A SUBTRACTIVE COLOR MEASUREMENT AND DIAGRAM SYSTEM ADAPTED FOR THE GRAPHIC ARTS

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Abstract: In the history of color measurement the adoption of the Standard observer in 1931 by the International Commission on Illumination (C.I.E.) and the introduction of the chromaticity diagram were significant events. Many modified and improved systems have been developed but nearly all can trace their origins back to the chromaticity diagram.

The chromaticity diagram and all other colorimetric diagram systems are based on additive mixture. Mixtures of colored lights will plot on a straight line on the chromaticity diagram. Subtractive mixtures, which occur when one ink is printed on another, cannot be predicted by this diagram.

Since additive and subtractive mixtures are fundamentally different, two different fundamental measurement and diagram systems are needed. The additive system was introduced more than fifty years ago. This paper is an effort to correct the omission of the subtractive system. The diagram has been specifically adapted for the Graphic Arts, although the basic system could be adapted for any application of subtractive color mixture.

The diagram for this subtractive system retains the important advantages of the GATF color triangle, but is based on spectrophotometer, rather than densitometer, measurements. Straight line relationships are retained in color mixture and individual plots are independent of strength or concentration as long as the colorant is relatively transparent. The plots should agree with visual judgments in a standard D-5000 viewing booth.

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Introduction

Graphic arts color workers usually start taking color measurements with a reflection densitometer. These measurements can be plotted on a GATF color triangle. The triangle is a subtractive diagram which is useful for making predictions of color mixture. Overprints of any two inks will plot on a straight line between them. The problem is with the densitometer which is not standardized and does not match eye response.

More accurate and standardized measurements which match eye response can be made with more expensive instruments such as a colorimeter or a spectrophotometer. The measurements can be plotted on a chromaticity diagram which John Yule termed "worse than useless" for the graphic arts (Yule, 1965). The chromaticity diagram represents an additive system which gives little or no information on color mixture. In some cases printed ink measurements on the chromaticity diagram can be misleading. Other colorimetric systems are also additive and therefore subject to the same drawbacks for the graphic arts.

We in the graphic arts have a choice between a useful inaccurate color measurement system and other systems which are accurate but essentially useless.

My aim is to make a color measurement system from spectrophotometric data and retain all the advantages of the GATF triangle (Preucil, 1960). Some of the procedures were known many years ago but were not put together into a single system (Trotter, 1962). The measurement and plotting are done in a manner similar to the CIE chromaticity diagram. A triangle, including hue error and grayness lines, is superimposed to give the plots real meaning for the graphic arts. The plots can be related to the complementary wavelength if desired. The straight line relationships of the GATF triangle are retained.

Over the years many color diagram systems have been proposed as ideal systems for all uses. Such an ideal, all encompassing diagram is probably not possible. In order to gain one advantage, other features may have to be sacrificed. When making a diagram for any specific purpose a priority list of desirable features should be made. Here is my list of a graphic arts measurement system.

1. The color measurements must be based on fundamental (spectrophotometric) data.

2. The diagram must be based on subtractive primaries. Subtractive mixtures must plot on a straight line between plots of the individual colors. Therefore, the gamut of reproducible colors may be represented by a triangle in any 3-color system.

3. Plots of single colors on the diagram must be independent of strength or concentration.

4. In addition to hue, the plots must give an indication of grayness.

5. Color plots should agree with eye response.

6. The color plots must be understandable by graphic arts workers.

Another desirable feature for the graphic arts would be to correlate the plots to masking factors. An approximate correlation may be possible but this requirement would conflict with the eye response requirement.

Low instrument cost would be desirable but unfortunately a spectrophotometer is needed to meet the other requirements. Therefore, at least in the immediate future, the required instrumentation will not be low cost.

Other industries using subtractive mixture may have a different list of priorities. Most of them are not limited to three primaries to reproduce the widest possible gamut of colors.

Equal visual spacing is a feature which would given a high priority by others. It is not on my list because, even if possible, it would probably conflict with the straight line plotting feature. While equal visual spacing would be useful for quality control, the other features listed are more important for the graphic arts.

Agreement with eye response was placed low on the list. This is not to say that accuracy is not important. However, if all the other requirements are met, an occasional disagreement with eye response would not be fatal. The GATF triangle has been useful for more than 20 years even though densitometer filters are not close to eye response. Questionable colors may be calculated in other systems. Computers make these options possible.

There are a number of essential physical requirements for a graphic arts measurement system.

1. The illumination must be 0°/45° (or 45°/0°) in order to simulate normal viewing conditions (Burns, 1980). Samples with different amounts of gloss will measure as they appear. Integrating spheres must not be used since they can cause incorrect measurements due to variations in surface gloss, especially in dark colors.

2. The sample must be illuminated by white light. Some papers and inks absorb light at one wave length and re-emit light at a longer wavelength. Instruments using monochromatic illumination cannot measure these samples correctly.

3. Since D-5000 has been selected as a standard for viewing in the graphic arts the illuminant for calculating color must be D-5000 (ANSI 1972).

Subtractive Color Diagrams

In 1962 I. F. Trotter described a method for measuring dye solutions in which concentration did not change the position of the plot (Trotter, 1962). Therefore, each dye could be characterized by a single point rather than a curved line as had been the case with the standard chromaticity diagram. In his system optical density was used rather than transmission. Optical density at each wavelength was multiplied by the same color matching functions used for calculating X,Y,Z in the chromaticity system to produce what Trotter termed X',Y' and Z'. The corresponding x', y' calculations were made in the same manner as the conventional chromaticity system. When his modified chromaticity coordinates were located on the chromaticity diagram he found that all mixtures of any two dyes plotted on a straight line. This is a useful feature in the selection of dyes.

In the Trotter diagram, colors plot in the exact opposite positions relative to the additive colors in a conventional chromaticity diagram. The yellows plot in the "blue" area, the cyans plot in the "red" area, and magentas plot in the additive "green" position. Since optical density is the logarithm of the reciprocal transmittance, this reversal of positioning is to be expected.

A new subtractive system should have the colors in the correct locations, consistent with CIE and GATF. In order to position the colors correctly the diagram must be turned upside down so that the plotting starts in the upper right corner. This technique is similar to the original GATF color triangle introduced in 1960 by Frank Preucil. He named the coordinated c and m (toward cyan or magenta) rather than x and y. GATF now uses a different method of locating the color plots on the triangle. Therefore, the choice of c and m to identify the coordinates for the new subtractive system should not cause any confusion.

Trotter used the 1931 CIE standard observer and illuminant C for his calculations. Since the proposed system is for the graphic arts, the illuminant chosen was D-5000 as specified by ANSI (1972). Therefore, the calculations should match the visual judgments from the standard D-5000 viewing booths. The CIE 1964 supplementary standard observer was used rather than the 1931 since it has been found to more accurately correlate with normal color vision. The sums of the color matching functions were normalized to 100 so that perfect non selective grays will always plot in the center of the diagram. These color matching functions are shown in Appendix I.

The calculation procedure may be summarized as follows:

1. The spectrophotometer measurements must be converted to density.

2. The density at each wavelength is multiplied by the corresponding color matching function from Appendix I.

3. The sum of each column (from step 2) is found and labeled DX, DY, and DZ (not X, Y, and Z).

4. The c and m coordinates are determined according to the following formulas:

$$c = \frac{DX}{DX + DY + DZ} \qquad (1)$$

$$m = \frac{DY}{DX + DY + DZ} \qquad (2)$$

Note the similarity of the formulas to the chromaticity formulas. The only real difference is the use of densities instead of percentages.

The new subtractive diagram needs a name. Since this system is based on spectrophotometric measurements and has linear relationships between mixed colors, the name chosen was " Spectralinear." The complete name would be "The Enco Spectralinear Diagram. The name applies to any system using the above coordinate calculations.

The spectrum locus may be determined by finding the color matching functions at each single wavelength and using them directly as DX, DY, and DZ with zero for all other wavelengths. The resultant c and m coordiantes will plot on the spectrum locus. This simplified system works because the values of c and m depend upon the relative rather than the absolute values of the three densities. Therefore, the single wavelength could have a 1.0 density which would result in three desities equal to the color matching functions. This explains why the spectrum locus for the Spectralinear and chromaticity systems are the same. (Figure 1)

The wavelengths represent absorbance rather than reflectance and are therefore complementary wavelenghts. The wavelength numbers in Figure 1 are followed by c which denotes their complementary nature.

While hue around the Spectralinear diagram is similar to the CIE chromaticity diagram the distance from the center to the spectrum locus is not. Strength or saturation are not in any way associated with this dimension. As a plot moves from the center toward the edge a decreasing percentage of grayness is indicated. Strength and saturation are in the third dimension. This is an important feature since a single measurement of any printed color, as long as it is within a reasonable printing range, is sufficient for evaluation of an ink.

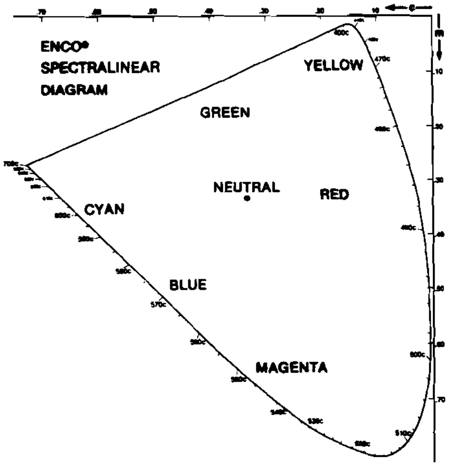

Figure 1. Spectrum Locus of the Enco® Spectralinear diagram.

Strength, the one parameter controlled on the press does not significantly change the plot of a single ink. If the white paper is used as zero density the strength dimension is almost exactly vertical. Light clean colors would plot toward the center of the Spectralinear diagram if an absolute white (instead of the paper) is used as zero density. Light tints increase rapidly in percent grayness if the paper grayness is included. Failure to use the white paper as zero density causes the third dimension to be curved, especially in the lighter colors. (Figure 2).

At this point the Spectralinear diagram could be considered complete. The first four items on the priority list seem to have been met while item five (eye response), remains to be proven. Item number six which states that the diagram must be easily understood by graphic arts workers has not been met. Therefore, all subsequent work on the diagram discussed below is simply to make it more compatible with the GATF color triangle .

The diagram of Figure 1 has a central neutral point and a spectrum locus calibrated to complementary dominant wavelength, which is not very meaningful in the graphic arts. We know that the distance from the center point to the spectrum locus is related to percent grayness, but

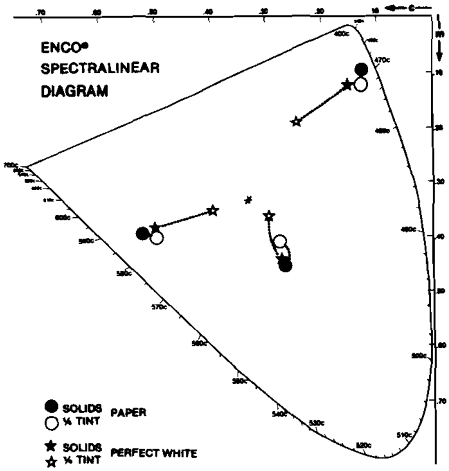

Figure 2. Increased grayness of light tints when a perfect white instead of the paper is used as zero density.

there is no scale. Since percent grayness is also one dimension of the GATF color triangle, it should be possible to draw the hue error and grayness lines of the GATF triangle on the Spectralinear diagram. In order to do this the ideal primary process inks must be calculated. Unfortunately there is probably no precise, non arbitrary definition of ideal process inks. My first attempt was to use the time honored technique of block reflectances. (Figure 3). In this technique the spectrum is divided

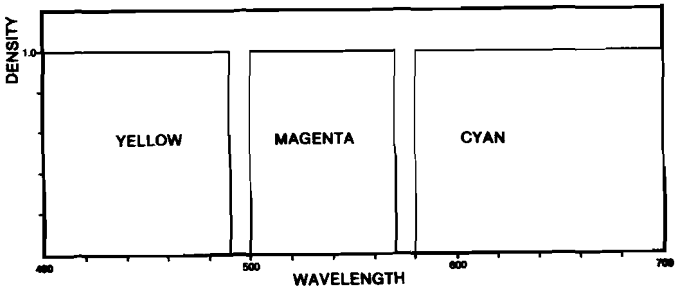

Figure 3. Block reflection density of three "ideal" process inks.

into three sections, (blue, green, and red) and either 100 percent or zero percent is taken across each section, depending upon which color is being calculated. For example, cyan would have 100 percent reflectance in the blue and green sections and zero in the red. In the subtractive system, using densities, the three sections must be labeled yellow, magenta and cyan. A cyan would have high density in the cyan section and zero in the other two. It is convenient to use 1.0 for the high density. The only remaining decision is the two places to divide the spectrum. Hans Neugabauer (1956) called these the "leap wavelengths" which he calculated to be 491 and 571 nanometers. Since my measurements were made at 10 nanometer intervals, from 400 nm through 490 nm was considered blue, 500 nm through 570 nm was considered green and 580 nm through 700 nm was red.

The ideal primaries were then calculated and plotted. (Figure 4). Straight lines between the points enclose the ideal gamut. Although the ideal primaries are not necessarily perfect colors, they should represent the widest total gamut possible with three primary inks.

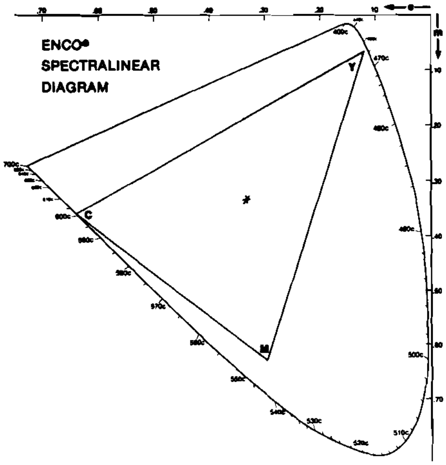

Figure 4. Plots of "ideal" primaries from Figure 3.

Yellow pigments and dyes are extremely pure colors which can sometimes fall outside the ideal gamut. No single ideal yellow could enclose all available yellows. Note in Figure 4 that a yellow near the yellow corner, simply by a small hue change, could fall outside the triangle. A yellow outside the ideal gamut is no problem on the Spectralinear diagram. The straight line relationships will still hold.

Using these so-called "ideal" primaries an anomaly was noted when a red pigment plotted outside the calculated ideal gamut. This was not expected. Although the red was not a fluorescent color and no measurement was below zero density (above 100 percent), it plotted outside the ideal gamut which should represent the least grayness possible. An examination of the spectrophotometric curve of the red pigment revealed that the density in the green region peaked at about 540 nanometers and declined steeply before reaching 570 nanometers (Figure 5). The so-called ideal red would still have the maximum density at 570 nanometers which, with the huge overlap in eye response, (Figure 6) adds a considerable amount of density in the X. Those familiar with the GATF system will understand that a higher red filter density of a red means a higher percent grayness. In the same manner a larger DX (primarily red density) means a higher percent grayness of a red. Therefore, for a subtractive system, the ideal primary inks must have low density where the overlap of eye response is greatest.

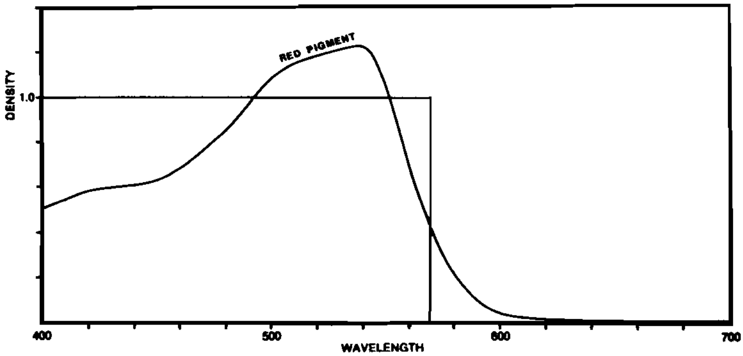

Figure 5. Block reflection density of "ideal" red vs. an actual red pigment.

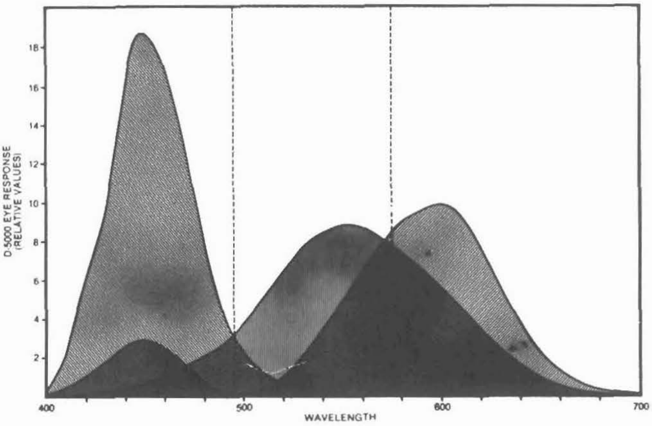

Figure 6. Color matching functions from Appendix I showing overlap.

A modification of the block relfection densities (Figure 3) is shown in Figure 7. The modified densities were calculated to place the high densities where the eye response overlap was at a minimum so that the ideal primaries would have the least possible grayness. The

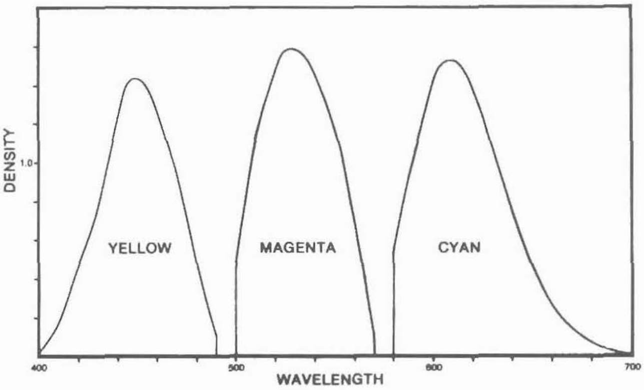

Figure 7. A modification of block reflection densities (from Figure 3) which increases the gamut of "ideal" inks.

wider gamut of the modified block relection densities is shown in Figure 8.

While the selection of ideal primaries is somewhat arbitrary, most calculations fall somewhere in the vicinity of the plots shown in Figure 8.

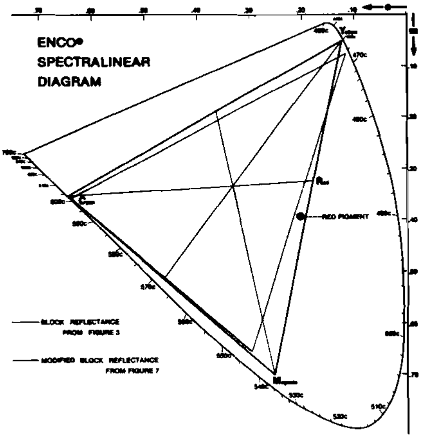

Figure 8. "Ideal" primaries from Figure 7 vs. "ideal" primaries from Figure 3. The modified response produces a larger gamut.

While a precise non-arbitrary calculation of ideal inks would be desirable, it is not essential. The ideal colors are only for reference and do not enter into placement of the plots.

Once the ideal primaries are determined the remainder of the hue error and grayness lines of the GATF triangle can be calculated and drawn in. (Figure 9)

The Spectralinear system retains the advantages of the GATF triangle but, in addition, is based on eye response. The straight line relationships are important because of their predictive value. (Figure 10). If the colorants are reasonably transparent, it is not necessary to make measurements at more than one strength for each colorant being tested. One measurement of each of the three primary inks can then represent the entire gamut of reproducible colors with that set of inks.

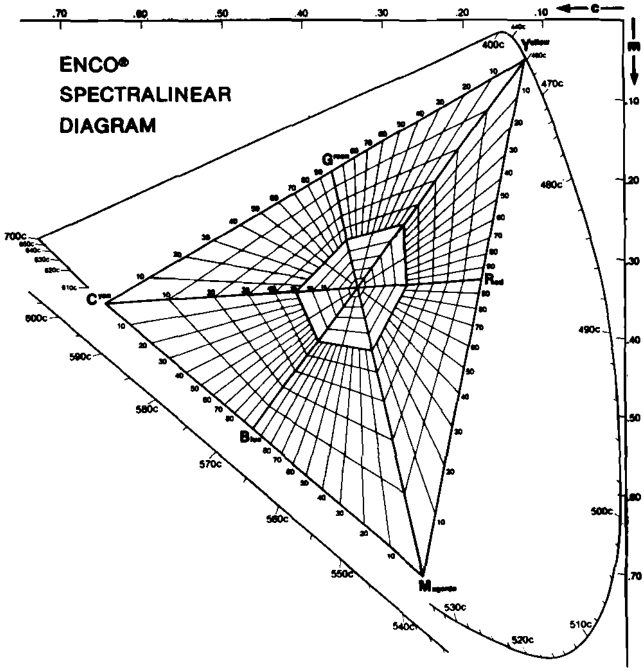

Figure 9. Enco ® Spectralinear triangle.

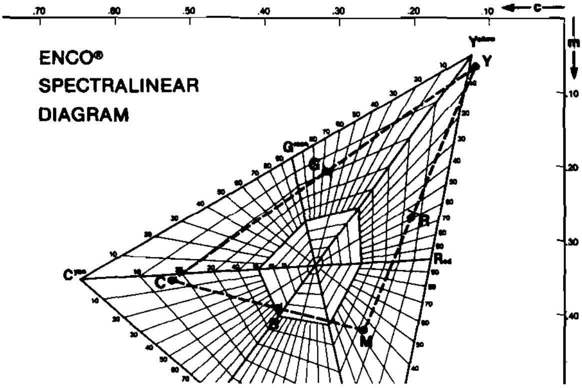

Figure 10. Color plots of a set of process inks on the Spectralinear diagram.

While the shape of the triangle is different than the GATF triangle, the hue error and grayness lines can be used to transfer the plots to the GATF triangle. (Figures 11, and 12). It is also possible to calculate the same hue and grayness shown in this diagram from the DX, DY, and DZ, but the calculation is complicated. While this would allow plotting directly on the GATF triangle, the plots depend upon the choice of ideal primaries. Direct calculation of some yellow measurements could result in negative quantities. For now it would be much easier and more fundamentally sound to use the plotting system as described, with hue error and grayness lines as a reference.

John Yule (1965) in his TAGA paper and his book (1967) claimed that, using the Trotter system, the dark colors are not accurate. My measurements of light and dark colors have not verified this claim. Calculated light and dark strengths of a single color, using the accepted formulas for changing concentration, (Hardy, 1936) fall at precisely the same spot. Any change in position of the plot with changes of ink film thickness indicates a real change in color. If, for any reason, a color plot should not agree with visual judgment the whole system should not be abandoned since the useful features would still make it worthwhile. The Spectralinear system should be used in conjunction with other standard systems until more experience is gained. Any color plotting system must be used with common sense. None of the color systems, including the Spectralinear system, is perfect. Therefore, we still need to look at the colors (under standard illumination) for visual interpretation.

Strength

Hue error and grayness are shown in the two dimensions of the Spectralinear diagram. The third dimension, which is totally separate from the other two, is usually referred to as strength in the graphic arts. In the dye industry it would be called concentration. Other terms for approximately the same dimension may include brightness, lightness, visual density or luminosity. In the remainder of this paper the third dimension will be referred to as strength.

While strength is separate from the placement of the plot on a two dimensional diagram, it is necessary to know the strength for a complete description of a color.

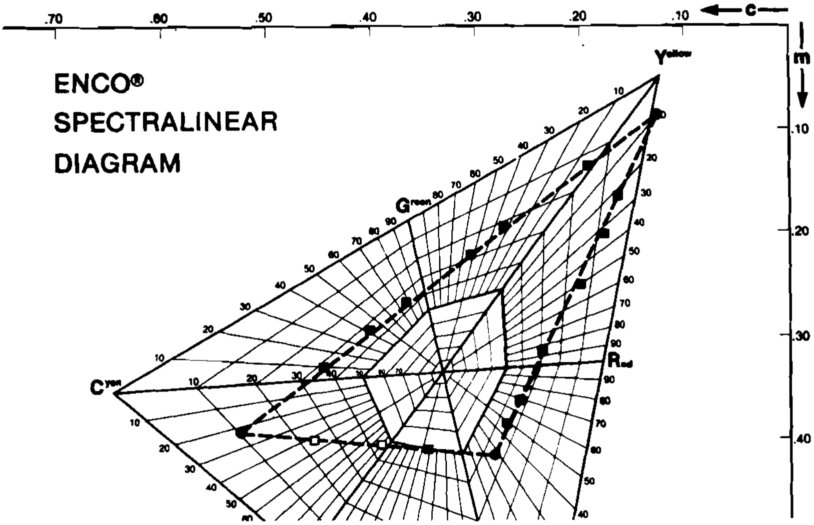

Figure 11. Spectralinear plots of inks from mixtures of three primary inks. The solid squares represent ink mixtures. The two open squares represent calculated mixtures.

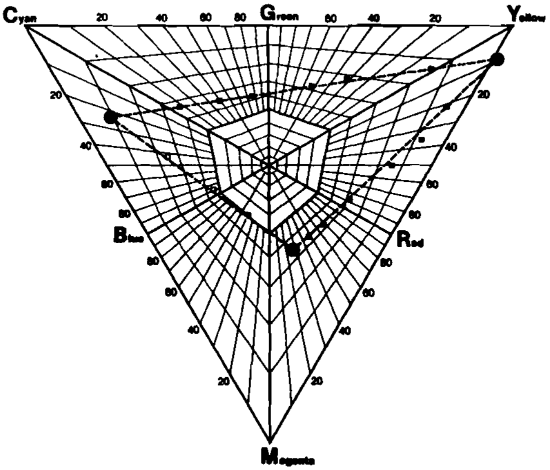

Figure 12. Color plots from Figure 11 transferred to the GATF triangle.

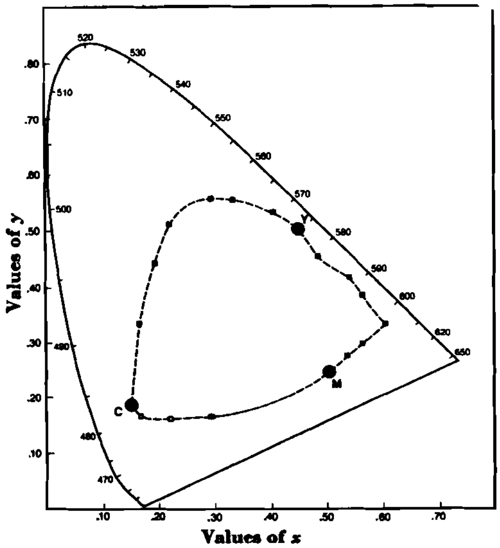

Figure 13. The colors from Figure 11 plotted on the CIE chromaticity diagram. (1931 Illuminant C).

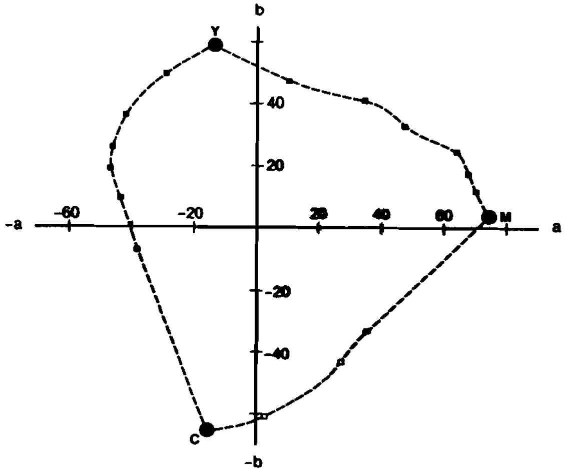

Figure 14. The colors from Figure 11 plotted in the Hunter Lab System.

Determining strength is not as simple as it would seem. The first thought would be to use one of three density summations as strength. The Y density may be expected to be similar to Y or luminosity. However, the difference in calculation makes this method suitable only for indicating the relative strengths of identical colorants. DX, DY, or DZ may be used to control the strength of a single colorant. For example, DZ could be used as an indication of yellow strength, or ink film thickness in a press run.

Luminosity or Y, as specified by the CIE, could be used as a measure of strength. It is a recognized international standard. However, it is now conclusive that the luminosity data are incorrect (MacAdam, 1983). Research is being done but right now there is no accurate accepted measure for strength (Kinney, 1983).

As an interim solution I have worked out my own strength function. It is not perfect but it is better than luminosity. The interim solution for strength is based on visual judgments of saturated ink colors. Five observers made 7 sets of visual judgments. Each set consisted of 57 separate evaluations. The object was to find a linear combination of the color matching functions which would calculate strength in accordance with the visual judgments. Unfortunately, the best correlation with eye response was from an empirically derived curve shown in Appendix II. It may be used in the same way as luminosity. The percent reflectance measurements, not density, are used in the calculation. After the calculation is made the answer may be converted to density.

Those not comfortable with the interim strength function may simply use Y. Luminosity has been used for more than 50 years. Another year or two of inaccurate strength calculations would not cause a crisis.

Finding an accurate strength function is not a small task. Unless it is done by someone in the graphic arts it will probably not be done with D-5000 illumination.

Other Subtractive Systems

Other subtractive systems have been attempted but none can meet all the requirements on my priority list. Spectrophotometric measurements make it possible to calculate the response with any filter. Some systems using calculated filters are useful but it is important to recognize their limitations.

Some early attempts at making a subtractive system involved starting with X, Y, and Z and converting to densities. Plots from these densities did not always result in straight line relationships with color mixtures. Calculations to regain the straight line feature are complex and are therefore not recommended.

Future Work

It is obvious that this system is not complete. One person working alone may never finish such a system. The strength calculation is an open problem. Precise determination of ideal colors is another. If no fundamental solutions can be found it may be necessary to select the best arbitrary solutions and make them standards.

While the color accuracy of the Spectralinear system is nearly always adequate for graphic arts purposes, greater accuracy would be desirable if it can be done without destroying the basic simplicity and without sacrificing desirable features. Some new basic research in subtractive color mixture may be required.

The problem of metameric colors has not been addressed. While it is not a high priority, the response of colors under illuminants other D-5000 must be worked out.

Eventually the graphic arts industry must confront the problem of setting fundamental color standards. Color specifications must be a part of the standards. The specifications should be as close to absolute as possible and still be meaningful to the printing industry. A true fundamental specification does not rely on a physical sample or a particular piece of equipment. A color measurement and diagram such as the one described here could be a first step in working toward that goal.

We cannot sit back and wait for the CIE or ANSI to introduce color systems and standards ideal for the graphic arts. They cannot be expected to know our special needs and problems.

Conclusion

For years many have wondered why the graphic arts industry has been slow to embrace colorimetric methods. It may be due to the fact that existing colorimetric systems do not provide very meaningful information for graphic arts uses. The Spectralinear system could serve as a bridge between colorimetric systems and the present graphic arts measurement systems which usually employ densitometers. The new, more meaningful color diagram may cause an increased interest in spectrophotometric measurements. Accurate, meaningful color specifications and eventually color standards, based on fundamental measurements could evolve from the new interest.

Those who could immediately benefit from the Spectralinear system would include anyone selecting new colorants for use in color printing or proofing. Plots on a single diagram will not predict metamerism but will rule out primaries which produce excessive grayness when mixed. Unsuitable primaries could therefore be screened out without wasting valuable time and effort on the computer or on actual mixtures. Grayness is not indicated on the CIE diagrams.

The hue error and grayness lines provide a criterion for judging colorants. Hue error is a number which tells how far the colorant is from an "ideal"primary. Percent grayness indicates how far the colorant is from an "ideal" purity. Therefore, even a novice, with no understanding of how the color plot was made can interpret the results by reference to the hue error and grayness lines. The results of color mixture are predictable since they fall on a straight line. For instance, it is easy to see that a magenta cannot be moved closer to the ideal primary simply by mixing in a blue colorant.

Some of the new spectrophotometers and computers make it relatively easy to try new systems. After the program has been made, the calculations for X Y Z, R G B, or DX DY DZ are quickly made from the spectrophtometric data. The user need not choose one system over another. All can be used and applied where appropriate.

Until the Spectralinear system has met the test of time it should not be used exclusively, especially when extreme accuracy is important. For the present time the Spectralinear system should be considered supplementary, useful for gaining a basic insight into color mixture problems.

The subtractive system could be useful in other industries. The basic diagram could be used without the hue error and grayness lines. They would probably prefer a different illuminant such as D-65 which could easily be programmed.

The average printing plant may not find an immediate use for the new subtractive diagram because present equipment costs are relatively high. With the rapid advances being made in electronics and programming, a suitable instrument in the near future may be in the price range of the current tristimulus colorimeters.

It is my hope that the graphic arts industry will recognize the need for a subtractive color measurement system. There is no reason why we in the graphic arts could not agree on a measurement system ideal for our use, just as the CIE did for themselves more than 50 years ago.

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Appendix I

CIE 1964 Color Matching Functions Weighted By Relative Spectral Power Distributions of Reference Illuminant D-5000 (ANSI)

λ	xS_{50}	yS_{50}	zS_{50}
400	0.0853	0.0088	0.4568
410	0.4347	0.0439	2.3700
420	1.1136	0.1123	6.2869
430	1.6508	0.1965	9.6728
440	2.6047	0.4080	15.8521
450	2.9341	0.6843	18.7392
460	2.4858	1.0186	17.0349
470	1.6227	1.4854	12.9736
480	0.6952	2.1180	7.9180
490	0.1352	2.7374	4.1163
500	0.0327	3.8692	2.2526
510	0.3285	5.1423	1.1656
520	1.0373	6.4899	0.6345
530	2.1917	7.8402	0.3350
540	3.4469	8.5079	0.1487
550	4.9190	8.9018	0.0442
560	6.4001	8.7500	
570	7.7914	8.1911	
580	9.1028	7.5392	
590	9.4912	6.3776	
600	9.9659	5.6432	
610	9.2870	4.6001	
620	7.6934	3.4577	
630	5.6241	2.3808	
640	3.8698	1.5582	
650	2.3306	0.9037	
660	1.3604	0.5194	
670	0.7596	0.2878	
680	0.3676	0.1386	
690	0.1579	0.0588	
700	0.0799	0.0298	

Appendix II

Empirical Visual Strength Function

λ	V_{83}
400	0.002
410	0.008
420	0.030
430	0.090
440	0.199
450	0.499
460	1.371
470	2.516
480	3.190
490	3.479
500	3.738
510	3.987
520	4.457
530	5.366
540	6.379
550	7.319
560	7.926
570	8.482
580	8.482
590	7.926
600	7.319
610	6.017
620	4.688
630	3.065
640	1.662
650	0.913
660	0.469
670	0.240
680	0.124
690	0.041
700	0.015