COLOR MEASUREMENT IN GRAPHIC REPRODUCTION—
Toward Epoch 2000*

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ABSTRACT

As graphic reproduction technology becomes more objective, and progresses from "craft" to engineering discipline, the need for objective measurement also grows. This paper investigates some of the possibilities for the measurement of color in graphics as we approach the year 2000.

The paper discusses instrumentation and its application in our industry — both in the laboratory and on the production line. Some light will be shed on the question of "Wideband versus Narrowband," as well as how to use colorimetric data in a context heretofore reserved for densitometry. The advantages of spectrophotometry are also discussed. The paper also discusses a laboratory application of spectrophotometry. Spectrophotometry is used to assess the precision of several models used to compute photometric halftone dot area. The Yule-Nielsen model was sufficiently precise, while the other models experimentally tested were not.

INTRODUCTION

Because color is playing an ever-increasing role in the graphic reproduction industry, it is becoming more and more important to effectively specify, measure, and understand color. The following systems are used for color specification and measurement. With the exception of densitometry, however, they have not enjoyed widespread use in graphics. However, colorimetry and spectrophotometry are what the future holds for us, so we will take a close look at these systems, as well as the more familiar densitometry.

Color as a Physical Phenomenon

A collimated beam of light may be passed through a prism, and we may observe the spectrum of the light. This spectrum may be passed through yet another prism, and the original composition may be obtained. This "analysis and synthesis" of light into and from spectral colors suggests a means of measuring color.

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If a red light were used in the experiment above, the spectrum would reveal mostly red light upon analysis, with small proportions of violet, blue, cyan, green, yellow, and orange.

We could tabulate the amount of light an object reflects in each of these spectral bands, and get some quantitative handle of an object's color. This is essentially what is done in spectrophotometry, which will be discussed below.

Most of the processes in printing operate in a non-linear manner. This means that the color produced by these processes must be assessed on a wavelength-by-wavelength basis, rather than whole bands at a time. In addition, in applications like colorant formulation, two objects which appear to have the same color to human observers (under one illuminant), but have different spectra, are regarded as having different colors. Thus, it is important in some applications to consider color in this context.

Color as a Visual Sensation

In the preponderence of situations, we are ultimately interested in how a colored object will appear. Thus, our primary interest will be color as it appears to a human observer, although other considerations will be important in our industry.

Hering argued that, just as black is the opposite of white, so do saturated colors come in opposite pairs. As human observers, we tend to see green as the opposite of red, yellow as the opposite of violet, blue as the opposite of orange, etc. This is the Opponent Colors model of color vision. It postulates three bipolar axes in color space; the first axis with white at one end, and black at the other; the other axes pit red against green and yellow against blue. All other colors are considered combinations of these three sensations. [1]

Conversely, Young and Helmholtz proposed a different model of color vision. They postulated three distinct sensations, but each sensation corresponded to roughly one-third of the visible spectrum. These distinct sensations correspond roughly to the amount of red, green, and blue light reaching the eye. [2]

This paper will consider both models of color vision, as well as color as a physical phenomenon.

DENSITOMETRY

The densitometer was first suggested by Hurter and Driffield, [3] who maintained that photographic processes could be made more objective by plotting the logarithm of opacity (now called the "density") of a reproduction as a function of the logarithm of the luminance of the original scene (again, essentially density). This plot, called an "H & D Curve," is still used extensively in photography. In printing, this curve is used to show tone reproduction; in it is plotted the density of the reproduction as a function of the density of the original.

Density Defined: Density is defined as the negative of the common logarithm of the fraction of light an object reflects:

$$D = -\log(R) \qquad (1)$$

The density of a colored object will depend upon the color of the object and the spectral sensitivity of the densitometer. Different color filters will yield different densities in much the same way as a processworker uses a filter to "hold" or "drop" a particular color. Thus, a blue object would have a low density if evaluated with a blue filter, but would exhibit a high density if evaluated through a red filter.

In this rudimentry way, densitometers can be used to "measure" color. For instance, an object with high blue and green filter densities, but with a low red filter density, would be expected to appear red. Similarly, we would expect objects with equal red, green, and blue components of density to appear neutral.

However, problems arise when using densitometers to measure color. These problems will be discussed below. It should be kept in mind that the densitometer is not intended to measure color as seen by human observers.

Densitometers in Graphic Reproduction: Because graphic reproduction densitometers were first used in the darkroom, their spectral sensitivities were intended to emulate the response of film. This enabled processworkers to determine the exposure through each color separation filter. These densities are called "Actinic Densities," because they predict photographic responses. [4, p 21]

It was eventually discovered that densitometers could be used to evaluate press sheets. While the densitometer is a fine device for evaluating the strength of ink films (sometimes erroneously referred to as "ink film thickness" measurements), [4, p 25] particularly for blacks (and colored inks, when using narrow-band filters), it does not measure color as seen by human observers.

In order for the densitometer to measure color as seen, it is necessary to have the spectral sensitivities are linearly related to those of the eye.

Wideband Versus Narrowband: Currently, there is a rift in the graphic reproduction industry concerning the bandwidth which is best for densitometers. Traditionally, densitometers measured density through three color separation filters; each component had a bandwidth of roughly 70 nanometers (about one-fourth of the visible spectrum). However, some of the instruments manufactured in the last decade are equipped with narrowband filters. The bandwidth of each gap is approximately 70 nanometers, roughly one-fourth the entire visible spectrum. This leaves too much of the spectrum unsampled, so SPI densitometry cannot be expected to permit measurement of masking requirements.

As a visual sensation, color is a wideband phenomenon. Thus, grayness, masking requirements, etc., are best determined by measurements made through wideband instruments. On the other hand, trapping, dot gain, and other related parameters, are narrowband in nature. Table 1, below, contains a summary of the classification of these phenomena.

This would seem to create a problem — are two different types of densitometers actually needed to obtain optimum results? Such would surely seem to be the case, judging by Table 1. However, we shall see below how to make one instrument do the work of two (or more), and have the best of all worlds.

TABLE 1.
Wideband and Narrowband Phenomena

WIDEBAND	NARROWBAND
Hue	Dot Area
Grayness	Trapping
Color Correction	Ink Strength
Transparency Evaluation	Ink Film Thickness

Color Correction Requirements: Wideband densitometry has proven convenient in determining the color correction requirements for a given set of printing conditions. The spectral products needed for these evaluations depend upon the spectral products of the color separating system, and the spectral power distribution of the source under which original and print are compared. If we assume that the spectral products of the color separating system match those of the Status T densitometer, and we view the prints by the same light used to expose the separations, the required spectral product will be very close to that of the densitometer, except it will contain some negative portions. If these negative portions are small enough, and other departures are likewise small, the densitometer may be used to determine these requirements.

Summary: The densitometer is widely used in the graphic reproduction industry, is inexpensive, but is not visually referenced. Thus, small differences in density can represent large differences in perceived color, and vice-versa. In addition, it seems that two different types are needed — narrowband, for evaluating ink strength, trap, and dot area; and wideband, for evaluating Hue, Grayness, color correction requirements, and press sheets.

COLORIMETRY

Colorimetry is the process of measuring color as a visual sensation, and thus draws heavily from the expected spectral sensitivities of human vision. It also differs from densitometry in that what are essentially reflectances, rather than their logarithms, are reported. This is a subtle difference, because it is easy to convert reflectance into densities, and vice-versa.

The spectral products of the colorimeter are believed to enjoy a linear relationship with the spectral sensitivities of human vision. While the two do not match, even in principle, it is believed that a simple transformation exists between the two. This is the necessary and sufficient condition color matching functions must fulfill. [5]

What a Colorimeter Measures: It may be convenient to think of a colorimeter as a reflectance meter (a densitometer without the logarithmic amplifier) with a very special set of filters. Indeed, this is one way colorimetry may be accomplished. These filters are selected so that each channel of the colorimeter will weight each wavelength in the spectrum according to the CIE Spectral Tristimulus Values.

Helmholtz and Young's trichromatic theory of color vision postulates a set of three coordinates for each sensation of color — one giving the amount of red, another the amount of green, and the third the amount of blue. Because the amount of light reaching the retina depends upon the amount of light available, these three coordinates (the Tristimulus Values X, Y, and Z) will be the reflectances weighted according to this scheme, multiplied by the corresponding tristimulus values of the illuminant, which are usually normalized so that the Y tristimulus value of the illuminant is 100.

What the Tristimulus Values Mean: The tristimulus value Y is weighted according to the visual sensation of brightness (according to the average of approximately 200 observers). The X tristimulus value is indicative of the amount of red, while the Z tristimulus value is indicative of the amount of blue. While it may be satisfactory to think of color in these terms, there are other, more elegant ways to interpret the tristimulus values.

Because they are primarily concerned with additive mixtures of light, television engineers will explain that the tristimulus values are analogous to the red, green, and blue phosphors of a color television screen. Just as any color (within the gamut of the screen) may be produced by selecting the correct combination of intensities for the red, green, and blue phosphors, any color possible may be produced by the proper combination of these three stimulii. Unfortunately, these three stimulii are imaginary, because they would have to be more saturated than spectral colors.

In addition to not having intuitive meaning, beyond that of so much redness and blueness, the tristimulus values X and Z (as well as the luminosity, Y) do not appear to be uniformly spaced. A difference of 5 units in bright areas appears much smaller than the same 5 unit difference in the darker areas. Recall that the tristimulus values are proportional to reflectances, and reflectances do not appear uniformly spaced, even for neutrals. For this reason, transformations on the tristimulus values have been developed. Probably the most popular of these were suggested by Adams [6] and refined by others.

Uniform Lightness Scales: Because reflectances are not uniformly spaced to the eye, the Y tristimulus value is transformed to provide a relatively uniform visual scale, called lightness. One of the first uniform lightness scale was the original Munsell Value scale, which would map lightness onto the square root of Y. [7] This was refined in 1943, and a fifth-degree polynomial in lightness provides the inverse of the desired transformation, rather than lightness as a function of Y. [8]

The Cube-Root lightness scale was suggested by Ladd and Pinney, [9] and refined by Glasser, McKinney, Reilley, and Schnelle. [10] In its present incarnation, we have:

$$L^* = 116 \sqrt[3]{Y/Y_0} - 16 \qquad (2)$$

where L^* is lightness; and
Y_0 is the Y tristimulus value of the illuminant (usually 100).

Lightness may form one coordinate of a visually uniform color space. Two additional visually uniform coordinates are needed.

The CIELAB Color Space: Adams considered the fact that reflectances do not form uniform visual scales, so he suggested performing the same transformation on the X and Z tristimulus values as may be done for Y to obtain Munsell Value. These transformed tristimulus values may be denoted Vx, Vy, and Vz. Then, to conform with Hering's Opponent Color model, Adams suggested that Vy be subtracted from Vx to yield a coordinate comparing red and green. Similarly, Vy may be subtracted from Vz to obtain a coordinate comparing yellow and blue. The third coordinate, which contrasts white and black, is simply Vy, which is brightness. This is referred to as Adam's Chromatic Value space. [6]

After undergoing a series of modifications, primarily with the relative scales of the coordinate axes and with the cube-root approximation to the Munsell Value function, the CIE adopted the 1976 L*a*b* Color Space, which is abbreviated as "CIELAB." The first coordinate, L*, is approximately 10 times the Munsell Value, so an L* of zero is a perfect black, while an L* of 100 is an absolute white. The a* coordinate is the red-green axis, while b* represents the yellow-blue axis.

The CIELUV Color Space: Adams suggested using transformations to modify the chromaticity diagram so that chromaticities (that component of an object's color separate from its luminosity) will be more uniformly spaced. The uniform chromaticities are then multiplied by lightness to remove the coordinates from chromaticity space, and scaled. Adams named this "Color Valence Space," [6] and it has been refined by Hunter and Wyszecki. Hunter's color space was based on the uniform chromaticity scale of Adams and the square-root formula for lightness; [11] while Wyszecki's color space, [12] which was adopted by CIE, was based on MacAdam's uniform chromaticity scale [13] and the cube-root formula for lightness.

Two scaling refinements were made to Wyszecki's color space, and the refined color space was adopted by CIE in 1976. This color space is referred to as the 1976 CIE L*, u*, v* Color Space, and is abbreviated, "CIELUV".

Intuitive Parameters: The L* parameter is the visual brightness (the same as with the CIELAB color space). The u* coordinate indicates the redness (versus the greenness), while the v* coordinate indicates the yellowness (versus the blueness). While these coordinates appear relatively uniform, only one of them has intuitive meaning.

Both CIELAB and CIELUV coordinates may be transformed into intuitive coordinates. Because the coordinate L* already has intuitive significance, it does not have to be transformed. The transformation on the other coordinates (either a* and b* or u* and v*) may be suggested by considering a "slice" of the color space. This slice, through the L* axis, allows us to consider the other two separately. These remaining coordinates may be transformed into polar form, with the angle representing Hue, and the radial distance representing Chroma, which is, intuitively, "freedom from gray." In other words, either color space may be used with either rectangular or cylindrical coordinates.

In addition, a value of saturation may be computed from the CIELUV coordinates, by dividing the chroma by the lightness. This is reinforced by the fact that we tend to think of saturation as that proportion of an object's lightness we perceive as chromatic, as opposed to the white component. It is not possible to compute saturation from CIELAB coordinates. [14, p 168]

Comparison of Colors: Uniform color spaces permit the assessment of not only absolute color, but color difference, as well. Thus, the color of an ink may not only be measured using colorimetry, but its color may be compared to that of the last ink used. The amount of visual change in appearance the new ink will cause may be quantitatively determined this way. Both the CIELUV and CIELAB color spaces are scaled so that a difference of one unit, in any direction, is roughly equal to the smallest difference a human observer is likely to perceive. The difference in color between two objects is the euclidean distance between their coordinates, and is represented by the symbol, ΔE^*.

Stamm investigated tolerances in color acceptance in package printing in terms of acceptable levels of ΔE^*, and discovered that a difference of six units was acceptable. [15] While this applied to package printing, and was restricted to variations throughout a press run, it provides an order of magnitude estimate of acceptable ΔE^* values in graphic reproduction.

Relative Color Difference: Because ΔE^* values form an interval scale, their magnitudes may be compared. For instance, if an OK press sheet has an average ΔE^* value of four, when compared to the proof, a press sheet with a ΔE^* value of two could be considered twice as close a match. (However, if it varies in the wrong direction, it might not be an acceptable press sheet.) The relative closeness of color matches may be evaluated this way.

A laboratory application would be to test a "crucial experiment," in which two or more competing models can be compared. The models can be entertained, and the precision of each model can be determined by its average ΔE^* value. (Actually, the geometric mean should be used, because the logarithm of ΔE^* tends to be gaussian distributed.) Statistical techniques, such as t-tests, ANOVA, and multiple range tests may be used on the log ΔE^* values.

Applications: Because colorimetry permits the evaluation of the color of objects in visually uniform and precise scales, it has many applications in graphic reproduction. The absolute color of an area to be printed may be specified. Or, a sample may be provided, along with a tolerance, specified in ΔE^* units. Colorimetry may also be used to evaluate different methods by comparing their color errors. Table 2 illustrates some of the applications of colorimetry in graphic reproduction, together with the parameters used for each application.

Using the Colorimeter as a Densitometer: There has been some discussion of the colorimeter taking the place of the densitometer in many graphic reproduction applications. Indeed, at least one manufacturer of densitometers has expressed an interest in manufacturing colorimeters. [16] To facilitate such a transition, it is desirable to be able to use a colorimeter for some of the tasks heretofore reserved for densitometers, such as color correction requirements. Methods which enable colorimetric data to be transformed into density-like quantities will be discussed below.

TABLE 2.
Applications of Colorimetry.

Absolute Colorimetry:	
Application:	Parameters:
Process Color Gamut Determination	$x, y; u', v'$
Ink Hue; Ink Saturation	$H^*; C^*/L^*$
Spot Color Specification	L^*, u^*, v^*
Color Difference Colorimetry:	
Application:	Parameters:
Press Sheet versus Proof	ΔE^*; Log ΔE^*
Press Sheet versus OK Press Sheet	ΔE^*; Log ΔE^*
Relative Color Difference Colorimetry:	
Application:	Parameters:
Comparison of Methods	Log ΔE_1^* - Log ΔE_2^*

Methods of Colorimetry: There are two primary methods of making colorimetric measurements. The first method involves the use of a device called a Filter Colorimeter, which contains a lamp, a photoelectric meter, and a set of three filters. This device is very similar in principle to a densitometer, and may be constructed to resemble (in appearance and operation, as well as in price) a densitometer. See Figure 1.

Such devices display the tristimulus values X, Y, and Z directly. Most will also transform X, Y, and Z into a uniform color scale, such as CIELAB. However, most are limited to one or two illuminants, and neither is apt to be the graphic reproduction standard, D50. Instead, the much bluer D65 is usually offered, which is used in other industries. Using a D65 colorimeter for prints being visually evaluated under a D50 proof light means that the colorimeter will not always measure colors the way they appear, which partially defeats the purpose of using a colorimeter. In addition, the CIELAB color space is not the best for the graphic reproduction industry, because it does not permit the calculation of saturation. [14, p 168]

The precision of a tristimulus colorimeter should certainly be high enough for color difference colorimetry, so press sheets may be compared to an "OK" press sheet this way. Many would be precise enough for absolute colorimetry and relative color difference colorimetry, which have more stringent precision requirements, although the other popular method of colorimetry, using a spectrophotometer, is generally preferred for these applications. This second method of colorimetry is called Spectrocolorimetry, and will be discussed in the section on Spectrophotometry.

Figure 1.
An inexpensive, portable filter colorimeter.

Summary: The colorimeter provides measurements of object color that are visually referenced. Thus, two objects which appear to have the same color will share the same set of tristimulus values. The tristimulus values may be transformed into visually uniform coordinates. The visually uniform coordinates L*, u*, and v* are scaled so that a difference of one unit corresponds roughly to a just-perceivable difference in color to human observers. The coordinates L*, u*, and v* may be transformed into parameters with intuitive meaning (Hue, Saturation, and Lightness). Three types of colorimetry were discussed: absolute colorimetry, for specification; color difference colorimetry, for comparison of prints; and relative color difference colorimetry, for the comparison of methods. Two methods of colorimetry were discussed. These two methods involve the use of Filter Colorimeters and Spectrocolorimeters.

SPECTROPHOTOMETRY

Just as the filter colorimeter may be regarded as being a specialized reflectance meter, so can the spectrophotometer be regarded as such, but it differs from the colorimeter because it measures the entire visible reflectance spectrum of an object, point-by-point. Some spectrophotometers measure the spectrum continuously; others measure at discrete points (usually every 10 or 20 nanometers throughout the range of 400 to 700 nanometers, for an abridged spectrum of 16 or 31 points). While colorimetry provides only three independent measurements, spectrophotometry provides much more information — at least 16 measurements.

The spectrophotometer measures color as a physical phenomenon, independent of a human observer. The reflectance spectrum may be integrated to obtain the tristimulus values, and the notion of color as a visual sensation may thus be introduced, as well. The spectrophotometer may thus be regarded as offering a reconciliation between these two notions of color. Because of this ability, the spectrophotometer is the most flexible color measurement instrument we shall discuss in this paper.

(A more flexible appearance measuring device, the goniospectrophotometer, permits spectra to be measured using different illumination/collection geometries. This enables gloss and color to be measured at the same time. However, this is primarily a laboratory instrument.)

For non-fluorescent materials, the spectrophotometer provides measurements which are independent of the illuminant. It is customary to evaluate ink mixtures for spot color under tungsten light, cool-white fluorescent light, as well as representative daylight. Because it measures an illuminant-independent reflectance spectrum, the spectrophotometer is able to accomplish this evaluation automatically and objectively. Indeed, if two reflectance spectra match, it may be assumed that the two objects will have the same color, no matter what source they are viewed under.

Fluorescent materials are relatively common in the printing industry. Many papers contain fluorescent materials, called "optical brightners," and many process yellow inks exhibit some degree of fluorescence. The effect of fluorescence on the color of printed materials has been investigated by Iwao, [17] and discussed briefly by Maurer. [18]

Spectrocolorimetry: As was mentioned before, the spectrophotometer may function as a colorimeter. Spectrophotometers designed for this purpose are sometimes referred to as Spectrocolorimeters, to distinguish them from Filter Colorimeters. The tristimulus values are computed by integrating the reflectance spectrum, when weighted according to the spectral products of the tristimulus values. This integration (summation) is usually performed by a computer which is a part of the spectrocolorimeter.

Most spectrocolorimeters offer a choice of several illuminants, which they have stored in a disk file. This usually means that standard Graphic representative daylight D50 can easily be inserted into the system, or used in place of one of the other daylight illuminants usually available (perhaps Illuminant C, which is not used that much anymore).

The Spectrophotometer as a Narrowband Instrument: Certain physical phenomena in graphic reproduction, such as halftone dot area on paper and ink strength, are inherently narrowband in nature, and are best evaluated using narrowband measurement. However, it was pointed out that narrowband densitometry (SPI and Status A) cannot be used to measure color as seen. The spectrophotometer offers a solution to this dilemma by offering the best of both worlds. The measurements it makes are narrowband, and thus may be applied to the physical models, but it sufficiently samples the spectrum, so color as a visual sensation may be addressed, as well.

Specialized spectrocolorimeters can be programmed to use the proper type of measurement (wideband or narrowband), depending on what they are being asked to accomplish. A major printing supplier offers this service, in its laboratory, [19] but this is a special test, rather than a routine quality-control function. Nevertheless, it illustrates the potential for spectrophotometric measurements in routine quality-control applications.

Summary: Spectrophotometry offers the flexibility needed to address both wideband and narrowband phenomenon with a single instrument. Thus, the hue and the dot gain of a colored halftone tint may be evaluated at the same time. This is because spectrophotometers, including spectrocolorimeters, make a sufficient number of narrowband measurements to permit accurate measurement of color. Many modern spectrophotometers contain computers; these computers can be programmed to accomplish standard graphic reproduction quality-control tasks, as well as evaluate direct image color differences. The spectrophotometer offers the best of both wideband and narrowband worlds, but is significantly more expensive than a densitometer.

COLORIMETERS FOR DENSITOMETRIC APPLICATIONS

Colorimeters are available for not much more money than a good densitometer. If the colorimeter is so much better at measuring color than the densitometer, why is the densitometer still used almost to the exclusion of the colorimeter? Perhaps the answer is that colorimetric measurements are difficult to apply to current graphic reproduction methods. Suggestions for using colorimetric measurements in applications heretofore reserved almost exclusively for densitometry will be discussed.

Colorimetric Densities

The tristimulus values X, Y, and Z are proportional to reflectances. One way to obtain densitometer-like numbers from a colorimeter is to simply convert the tristimulus values into densities. These densities are called Colorimetric Densities, and may be computed by dividing each tristimulus value by the corresponding tristimulus value of the paper (to obtain a reflectance), and then computing the negative of the logarithm, as was done in Equation (1). (A more efficient means would be to simply subtract the logarithm of each tristimulus value from the logarithm of the corresponding tristimulus value of the paper.)

This method is not satisfactory for most applications, such as computing hue error and grayness, because the color matching functions (which weight the tristimulus values) overlap significantly, while the Status T spectral products overlap only slightly. Hue error and grayness values computed from these colorimetric densities are significantly higher than those computed from Status T density measurements. One result is that ink gamuts and masking requirements cannot be assessed this way.

MacAdam computed the set of color matching functions with no negative portions that overlap the least. [20] In order for a set of color matching functions to have no negative portions, the chromaticities of the primaries must enclose the spectrum locus on a chromaticity diagram. The chromaticities of the primaries define a linear transformation of tristimulus values. This transformed set of tristimulus values could be converted into colorimetric densities the same way X, Y, and Z can. Such a set of tristimulus values, with less overlap, would tend to yield hue error and grayness values closer to those obtained with Status T densitometry.

MacAdam's transformation was investigated by Pearson and Yule, who converted a densitometer so that its spectral products corresponded to MacAdam's transformed color matching functions. They compared color triangles for a set of process inks computed from Status T measurements to those obtained from the measurements defined by MacAdam's transformation, [21] and obtained a significantly attenuated gamut for the ink set. A closer match would be desirable.

<u>Status "TC"</u>: One possibility is to choose the transformation to provide the most agreement with Status T measurements. (The optimal solution would be to choose the transformation which is defined by the spectral sensitivities of the color separation system, but we may consider the Status T spectral products representitive of the spectral sensitivities used in color separation.) The transformed color matching functions could be the projection of the Status T spectral products onto color matching vector space. Colorimetric densities defined this way may be referred to as Status TC densities, because they are colorimetric counterparts of Status T densities.

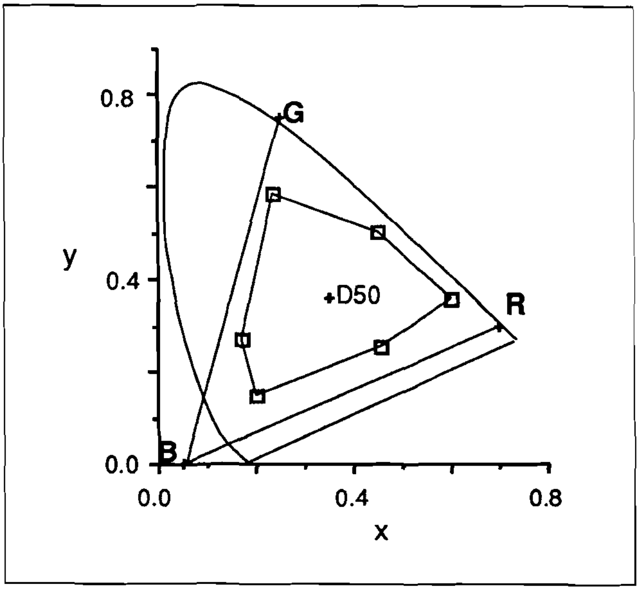

Figure 2.
Process Color Gamut and Suggested Status TC Chromaticities.

Such a set of transformations was computed by regressing the Status T spectral responses onto the color matching functions (multiplied by the spectral power distribution of the D50 illuminant, and normalized to unit sum). These regressions were constrained so that the sum of each spectral product would be unity. Unfortunately, some inks (magentas, in particular) exhibited negative reflectances under this transformation, and others (cyans and yellows) exhibited reflectances in the tertiary bands greater than unity. This "whiter than white" and "blacker than black" behavior is clearly unacceptable. The transformation was adjusted slightly, so that it enclosed the gamut of a set of process inks with higher probability.

The adjusted set of transformations are defined by the chromaticity coordinates: (0.70, 0.30) for the Red; (0.25, 0.75) for the Green, and (0.05, 0.00) for the Blue. This suggested set of transformations applies only to tristimulus values measured using standard illuminant D50, and appears below:

$$\begin{aligned} Dr &= -\log[1/3(5X/X_0 - 2Y/Y_0)] \\ Dg &= -\log[1/9(-5X/X_0 + 14Y/Y_0)] \\ Db &= -\log[1/35(-5X/X_0 + 7Y/Y_0 + 35Z/Z_0)] \end{aligned} \qquad (2)$$

X_0, Y_0, and Z_0 are the tristimulus values of the illuminant; they are normally 96.38, 100, and 82.41, respectively. However, if "zeroed on paper" measurements are desired, and the instrument is not nulled on the paper, these should be replaced by the tristimulus values of the paper.

Figure 2 shows the chromaticities of a set of process colors (provided by 3M Color Key® color proofing material), and how this gamut is enclosed completely by the primaries, which form the large triangle.

Both Status T densities and the suggested Status TC densities were used to plot a Preucil color triangle, which appears in Figure 3. Note that the gamut indicated by the suggested Status TC densities corresponds closely to the gamut indicated by Status T densities.

Graphical Methods:

Another possible method of using colorimetric measurements similarly to densities is with color diagrams, particularly the Color Circle and Color Hexagon. [22] The hue error and grayness values of the Color Key process colors used above were determined using the normal method. The position in the Preucil color circle was determined, and the measure of the angle from the three o'clock position to each color's position was determined. This angle is the standard angle used in polar coordinates, and is made in a counter-clockwise direction. Thus, a yellow with no hue error plots at 30 degrees, a cyan with no hue error at 150 degrees, and a magenta with no hue error at 270 degrees (or -90 degrees).

The CIELUV Hue Angle measure, H*, was calculated for each color, as well. These angle measures appear in Table 3.

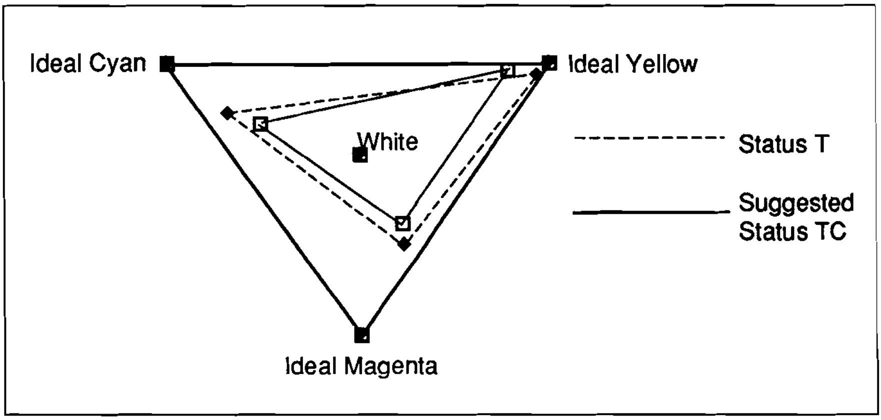

Figure 3.
Process Color Gamuts: Status T and Suggested Status TC.

Table 3.
Hue Angle: Color Circle and CIELUV.

Color:	Color Circle:	CIELUV:
Cyan	162	221
Magenta	-59	-7
Yellow	27	76
Blue	-26	9
Green	98	145
Red	-141	-89

The average difference between each pair is 49 degrees, with a standard deviation of 2.2 degrees. Thus, a 95 percent confidence interval for the differential goes from 44 degrees to 54 degrees. However, this is a limited sample, and this figure would apply only to similar materials.

This means that if a rectangular plot of the coordinates (u^*, v^*) were rotated approximately 50 degrees clockwise, the angular positions of the colors would tend to agree. However, the radial distance from the center would not necessarily match. A further study, incorporating more extensive sampling, is planned.

EXPERIMENTAL —

Yule-Nielsen versus Murray-Davies versus Proportionality

The use of spectrophotometry for laboratory applications will be illustrated with an experimental example. Three models which are used to predict the density of a halftone tint from the halftone dot area on paper were evaluated for precision. The experimental data were measured and collected by the author, and appear in the *1985 TAGA Proceedings,* [23] and are spectrophotometric measurements of Color Key® color proofing material.

Two short tone scales in each of the process colors were produced and measured. Each scale contained a white, three different halftone tints, and a solid. Thus, 18 halftone tints were measured, every 20 nanometers, between 400 and 700 nanometers.

The Three Models:

The Proportionality Assumption: As a first-order approximation, the density of a halftone tint (Dt) may be approximated by the product of the halftone dot area (a) and the density of the solid (Ds). Not surprisingly, this is called the Proportionality Assumption, and forms much of the theoretical basis of color correction by photographic masking. [4, p 267] In equation form, it is:

$$Dt = a\,Ds \qquad (3)$$

The Murray-Davies Model: Under the assumption that the absorptances, rather the densities, of halftone tints will be proportional, Murray and Davies proposed the following equation:

$$Dt = -\log[1 - a(1 - 10^{-Ds})] \qquad (4)$$

The Yule-Nielsen Model: Yule and Nielsen determined the effect of the penetration of light into the paper, and its re-emergence through the halftone dot, and derived the following equation: [24]

$$Dt = -n \log[1 - 10^{-Ds/n})] \qquad (5)$$

The value of the parameter m depends upon the halftone screen ruling and the paper (as well as some secondary factors). Yule and Nielsen provided a short table of n in their paper, and Pearson suggested that a value of 1.7 be used under general conditions, [25] in lack of specific information on the paper and

Table 4.
Effective Halftone Dot Areas on Paper.

Tint	$\hat{a}_P$	$\hat{a}_M$	$\hat{a}_Y$
Yellow 1 Light	0.157	0.417	0.299
Yellow 1 Medium	0.360	0.722	0.577
Yellow 1 Dark	0.542	0.867	0.751
Yellow 2 Light	0.201	0.496	0.365
Yellow 2 Medium	0.409	0.766	0.627
Yellow 2 Dark	0.580	0.886	0.780
Magenta 1 Light	0.228	0.366	0.305
Magenta 1 Medium	0.481	0.657	0.583
Magenta 1 Dark	0.704	0.839	0.784
Magenta 2 Light	0.215	0.415	0.328
Magenta 2 Medium	0.410	0.665	0.560
Magenta 2 Dark	0.533	0.780	0.682
Cyan 1 Light	0.181	0.375	0.288
Cyan 1 Medium	0.402	0.673	0.561
Cyan 1 Dark	0.565	0.814	0.717
Cyan 2 Light	0.180	0.377	0.289
Cyan 2 Medium	0.377	0.652	0.538
Cyan 2 Dark	0.540	0.801	0.699

screen ruling. Note that using a n-value of one reduces (5) to (4), and as the n-value is increased without bound (5) approaches (3).

Extrapolating the values in Yule and Nielsen's table, a value of 1.8 was chosen for this study; a halftone screen ruling of 133 lines per inch and coated paper were used.

Effective Halftone Dot Area and Entertaining the Models:
Using either equation (3), (4), or (5), an estimate for the density of a halftone tint may be estimated, given the density of the solid and the halftone dot area on paper. The densities of the solids were measured, so they may be assumed to be known. Each density estimation, then, hinges on the value of the dot area used.

Each model will be given the benefit of the doubt in this regard. The estimations of each model will be based upon the best value of the dot area for that model — specifically, the value of a will be chosen for each model so that the agreement between estimated and observed density spectra is maximized. The squared difference between the two densities will be summed, and the value of a will be adjusted to minimize this sum.

Entertaining the proportionality assumption, the best value of a is:

$$\hat{a}_P = \Sigma Ds\ Dt / \Sigma Ds^2 \qquad (6)$$

where the circumflex (^) indicates that a is being estimated, and the subscript, P, denotes the proportionality assumption.

Because of their non-linear nature it is not possible to calculate in closed form the best values of a for the other two models. However, the same criterion will be used, and the sum of the squared density differences will be minimized.

The effective halftone dot areas for each (tint, model) combination appear in Table 4. While the values are different for each model, it should be kept in mind that *all* values are equally valid at this point. Each value was chosen to maximize the agreement between observed and estimated spectra, under that model . The models will be evaluated by each model's ability to reconstruct the density spectra of the tints.

RMS Density Errors and Lack-of-Fit:

The criterion applied to these models is the ability to reconstruct the reflectance spectrum of the tints, given the spectrum of the solid and the effective dot area appropriate for the model being used. The effective dot areas were selected to minimize the RMS Density Error of each model, so this was the statistic used. RMS Error is a convenient statistic, because it is usually included in the detail of a regression program's output. The RMS Density Errors of each model's predictions appear in Table 5.

The RMS Density Error of the instrument used to measure the density spectra is believed to be 0.011 density units. [23] For a sample of this size (90 degrees of freedom), approximately 0.015 density units may be attributed to measurement error. Pooled RMS Density Errors (i.e., for all eighteen tints) greater than this value probably contain a component of error.

The pooled RMS Density Error of the proportionality estimates was 0.0248 density units; higher than the critical value and more than twice that attributable to chance alone. For the Murray-Davies estimates, the pooled RMS Density Error was better; 0.0189 density units. Again, this is higher than the critical level, so it may be concluded that some of the error lack of fit. A pooled RMS Density Error of 0.012 for the Yule-Nielsen estimates indicates no significant lack-of-fit.

<ins>Summary</ins>: Three models were tested for their ability to reconstruct the density spectrum of halftone tints. Of the three models, only the Yule-Nielsen model demonstrated no lack-of-fit. The proportionality assumption and the Murray-Davies model both contained a component of error attributable to the model.

Table 5.
RMS Density Errors.

Tint:	Proportionality	Murray-Davies	Yule-Nielsen
Yellow 1 Light	0.0131	0.0102	0.0074
Yellow 1 Medium	0.0161	0.0237	0.0134
Yellow 1 Dark	0.0191	0.0260	0.0145
Yellow 2 Light	0.0134	0.0194	0.0140
Yellow 2 Medium	0.0194	0.0312	0.0213
Yellow 2 Dark	0.0204	0.0357	0.0247
Magenta 1 Light	0.0172	0.0058	0.0093
Magenta 1 Medium	0.0230	0.0040	0.0102
Magenta 1 Dark	0.0217	0.0035	0.0103
Magenta 2 Light	0.0225	0.0090	0.0065
Magenta 2 Medium	0.0285	0.0170	0.0025
Magenta 2 Dark	0.0188	0.0312	0.0121
Cyan 1 Light	0.0196	0.0084	0.0043
Cyan 1 Medium	0.0383	0.0117	0.0119
Cyan 1 Dark	0.0385	0.0136	0.0096
Cyan 2 Light	0.0194	0.0115	0.0063
Cyan 2 Medium	0.0357	0.0139	0.0083
Cyan 2 Dark	0.0364	0.0180	0.0050
Pooled RMS Error	0.0248	0.0189	0.0120

CONCLUSIONS

Narrow- and Wideband Densitometry each have their relative merits over the other. Although it does not provide realistic measurements of color, the wideband densitometer will continue to be used for evaluation of hue, grayness, and saturation in printing, as well as for measuring actinic densities, which anticipate the response of color-separating systems. Narrowband densitometers have an edge in evaluating ink strength, trapping, and dot gain, but leave too much of the spectrum unsampled for measuring color.

Absolute Colorimetry provides a means of specifying and determining process ink set gamuts, specifying colors to be reproduced by spot or process color, and evaluating ink hue, saturation, and grayness. The CIELUV color space offers the advantage of enabling the calculation of Saturation, an important printing parameter, while some of the other color spaces do not.

Color-Difference Colorimetry provides a quantitative perspective to how much of a difference (in the numbers) makes a difference. ΔE^* values of one or less tend to indicate no visible difference, while ΔE^* values higher than six have been accepted. Color-difference colorimetry may be used to evaluate press sheet versus proof or OK press sheet using direct image measurements.

Relative Color-Difference Colorimetry can be used to asses the relative merit of one method over another. The logarithm of the ratio of the ΔE^* values is a useful variable to this end.

Spectrophotometry is a flexible color measuring method; it combines the advantages of narrowband and wideband measurements. Thus, it is suitable for measuring color as a visual phenomenon and the physical parameters, such as dot gain and trapping, as well. In other words, the spectrophotometer provides the best of both worlds in one instrument, and will start to be applied in graphic reproduction production environments as smaller, less expensive units become available. Spectrophotometers may be customized for graphic reproduction applications in the same way that computerized densitometers automatically compute trap, dot gain, and other parameters on demand.

Colorimetry can be used in applications thought to be reserved for densitometers. It is possible to transform tristimulus values into densities that are colorimetric counterparts of Status T densities; these densities may then be used in the same way as Status T densities. It was also discovered that the CIELUV Hue Angle, H^*, corresponded closely to the hue angle on a Preucil Color Circle rotated 50 degrees clockwise.

Spectrophotometry was used to evaluate three models for estimating halftone density. The Yule-Nielsen model was discovered to provide acceptable accuracy, while the Murray-Davies and proportionality models contained a significant component of error, which hinders the precision of these models.

ACKNOWLEDGMENTS

The author would like to extend his thanks to Mr. Irving Pobboravsky of the RIT Research Corporation, Dr. Julius Silver of the RIT School of Printing, Mr. Philip Tobias of Tobias Associates, Mr. George Leyda of 3M, Mrs. Lynn Tesar of the Ridgewood Library, and Mr. Alan Walden, as well as the author's family and friends, for their assistance in preparing this paper.

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