Color scanner colorimetric design requirements

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ABSTRACT

Device independent color requires that all color imaging devices "speak" in CIE colorimetric terms. A color image scanner is one component of the desktop color imaging chain that needs to be colorimetric if color is to be device independent. Most commercial color scanners are not colorimetric. Instead, they are built as color densitometers, emulating commercial graphic arts scanners. There are a wide variety of spectral response options if the design goal is a colorimetric scanner. This paper explores "almost" color mixture spectral response options using Neugebauer's Colorimetric Quality Factor (CQF) as a design merit function. A set of empirical equations relating the average CIEL*a*b* color difference to the CQF under three CIE illuminants (A, F2 and D65) is developed, based on a database of over 1000 colors representing a wide variety of colorants and color imaging technologies. Our goal is to empirically bridge this gap between the CQF specification for each channel and the scanner's colorimetric performance, in terms of CIEL*a*b* color difference. For spectral response functions that have a high CQF, a "universal" transformation matrix is described for transforming "almost" colorimetric scanner RGB data to approximate CIE XYZ tristimulus data. Scanner peak wavelength and bandwidth requirements for colorimetric and densitometric applications are also reported.

1.0 INTRODUCTION

As each day passes we hear more and more hype about desktop color publishing. Today the simple process of scanning and printing a color image is fraught with great difficulty for the user without special skills. (Even for some of those users *with* special skills the process can be very frustrating.) What is the problem? Simply stated the typical desktop devices do not "speak" CIE colorimetry, so the process of scanning and printing is, at best, subject to a lot of "tweaking". One major component of the problem is the color desktop scanner, which is the focus of this paper.

For "device independent color" all of the elements of the color reproduction system must converse in a common languagethat of CIE colorimetry. For the scanner the requirements are three values that are either CIE XYZ tristimulus values for a specific CIE illuminant, or colorimetric RGB's (a linear transformation of XYZ). To satisfy this requirement the overall scanner spectral response functions must be linear transformations of the CIE color matching functions, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$. Progress in this area has been hampered because designers are trying to optimize a scanner designed around a color densitometer emulating high-end graphic arts scanners. Although the color densitometry approach produces workable results for the commercial printing process, it wreaks havoc with attempts to yield colorimetric data from scanned images. Assorted empirical approaches to derive colorimetric data from a non-colorimetric scanner have met with varying degrees of success[1,2] but optimum results require knowledge of the colorant set to be scanned. Metamerism is always lurking in the wings to foil any empirical scanner calibration scheme. In the case of the scanner, metamerism can manifest itself in two ways. In the first case the scanner outputs the same triplet of numbers for colors that are visually different. (This phenomenon has recently earned the moniker of a scanner "gamut" limitation.) The converse of the first case, which can be quite common when scanning colors composed of different colorant sets such as dyes in photographic paper versus dyes in some printers, is where two colors formed by different colorants match but the scanner outputs a different set of three values. Grays formed with three or more colorants are particularly troublesome in this regard, particularly if the colorants are unique.

Designing a scanner having spectral responses that are linear transformations of the CIE color mixture curves solves the metamerism problem, but the practical engineering questions is; “How close do the spectral responses have to be?” This is not a new problem. It was faced by the early filter colorimeter designers and color TV camera designers. Today there are more options available to scanner designer, because the available computing power on the desktop enables, and encourages, the use of RGB transformation matrices. But having more options requires additional scanner design tools to make optimum design trade-offs. In 1988[3] we suggested the idea of “almost” color mixture functions (CMF), where the “almost” was determined by Neugebauer’s[4] colorimetric quality factor. However, the CQF has been criticized on the basis that it only describes the “quality” of one spectral response of a set of three[5]. Additionally, there is no relationship between each of the three CQFs and the overall color reproduction. A few authors [6,7,8] have used the CQF metric in the analysis of color separation systems and scanner design, but no consensus has emerged regarding a suggested value of CQF. Neither is there a consensus on how the CQFs from the three spectral responses should be combined. Our goal is to empirically bridge this gap between the CQF specification for each channel and the scanner’s colorimetric performance, in terms of CIEL*a*b* color difference.

2. THEORY

A highly schematic optical path diagram of a color scanner is illustrated in Figure 1. Five wavelength-dependant optical components contribute to the spectral response of each of the three channels:

- the scanner light source with spectral power distribution $E_s(\lambda)$;
- the standard illuminant with spectral power distribution $E_r(\lambda)$;
- colored surface with spectral reflectance factor $\rho(\lambda)$;
- spectral transmittance of the optical elements, including any filters $F_i(\lambda)$, i=1,2,3, and;
- photodetector spectral responsivity $R(\lambda)$.

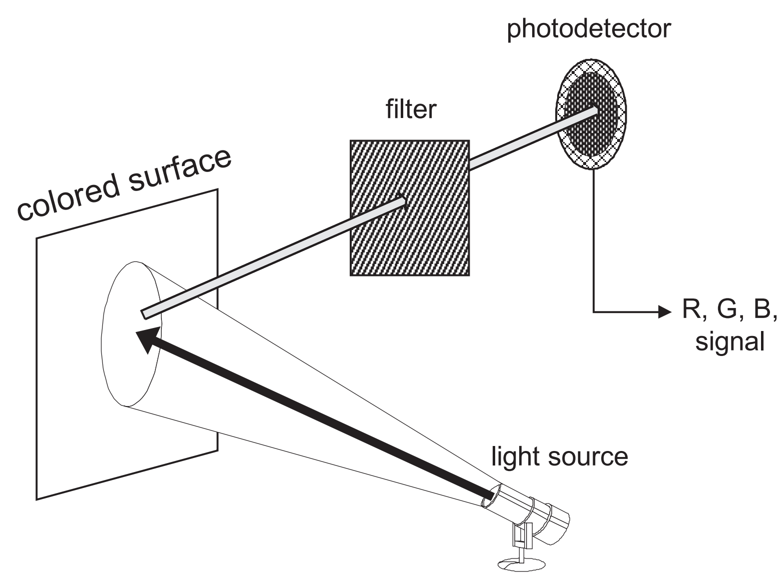

Figure 1 Schematic of the optical path of a color scanner.

The design task is to determine and adjust the spectral transmittance of the optical elements, usually the filter, to achieve a color mixture curve, $S_i(\lambda)$, defined by Equation (1).

$$S_i(\lambda) = \frac{R(\lambda)\, F_i(\lambda)\, E_s(\lambda)}{E_r(\lambda)} \qquad (1)$$

2.1 Colorimetric Quality Factor

Numerous possibilities for the design targets of $S_i(\lambda)$ are possible. Several authors(9,10,11) suggest CMFs that are all positive and have various bandwidths. Another possibility is to use the algorithm in reference (3) to generate other, "almost", CMFs that have a high CQF.

Neugebauer(4), in 1956, provided a criterion which he called the "quality factor". Later, Gosling and Yule(6) extended the method and named the factor the "colorimetric quality factor" or CQF. The CQF has the property that it is 1.0 if any spectral response curve of one of the three channels is a CMF. As the spectral response curve departs from a color mixture curve, the CQF decreases to zero.

Neugebauer's technique is to expand the spectral response curve in terms of three orthonormal color mixture curves, originally proposed by MacAdam(12). The CQF for the i^{th} channel is defined as follows:

$$CQF_i = \frac{\left[\sum_{over\,\lambda} S_i(\lambda)C_1(\lambda)\right]^2 + \left[\sum_{over\,\lambda} S_i(\lambda)C_2(\lambda)\right]^2 + \left[\sum_{over\,\lambda} S_i(\lambda)C_3(\lambda)\right]^2}{\sum_{over\,\lambda} S_i^{\,2}(\lambda)} \quad (2)$$

where one such orthonormal set(13) of color mixture functions is:

$$\begin{aligned} C_1(\lambda) &= 0.4070\,\bar{x}(\lambda) + 0.5525\,\bar{y}(\lambda) \\ C_2(\lambda) &= 0.4050\,\bar{x}(\lambda) - 0.0420\,\bar{y}(\lambda) \\ C_3(\lambda) &= 0.1787\,\bar{x}(\lambda) + 0.1001\,\bar{y}(\lambda) + 0.2811\,\bar{z}(\lambda) \end{aligned} \quad (3)$$

with $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ the CIE color matching functions for the 1931, 2^o standard observer, and, $S_i(\lambda)$ = the spectral response curve without the scanner or viewing illuminant defined by Equation (1). The three quantities inside the brackets in Equation(2) are the coefficients in the orthonormal expansion of each spectral response function. This approach is exactly analogous to Fourier analysis of spatial signals where the orthonormal set of functions are sines and cosines. The set of functions, $C_i(\lambda)$, have the following properties, Equation (4) which are the definitions of orthonormal:

$$\begin{aligned} &\sum C_i(\lambda)C_j(\lambda) = 0 \text{ for all } i \neq j \\ &\sum_{over\,\lambda} [Ci(\lambda)]^2 = 1 \end{aligned} \quad (4)$$

The summations in Equation(2), $\Sigma S_i(\lambda)C_j(\lambda)$, yield coefficients, a_j, j = 1,2,3, that minimize the mean-square difference between the response curve and its representation by the linear combination of the orthonormal CMFs.

The CQF, in essence, is the fraction of the total mean-square-error that is accounted for by the first three terms of the orthonormal expansion of the spectral response of each color analysis channel. It is often useful to think of it as the square of the more familiar correlation coefficient.

In practice, a color scanner may use a light source that is not necessarily the source for which the tristimulus values are desired. The requirement, from Equation(1), is that the overall spectral response be equivalent to the spectral response for the selected CIE illuminant. In principle this is correct but fluorescent colorants can foil this method. A robust approach would suggest a light source with approximately the desired spectral power distribution. Fluorescent lamps with their line spectral superimposed on the phosphor spectrum, would require expensive "notch" optical filters to attenuate the line spectra output.

2.3 Transformation Matrix

In most practical cases, for reasons of simplicity, the design target spectral responses will not be the CIE $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ CMFs. Rather, they will be a set of "almost" CMF's. If the CQF is exactly 1.0, then the actual design curves are CMFs, and the transformation matrix from the scanner RGBs and CIE XYZ tristimulus values can be determined by straightforward primary transformation techniques. However, if the CQFs of any of the three channels is not 1.00, then the best one can hope for is a 3x3 matrix transformation in a least-squares sense. Schanda and Lux[14] provided a method that, only incidentally, capitalizes on computations performed to compute the CQF according to Equation(2). The first step is to compute the orthonormal CMF's, which we can write in matrix notation as:

$$\begin{bmatrix} C_1(\lambda) \\ C_2(\lambda) \\ C_3(\lambda) \end{bmatrix} = [O] \begin{bmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{bmatrix} \qquad (5)$$

Next we form a matrix of the coefficients (orthonormal functions weights) that were used to calculate the CQFs for each channel. This 3x3 matrix, [A], has as the first row the three coefficients for the red channel, the next row the coefficients for the green channel and the third row the blue channel coefficients, all calculated according to the numerator of Equation(2). For the $r(\lambda)$, $g(\lambda)$, and $b(\lambda)$ spectral responses we have,

$$\begin{bmatrix} r(\lambda) \\ b(\lambda) \\ g(\lambda) \end{bmatrix} = [A][O] \begin{bmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{bmatrix} = [B] \begin{bmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{bmatrix} \qquad (6)$$

Inverting [B], the 3x3 matrix in equation(6), yields the least squares transformation from RGB to XYZ. (Recall that $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are also tristimulus values for the spectral colors; spectral tristimulus values.)

$$\begin{bmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{bmatrix} = [B]^{-1} \begin{bmatrix} r(\lambda) \\ g(\lambda) \\ b(\lambda) \end{bmatrix} \qquad (7)$$

3.0 SIMULATION EXPERIMENT

A computer simulation was performed for the express purpose of generating data to determine if a useful relationship could be established between the individual channel CQFs and the scanner colorimetric performance characterized by a CIEL*a*b* color difference. The experiment consisted of computing the CIE XYZ tristimulus values of a hypothetical scanner with a set of $r(\lambda)$, $g(\lambda)$, $b(\lambda)$ spectral response functions and its least-squares transformation matrix, and comparing these values to the actual XYZ tristimulus values for a selected CIE standard illuminant.

3.1 Spectral Response Functions

The critical component of the simulation are the three relative spectral response functions (SRF) comprising a "filter" set. One choice is to model these SRFs with mathematical functions. In the interest of robustness, realistic spectral response functions, all positive, were drawn from a wide variety of sources that have been used to define such functions. These included, traditional color separation filters, color photographic film spectral sensitivity curves, measured spectral responses from a graphic arts scanner, and synthetic "almost" color mixture curves[3]. These were mixed and matched to form 17 arbitrary sets of rgb spectral response functions. The guiding matching criterion was that the individual CQFs of the set be close. No scanner designer would choose markedly different CQFs by choice.

3.2 Simulation

Once the sets of SRFs were established, the CQF and the normalized transformation matrix was computed for each set according to Equations(7) and (2). This makes the CQFs constant, independent of the scanner light source and viewing illuminant. The transformation matrix is scaled for each of the three illuminants used in the simulation, CIE illuminant A (tungsten lamp), F2 (cool-white florescent) and D65 (daylight). Scanner and viewing illuminants are assumed to be the same for the simulation.

The basic process was as follows:

- Select a color, from a database of 1265 colors. (The robustness of the results hinges on the number of different colorant sets represented by the colors. For this study measured samples from ink jet, wax thermal, dye thermal, electrophotographic, and commercial printing technologies were used.)
- Using the color's spectral reflectance curve (10nm data) compute the scanner integrated RGB, Equation(1), responses for each of the 17 SRF's, and the selected CIE illuminant. From the same spectral data compute the CIE XYZ tristimulus values using ASTM E 308-85 weights.
- Transform the scanner RGBs, through the respective matrix, to X'Y'Z'.
- Convert both sets of XYZs to CIE L*a*b* and compute the color difference.

This process resulted in a total of 64515 evaluations; 1265(colors) x 3(illuminants) x 17(spectral response function sets).

4.0 SIMULATION RESULTS

For each illuminant there were 17 sets of data comprising RGB channel CQF and the average color difference. The simplest formulation was to take the average of the RGB CQFs and fit a function of the form:

$$\Delta E = a1[\,1 - \overline{\mathrm{CQF}}\,]^{\,p} \qquad (8)$$

The results are shown in Figure 2, and the function parameters for the three illuminants are listed in Table 1.

Best performance, in terms of the smallest ΔE, is obtained with illuminant F2, then D65 and finally A. The specific reason for this is unknown, but it may be related to the slope in the illuminant spectral power distribution across the visible spectrum. A few of the more widely scattered data points in Figure 1 are associated with SRFs that are not smooth; e.g. those from optical elements that have multilayer coatings. The implication of these results is that smooth SRFs are in order.

CIE Illuminant	Parameter Values		Standard Error of the Estimate
	a_1	p	
D65	23.94	0.505	1.24
F2	24.83	0.624	1.17
A	41.24	0.595	2.72

Table 1. Parameter values for Equation (8) which is shown as the solid line in Figure (2).

The ratio of the standard deviation of the CIEl*a*b* color differences to the average color difference, ΔE, typically was less than one. Beyond this calculation, the details of the color difference was not explored.

It was discovered that the 17 normalized RGB to XYZ transformation matrices were remarkably similar for SRF sets that have an average CQF ≥ 0.8. Table 2 shows the average matrix coefficients, and the coefficient standard deviations. For some of the matrix elements the standard deviation is greater than the mean value. This just means that the coefficient can become negative. The existence of the average matrix should not be a surprise. High CQFs imply a limited variation in the SRF characteristics for each of the RGB channels, thus a reasonably constant transform matrix.

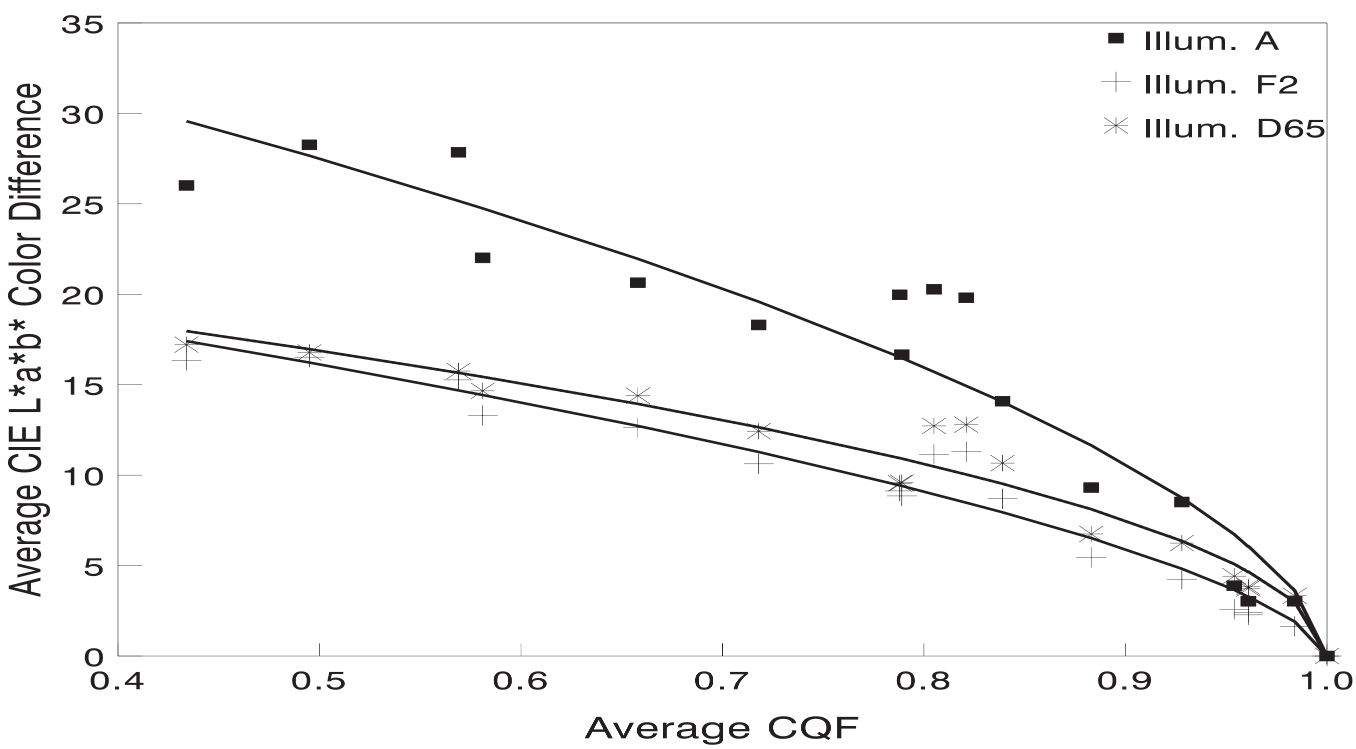

Figure 2 Average CIEL*a*b* color difference versus average CQF for three CIE illuminants; A, F2 and D65.

Average Normalized Transformation Matrix RGB to XYZ			Transformation Matrix Coefficient Standard Deviations		
0.621	0.218	0.161	0.0235	0.0285	0.0103
0.322	0.671	0.014	0.0709	0.0688	0.0322
0.0043	0.0133	0.982	0.0212	0.0531	0.0485

Table 2. Values of the average RGB to XYZ transformation matrix for CQF≥ 0.8 in the left three columns. The right three columns list the standard deviation of the coefficients.

5.0 DISCUSSION

One factor that the CQF does not address is the selection of the wavelength of peak spectral response. It is entirely possible to choose three very high CQF spectral response functions that will have poor colorimetric performance. The primary reason is peak wavelength selection. In a previous work[3] it was suggest that the wavelength peaks occur at, or very near, 450nm for "blue", 540nm for "green", and 605nm for "red". This study does not alter these conclusions.

Given that most desktop color scanners are designed along the lines of color densitometers, it is interesting to compare the colorimetric requirements to the densitometric requirements. First the color densitometer should have a wavelength bandpass that is as narrow as possible so that the underlying assumptions regarding "color correction" are valid. Practical compromises are needed so a sufficient amount of power can get to the photodetector for adequate signal-to-noise ratio (SNR). These usually take the form of a wide spectral bandwidth, which causes the assumptions upon which the traditional color corrections are based to fail. A colorimetric scanner, on the other hand, demands spectral bandwidths on the order of 150nm, and with these wide bandwidths adequate SNR should not be an issue.

The second major consideration is the wavelength of peak response. Densitometry dictates that it should be placed at the maximum absorption of the colorant. For photographic dyes the average of the peak absorptions are at 445nm for the yellow dye, 540nm for the magenta dye, and 660nm for the cyan dye. Comparison of these wavelengths and the wavelengths of peak response for the colorimetric scanner reveal that the only discrepancy is the "red" channel; densitometry says the peak should be at 660nm and colorimetry should be at 605nm. A small change in the red scanner channel peak response could lead to significant improvements in desktop scanners.

6.0 CONCLUSIONS

The average of the CQFs of the three scanner channels, RGB, along with the empirically derived curves reported here can be used as a design tool for color scanners. The empirical equations predict the average CIEL*a*b* color difference with a standard error of 1.24 to 2.72, depending on the illuminant.

CQF requirements depend on the CIE illuminant for which the scanner is designed. Generally, for CIEL*a*b* color differences <5, the average CQF of the three channels should be 0.95 or greater.

For CQFs ≥ 0.8, an approximately constant least-squares RGB-to-XYZ 3x3 transformation exists that may have wide applicability. However, it is not a substitute for the specific (possibly least-squares) transformation matrix for any given scanner, but could be useful when no other specific spectral response information is available.

The colorimetric performance of scanners designed as color densitometers can probably be improved by shifting the red filter response to have its peak at 605nm instead of the customary longer wavelength.

Desktop color scanning will only become device independent when these scanners become true colorimetric devices. Until then the user will struggle with inadequate solutions which will not contribute to the growth of the business.

7.0 ACKNOWLEDGEMENTS

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