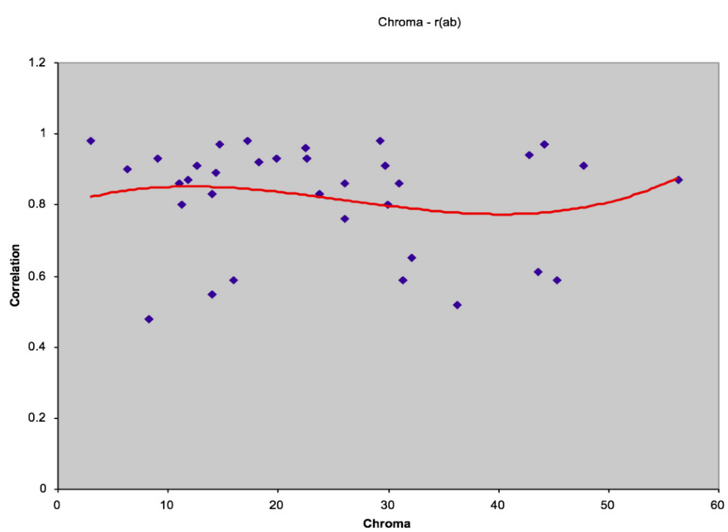

Figure 9 Performance DE_{ab} vs. Chroma

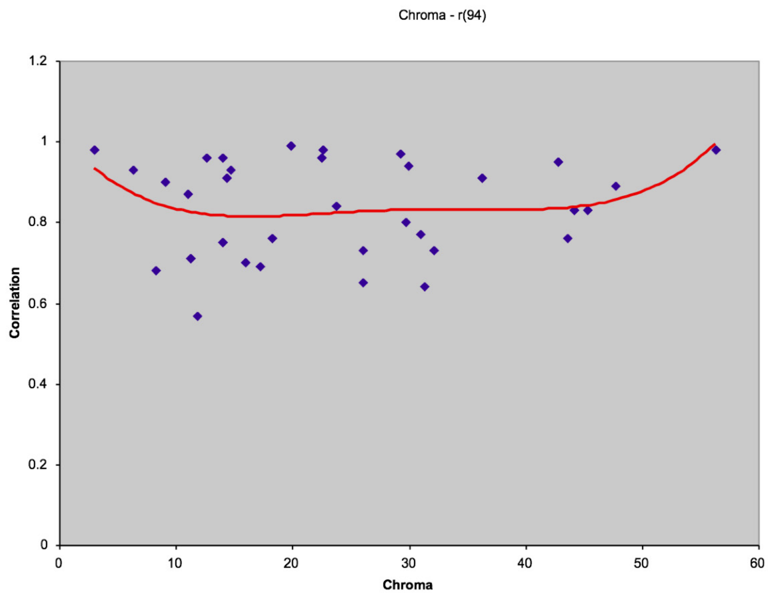

Figure 10 Performance DE94 vs. Chroma

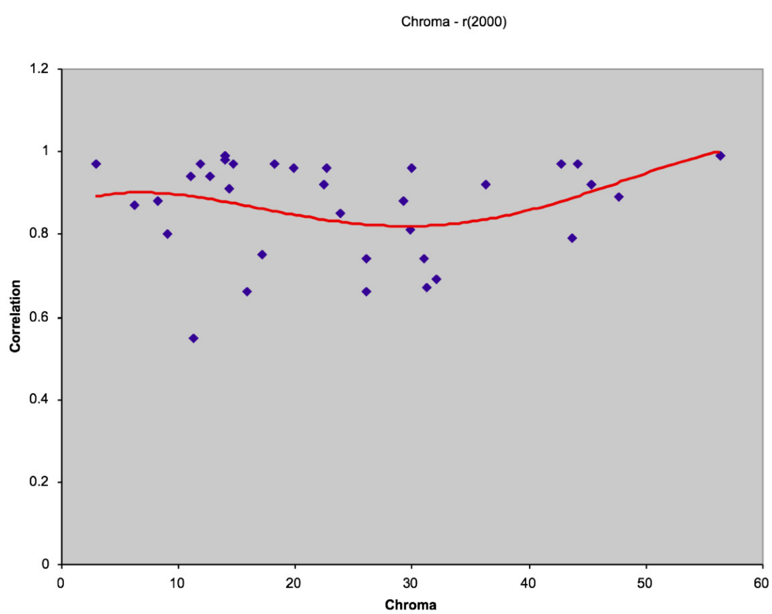

Figure 11 Performance DE2000 vs. Chroma

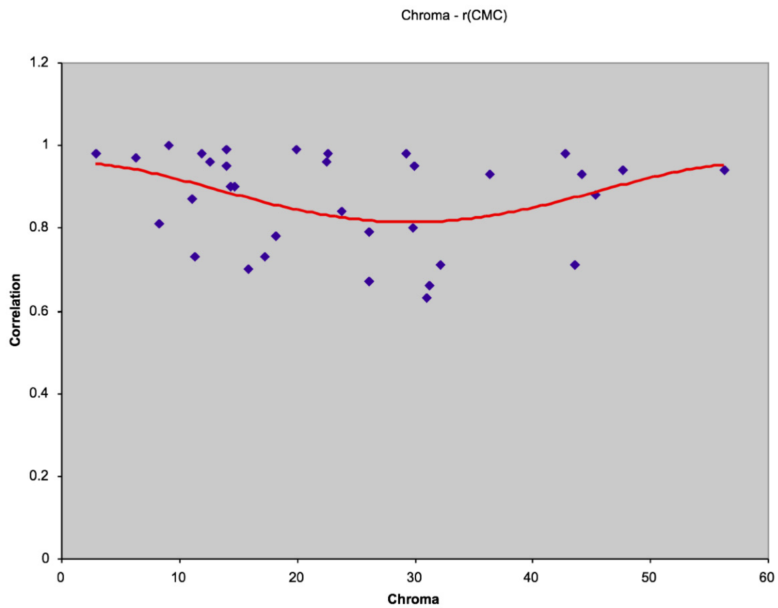

Figure 12 Performance DE_{CMC} vs. Chroma

From these figures it can be seen that DE2000 and DE_{CMC} show similar behavior throughout the chroma range of the tested samples. The DE_{CMC}-equation shows a more coherent correlation in the low chroma area. This is important since the human visual system is quite sensitive in regards to small changes in this area.

In the high chroma area (>40) the DE2000 equation shows a more coherent relation to the perceived differences then the DE_{CMC}-equation. Overall the DE2000 and the DE_{CMC}-equation show a very similar behavior with a slight advantage for the DE_{CMC}-equation, since the r^2-values are in a more coherent band compared to the DE2000-equation.

<u>Correlation vs. Hue Angle</u>

The third evaluation of the color difference equations was against the Hue Angle of the color samples. The graphs for this are shown in figure 13 – 16.

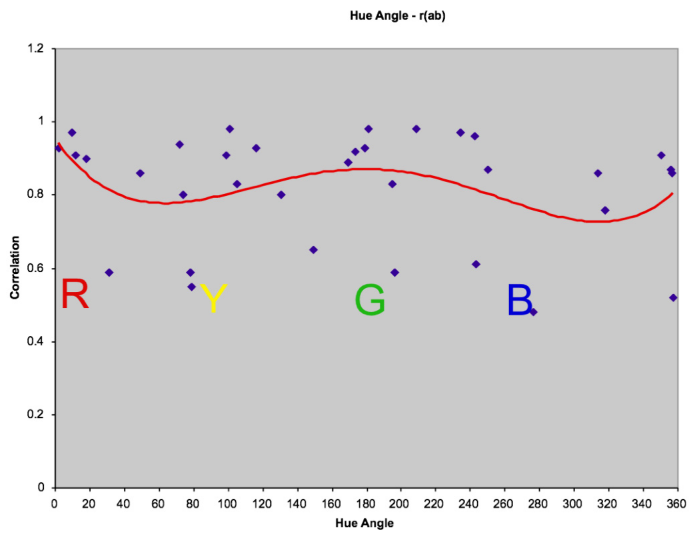

Figure 13 Performance DE_{ab} vs. Hue Angle

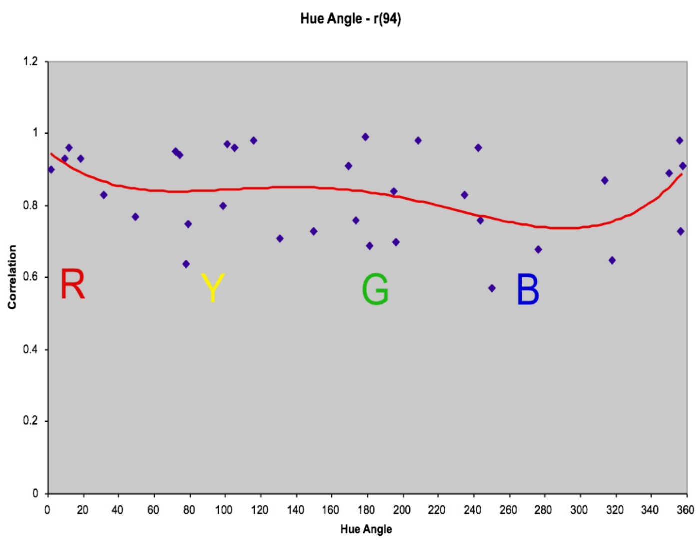

Figure 14 Performance DE94 vs. Hue Angle

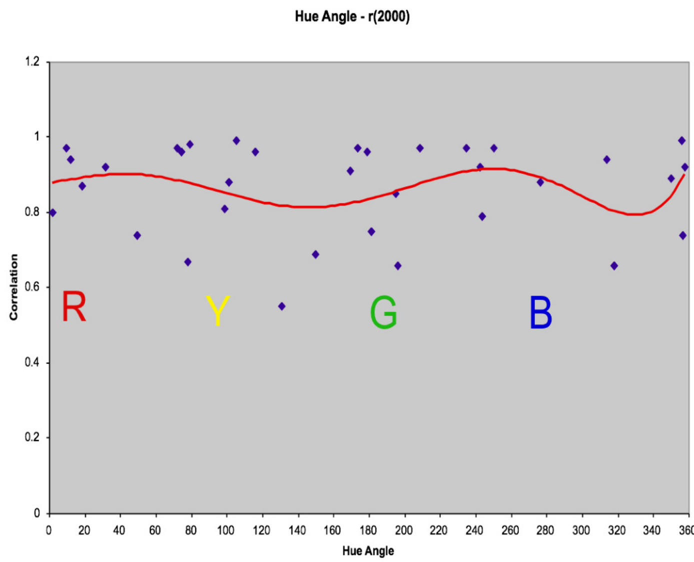

Figure 15 Performance DE 2000 vs. Hue Angle

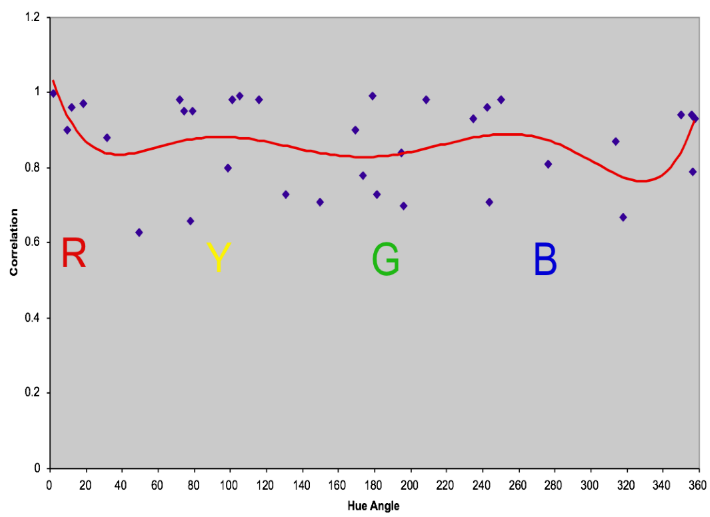

Figure 16 Performance DE_{CMC} vs. Hue Angle

From Figures 13 to 16 it can be seen that DE_{ab}, DE94 and show a negative trend towards the blue-violet region of the hue angle chart. The DE2000 and the DE_{CMC}-equation show a slight dip in the correlation on how the observers saw the visual differences versus the numerical expression of these differences in the blue/violet region. The curve for DE_{CMC} and DE2000 are quite similar over the complete hue angle chart.

It needs to be mentioned that the correlation values for the DE_{CMC}-equation lie in a narrower band in comparison to the DE2000- equation. Therefore the DECMC-equation has a slight advantage over the DE2000-equation in regards to the performance of all four equations for expressing differences in regards to the Hue Angle.

Relation to Images

In this research only solid colors and their variations have been evaluated. There has been no consideration on how surrounding colors might influence the perception of color differences. The following images have been modified the same way, but it is clearly visible how the surrounding colors and the type of images are influenced in different ways.

Figure 17 Light colored images with 5 sample points

This image has been slightly altered as it can be seen on the right hand picture. Five spots were chosen and their L*a*b*-values determined using the eyedropper tool in Photoshop with a 3 x 3 sampling average. The DE-values for the four different equations were obtained from Lindbloom's website (Lindbloom, 2007)

	Standard (left image)			Sample (right image)			DE_{ab}	DE94	DE2000	DE_{CMC}
	L*	a*	b*	L*	a*	b*				
1	86	6	5	84	9	1	5.39	4.86	4.95	7.98
2	73	3	-12	70	6	-13	4.35	3.87	4.16	3.79
3	79	17	58	76	21	48	11.18	5.27	5.71	6.10
4	96	-1	-2	95	0	-3	1.73	1.68	1.80	1.90
5	28	-17	14	25	-12	10	7.07	4.39	4.43	4.19

Table 3 L*a*b*-values from the above images and their respective DE-values in four different equations

It can be seen from this table that the DE-values are quite different from each other depending which color difference equation is being used. For example spot #3 (Orange fruit) shows a very large DE_{ab}, but a lower value in the DE2000 equation. In comparison spot#1 (curtain) has a large DE_{CMC}-value, which reflects the perceived visual difference. In this case for a lighter color the DE_{CMC}-equation shows more drastic the perceived difference, whereas the orange fruit has a large DE_{ab}-value and a lower DE2000 or DE_{CMC}-value which reflects that the difference seen is not as large as the original DE_{ab}-value suggests.

In order to understand how the surrounding colors influence our perception of difference the same exercise was repeated with a dark colored image.

Figure 18 Dark colored images with 5 sample points

	Standard (left image)			Sample (right image)			DE_{ab}	DE94	DE2000	DE_{CMC}
	L*	a*	b*	L*	a*	B*				
1	83	-1	25	81	1	18	7.54	4.12	4.34	4.28
2	38	-3	-6	36	3	-11	7.59	6.36	7.63	8.19
3	30	1	-30	28	6	-33	6.16	4.06	3.21	4.43
4	55	5	27	52	11	19	10.4	7.07	8.54	8.80
5	38	39	14	36	43	7	8.31	5.24	4.99	5.77

Table 4 L*a*b*-values from the above images and their respective DE-values in four different equations.

The same modification that has been applied to the light colored image (Figure 17) was also applied to the dark colored image. Overall the perceived general difference between the two dark pictures is not as obvious as it is with Figure 17. The only outstanding color differences are that of spot #1 and #4. The color differences in the curtain and the candle are easily picked-up by the observer. The color difference in spot #3 (blue wool) is not as large in the DE2000 or DE_{CMC} equation as suggested by the DE_{ab}-value. This shows that is important to use a color difference equation that correlates well with the way human observer perceive color differences. The DE2000 and DE_{CMC}-equation are doing this quite well as was shown in this study.

Due to the wide range of images it is important to know which color difference equation performs uniformly from light to dark colors and through the complete hue and chroma range.

A new color model CIECAM02 has been established (Moroney et al. 2005) which takes also into consideration the viewing conditions and surrounding colors and how they influence the perception of color. The CIECAM02 color space is a uniform color space but no color differencing formula exists yet for this color model.

Conclusions

This study has shown that it is quite important to know which of the four color difference equations has the most coherent and linear performance vs. lightness, chroma and hue of the evaluated color samples. The DE_{CMC} equation shows a slight advantage over the DE2000 equation in regards to lightness, chroma and hue due to having the correlation values (r^2) in a narrower band then the DE2000 equation.

From this study it can also be seen how important it is to specify which color difference equation was used to describe the difference between two colors. Quite often in literature it is only mentioned that DE-values were determined, but which equation was used is not always clear. One can only assume that if no indices following the letters DE were used that the DE_{ab}-equation was used to determine color differences.

It has been determined that the DE_{CMC} and the CIEDE2000 equation correlate quite well with the way the human observers perceived color difference. This report looked only at solid colors and made only comments in regards to pictorial imagery. For the evaluation of color differences of single colors on a printed product, such as corporate colors, it is quite useful to know that the DE_{CMC} and/or DE2000 equation will reflect numerically quite accurately how human color vision will experience color differences.

All these color difference equation do not take into consideration any influences of surrounding colors and other influences on how color differences are being perceived, since the color standard and its variations were viewed under the same lighting and surrounding color conditions.

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