Color, Color Measurement and Colorant Formulation in the Textile Industry

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THIS paper reviews some observations concerning the application of spectrophotometry and color science to problems associated with the coloration of textile materials. Although many of the ideas and data presented here have been developed in the course of 25 years, they have not previously been organized into a cohesive presentation.

The color of a textile material is often one of its most important features. While many other physical, chemical and mechanical properties are important in the design of textiles, styles and fashion dictate a major role for color.

ABSTRACT

Color is one of the most important attributes of a textile material. From the earliest availability of optical devices suitable for measuring the relative proportions of different wavelengths of light reflected or transmitted by a textile material, attempts have been made to relate these measurements to the color sensation produced in the mind of the observer.

The past, present and future of instrumental color measurement are critically reviewed. Attention is called to fundamental limitations in the ability to designate the perceived color of an object by a set of numbers. The theory and practice of instrumental colorant formulation are discussed.

KEY TERMS

Color
Color Matching
Color Measurement
Colorant Formulation
Instrumental Color Measurement
Metamerism

A. C. Hardy's research at M.I.T. from 1928 to 1935 resulted in the development of a recording spectrophotometer. This instrument, commercially developed by General Electric, permitted measuring the reflectance of a material rapidly and precisely. Hardy was so confident of the future for this type device that he stated (*1*) in 1932, "The utilization of color measurement is in its infancy . . . it seems inevitable that the control of color processes will be eventually taken over by men possessed of an accurate knowledge of the subject of color and equipped with suitable instruments." We may only now be close to this goal.

From about 1935 to 1945 considerable research was devoted to the industrial development of a method of color measurement. It is impossible to credit adequately those concerned, for much of the significant work in textiles was not published, but Pineo and Stearns at the American Cyanamid Laboratories, I. H. Godlove of General Aniline, Simon at Sidney Blumenthal, O'Neill at Pacific Mills, Hanlon at Mohawk Carpet Mills and Ingle at Monsanto come immediately to mind. In addition to the work in industry, basic studies were being carried out at the National Bureau of Standards by Judd and Keegan and at the Department of Agriculture by Nickerson. Hardy and his staff at M.I.T. provided the nucleus for many contributors to the early efforts in this field. The classic *Handbook of Colorimetry* prepared under their direction was first published in 1936. Its concise, presentation of the facts has maintained the importance of this publication for over 30 years (*2*). The experiments carried out by MacAdam while working in this laboratory provided the basis for his contributions to our knowledge of color difference perception and the mathematics of the implied color space.

Despite this substantial effort, as late as 1954 Derby could correctly state (*3*), "Within the last ten years, progress has been made in instrumentation and techniques which should encourage the wide use of instrumental color control of textiles. That the practical realization of such programs is not widespread is evidenced by the fact that, to the author's knowledge, no more than ten spectrophotometers are actively engaged in such work in the United States. This is partly due to the high cost of the instrumentation and partly to the general feeling that such methods are complicated and of dubious practical value."

While reflectance or transmittance could be measured rapidly and with considerable precision by using the Hardy instrument, the resultant curve, which plots reflectance or transmission as a function of wavelength, was not readily interpreted in terms of visual results, particularly for small color differences.

To relate two reflectance curves to the visual difference one had to resort to the psycho-physical theory of color measurement, formalized by the Commission Internationale de l'Eclairage (C.I.E.), in 1931, which requires a fairly complicated integration. The procedure has been well documented, particularly in the *Handbook of Colorimetry* (*2*).

The historical development that led to this system are clearly discussed by Wright in his book, *The Measurement of Color* (*4*)

A few instruments were provided with mechanical or electrical integrators—the early M.I.T. instrument had a prototype of a modern digital readout—but most work had to be done by hand with the aid of a desk calculator. The procedure was slow and tedious, and results were often inaccurate. Routine use of statistical analysis was also impractical, for one rarely could afford the effort of two integrations. Thus, when Davidson and Imm (*5*) produced their mechanical integrator based on the Librascope ball and disc integrator in 1949, the way was opened to a greater use of colorimetry as opposed to the previous reliance on spectrophotometry.

Note should be made here of Hunter's ingenious experiments at the National Bureau of Standards (*6*) which enabled the required integration to be carried out by carefully matching filter transmissions and photocell sensitivities and provided the basis for all modern filter-photocell colorimeters.

In our laboratory, upon acquiring a Librascope integrator, we became aware of the great increase in precision associated with continuous integration. In addition, multiple measurements within and between samples became commonplace, the standard deviation of the means of even two measurements rarely exceeding 0.0005 in chromaticity coordinates (x, y) for reasonably uniform samples. The application of simple statistical techniques to these data paid great dividends. The importance of this approach in attaining the precision required cannot be overemphasized. However, in the last 20 years the greatest gain has been in the area of more rapid data acquisition and the use of digital readout devices which enable the rapid evaluation of virtually any functional relation between the variables involved by interfacing with high-speed computers. These are conveniences; the basic problems unfortunately still plague us.

The major problems associated with the coloration of textiles are as follows:

- Color Formulation. This primary problem comprises the production of a formulation of colorants having the desired physical and chemical properties, which in addition produces the desired color (or shade) on a textile. In the textile industry, colorant formulation generally implies color matching.
- Color Control. Once the customer has accepted a formulation and production is started, it is necessary to control the process variables so as to maintain and deliver the color desired.
- Color Tolerances. Inherent in the decision as to whether the process is in or out of control is the necessity for establishing tolerances.
- Standards. In a number of instances it is desirable to maintain "standard" colors. The colors of military uniforms, insignia and flags, and historical emblems are an example. Some physical samples may fade or change color with time. Therefore, a method of specifying the color without retaining a sample is desirable.
- Color Faults and Their Evaluation. If, for any reason, a problem arises in production of the desired shade, formulation, fastness, etc., spectrophotometry and colorimetry are useful tools in solving the problem.

We shall consider each of these problems in turn, confining most of our remarks to the problem of colorant formulation (*7*).

Although "color matching" is often used interchangeably with "colorant formulation" when discussing the application of instrumentation to the problem, it is my conviction that a distinction between the two should be made. While instrumental colorant formulation is very feasible and has been extensively practiced over the last 20 years, one never produced a color match by instrumental methods except by implication (and in most cases, chance!). The following paragraphs will discuss in some detail, first, the color matching problem and then, the colorant formulation problem.

Color Matching

The color of an object poses no great difficulty to the average observer, although its description may. Color as an element of appearance is readily determined with considerable discrimination, [for simplicity, we will restrict our discussion to object color (*8, 9*)]. As with many other phenomena in nature, a detailed quantitative comprehension of the entire process is not easily attained.

The study of atomic and molecular structure is a well known example of this type problem. Complex organic molecules contort, react, interchange atoms, etc., with little concern for those versed in the intricate mathematics of quantum mechanics to follow and explain their behavior—so it is with color and the eye.

Simply stated, color matching implies

$$\text{Color A} \equiv \text{Color B} \qquad (1)$$

The difficulty arises with the meaning of equals ($\equiv$).* It seems that what is implied is that the sensation of color is equal,† or that

$$\text{Color sensation A} \equiv \text{Color sensation B}$$

The problem in color matching is: given color A (sensation A), how are the variables available adjusted to reproduce this visual response (on fabric, plastic, paper, or leather, for example)? This is a very complicated problem for which no universally accepted solution can be stated. An important advance in color science resulted from studies which determined that three suitably chosen variables are generally necessary to describe a color.

An excellent review and discussion of the trivariance of vision has been given by LeGrand (*10*).

Recent important studies by Evans (*11*) on the variables of perceived color indicate that three variables may not be sufficient to describe color in the natural view, i.e., surrounded by other colors.

While not refuting the trivariance of color, the work of Land et al. on retinex theory (*12*) should be carefully read by those puzzled by the problem of maintaining reasonable constancy of object color in the natural scene despite tremendous fluctuations in the physical quantities involved.

It is not essential to the arguments presented here that a commitment be made as to the number of variables involved. The conclusions are not affected by the choice of this number.

If for the sake of argument and simplicity we confine ourselves to the three variables, hue, saturation and brightness (*8, 13*), a human color perception may be described as:

$$\text{Color A} \equiv (H, S, B)_{\text{a}} \qquad (2)$$

This resultant visual sensation may, in turn, be related to many variables in the observer's environment or within his responsive system. Thus the three variables may be related (*8*) as follows:

$$(H, S, B) = f\,(E, R, r, g, b, M, S, A, O, T, \ldots, u, v, w) \quad (3)$$

where the product of E and R represents the spectral composition of the light striking the eye, r, g, b define the particular observer's spectral sensitivity, M his memory, S the nature of the surroundings, A the state of adaptation of the observer, O the nature of surrounding objects, T the observer's attitude, and u, v, w are other unspecified variables relating to the particular case.

Some basic facts need to be summarized at this point: (1) the color of an object is a visual sensation, therefore, always related to the eye, brain and related response systems; (2) the general functional relationship in terms of the psychological scales, hue, saturation and brightness, is related in a fairly complicated and generally unknown way to the measurable variables.

It should be clear from the preceding considerations that color cannot really be determined or measured by any means other than the eye. This point, although not explicitly made, is interwoven in all the discussions of color measurement by Wright (*4*), Le Grand (*10*) and Hunt (*14*).

The color matcher's problem is to manipulate the variables at hand (dyes, concentrations, finishes, etc.) so that

$$\text{Color A} \equiv (H, S, B,)_{\text{A}} \equiv \text{Color B} \equiv (H, S, B)_{\text{B}} \quad (4)$$

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† In general, the statement should be appearance A $\equiv$ appearance B where terms such as size, shape, location, texture and gloss are considered. For this paper we will consider only the color aspect.

* Following Wright (*4*), we have avoided the algebraic implications of the equals symbol ($=$). Except where it is desired to show an actual functional equality, the sign ($\equiv$) should be read "matches."

Substituting eq. (3) into this equivalency yields a reasonably concise statement of the problem:

$$f\,(E, R, r, g, b, M, S, O, T, \ldots)_a \equiv f\,(E, R, r, g, b, M, S, O, T, \ldots)_b$$

Since the color matcher is restricted in the number of variables he can control or manipulate, his dilemma under many practical situations is apparent.

However, by placing certain restrictions on the functional variables involved, it is possible to relate instrumental measurement to visual experience and, consequently, obtain many useful results.

First, one eliminates all variables in eq. (3) except $(E, R, r, g, b,)$ by either keeping them constant or so arranging conditions that they are zero. Under these restrictions only the reflectance R can affect the comparison of the two samples by any one observer. In view of this point, E and $r, g, b,$ were standardized or fixed by definition in 1931. The result was the C.I.E. system of color measurement which has been described in great detail elsewhere (*2, 4, 9*).

In this system,

$$\text{Color} \equiv (X, Y, Z) = f\,(E_{\text{std}}\, R, \bar{x}, \bar{y}, \bar{z}) \quad (5)$$

or, for E_{std} and $\bar{x}$, $\bar{y}$, $\bar{z}$, constant,

$$\text{Color} \equiv F\,(R) \quad (6)$$

Under the assumptions and restrictions imposed, we now have:

$$\text{Color A} \equiv (X, Y, Z)_a \equiv \text{Color B} \equiv (X, Y, Z)_b \quad (7)$$

as the basic instrumental color measurement equation.

It should be carefully noted that these results are implicitly related to the eye since,

$$f\,(\bar{x}, \bar{y}, \bar{z})\ (\text{standard observer}) = \text{avg. of } f\,(r,\ g, b,) \text{ for } n \text{ observers}$$

Since reflectance is the only variable, in the case of one observer examining the two samples under one light source, (for example, the standard observer in standard illuminant C), it is clear that if $R_a = R_b$, then color A will be equivalent or "match" color B (under the restrictions imposed above).

Part of the answer to the matching question then, is as follows. Add dyes in the proper amount and having spectral characteristics such that one produces identical reflectances for the standard and the match. One method of doing this (probably the only method guaranteeing success), has been detailed by Saltzman (*15*) as color matching by colorant identification.

Often, it is possible to obtain closely similar reflectances without resorting to identical colorants. The elegance of this approach is that the match will be largely independent of observer and illumination conditions, provided the restrictions introduced are complied with.

One determines that $R_a = R_b$ by measuring the two samples on a spectrophotometer. Such a procedure may not be completely satisfactory, since R in the preceding equations refers to the observer's illuminating and viewing conditions, and these may be far from those employed in any particular instrument. The problems inherent in reliably measuring R have been treated in detail elsewhere (*9, 16*) and will not be discussed further here. However, when a spectrophotometer is used to measure the reflectance difference between two samples, since both samples are measured on the same instrument, that the result will at least be comparative and proportional to the visual results. If there is any appreciable difference in texture between A and B, this experience is apt to be poor.

In order to proceed with the practical possibilities, let us assume that instrumentation is available that permits a reliable measure of R [Actually, modern instruments produce satisfactory results in most cases if proper care is taken in sample preparation and presentation (*17*).]

A reliable reflectance measurement might best be defined as one which, when substituted in our functional relation for object color, produces results in agreement with observations of the average observer under standard viewing conditions.

A common method employed by visual color matchers that approximates the use of a spectrophotometer is to examine the two samples under as many light sources as possible (north light, artificial daylight, tungsten light, fluorescent light, "overhand", etc.). If the samples match under all these conditions, the chance of the reflectances being significantly different is rather remote.

Often, due to technical requirements other than color, such as chemical stability and cost, colorants must be used which cannot result in R_a being equal to R_b. Under these circumstances, since the color, as seen by the observer, is an integrated result of the interaction of the light sources, reflectance, and observer sensitivity (in the simple case), there are a very many combinations which fulfill the basic equation.

$$(X, Y, Z)_A \equiv (X, Y, Z)_B \quad (8)$$

An example taken from practice is shown in Fig. 1. This represents a compromise made by the color matcher because the available dyes for fiber B cannot possibly duplicate the reflectance (R_a) on fiber A.

In general, these combinations are apt to be quite sensitive to the nature of the light source and to the observer. Such matches are called metameric or conditional. They are a general source of complaints by customers regarding the quality of the match. In fact, in my opinion, the major success of instrumental color formulation has been to finda better solution to the metameric problem. In more pragmatic terms, one needs to discover whether the shade should be adjusted by adding a red and yellow dye or just an orange.

Before the use of instrumental methods very few colorists were skilled enough to answer this question properly under all circumstances, although the examination of the sample and standard through a cobalt blue filter of proper thickness generally provides the solution to the "orange problem" mentioned above. A clear discussion of metamerism in terms of colorimetry has been given by Wyszecki (*18*).

Colorant Formulation

The textile color matcher has at his disposal hundreds of dyes. How does he select the particular dyes and concentrations to satisfy the required functional relations? Although extremely important technically, the methods of evaluating dyes for their chemical and physical properties or relative fiber affinities will not be dealt with here, and the availability of a

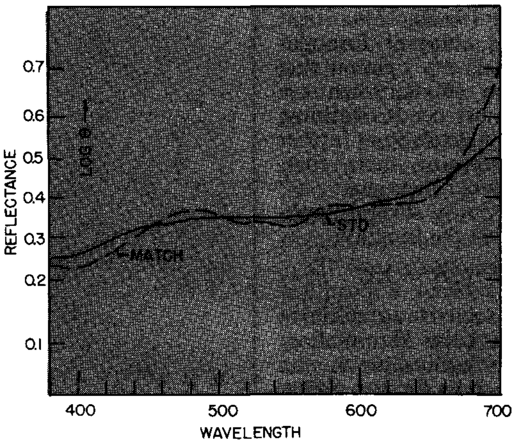

Fig. 1. Commercial metameric match prepared by visual color matching. Available colorants cannot match standard reflectance curve.

range (20-30) of dyes available displaying the requisite properties of chemical stability, cost and ease of application will be assumed. The question remains, how does one determine the quantity of the selected dyes necessary to obtain the desired values of reflectance at different wavelengths?

The reflectance of a textile material, due to scattering and surface reflection, is not a simple function of the molecular absorption characteristics of the applied dyes. In addition, the fiber has its own characteristic absorptions.

A considerable amount of research effort has produced a number of analytical and empirical relations of the form

$$C = f(R) \qquad (9)$$

or

$$R = F(C) \qquad (10)$$

It is not sufficient merely to find a relationship that satisfies eq. (9). In order to be useful, it must be an additive function for each dye and substrate over the concentration range of interest, thus

$$F(R)_{\text{total}} = F(R)_{\text{dye 1}} + F(R)_{\text{dye 2}} + F(R)_{f} + \ldots \qquad (11)$$

This important point was made by Parks and Stearns in a paper (*19*) detailing the principles of instrumental color (colorant) formulation.

A simple relationship for solutions which follow Beer's Law illustrates such a function, where the additive function relating concentration to transmission is

$$A = \log (1/T) = KC \qquad (12)$$

Thus, for three dyes, one has the simple expression

$$A_{\text{total}} = A_1 + A_2 + A_3 \qquad (13)$$

The mathematical details, assumptions and boundary value solutions for reflectance of turbid media have been reviewed elsewhere (*9, 20, 21*).

With respect to colorant formulation on textiles, it is my opinion that sufficiently precise relationships are available to suit most needs. Refining the present functional relations further and generally increasing their complexity would engender little gain.

It has been shown by several methods (*20, 22, 23*) that the function

$$\theta = (1-R)^2/2R = KC \qquad (14)$$

is a good approach to an additive function for textile color formulation. This expression is equivalent to the Kubelka-Munk analysis for the reflection of turbid media having zero transmission. In their two-constant theory, $\theta = K/S$, where K is an absorption coefficient and S is a scattering coefficient. It should be noted that Pineo (*22*) derived an identical expression independently without the necessary restrictions placed on the Kubelka-Munk analysis. For low values of R, the surface reflection of the material R_s should be subtracted before applying eq. (14). R_s is generally less than 2%. In most textile applications K/S is taken as a ratio, with absolute values for either constant being unknown, hence is more conveniently designated θ.

Since $\theta = KC$ is an additive function, we have

$$\theta_T = \theta_f + \theta_{D1} + \theta_{D2} + \theta_{D3} \qquad (15)$$

for a three-dye (D_1, D_2, D_3) system plus substrate (θ_f).

As eq. (14) relates concentration to reflectance, the conditions $R_A = R_B$ will be satisfied if $\theta_A = \theta_B$, where both equalities refer to the complete visible spectrum (approximately 400-700 nm).

The "matching equations" in terms of dye concentrations are then

$$\theta_A = \theta_B = C_1\theta_{D1}' + C_2\theta_{D2}' + C_3\theta_{D3} + \theta_f \qquad (16)$$

where θ_{D1} is the value of $\{[(1-R)^2/2R]-\theta_f\}$ for a unit concentration of dye $_{D1}$.

Colorants must be found whose spectral absorption characteristics are such that concentrations can be found to satisfy eq. (16) at all wavelengths. It is obvious that without a high-speed computer or some special technique, such a solution would be rather difficult to find. Some hint as to the solution may be obtained by noting for example, that in order to match a blue we should not choose a brown dye. By this logical procedure, the number of random trials can be drastically reduced.

An ingenious method of solution of eq. (16) was patented in 1938 by Pineo (*22*). It involved devising a system wherein a spectrophotometer plots the function log θ as an ordinate instead of reflectance. Curves are produced whose shape (ratio of absorption as a function of wavelength) is independent of concentration; changes in concentration merely displace the curves vertically, as shown in Fig. 2. In order that a solution to the matching equation at all wavelengths be possible, it is necessary that some vertical displacement of the curves for individual dyes (log $\theta_{\text{dye 1}}$, etc.) permit superposition on the log θ_a curve. If this appears possible, the concentrations may be obtained by solution of three simultaneous equations or by the nomographical method developed by Stearns (*17*).

This procedure, which has been discussed in considerable detail elsewhere (*24*), is illustrated for a simple three-dye combination in Fig. 3. This method has been in existence for more than 30 years but still has considerable utility in the solution of problems involving textile colorants.

Nearly all reflectance curves recorded in our laboratories are drawn with log θ as the ordinate. The utility of this type of presentation is due to its acquisition speed (55 sec), flexibility and simplicity of interpretation. Simple formulations of two or three dyes, with clearly separated absorption maxima can be prepared in a few minutes; more complicated ones for five or six colors with badly overlapping absorption bands take somewhat longer.

Selection of colorants is readily carried out by inspection, since the curve shape is constant regardless of concentration (as long as $\theta = KC$). In most instances, selection of colorants for other methods of computation is done by this method in our laboratory.

It should be noted that the curve shape will also be independent of concentration in the case of a number of other additive functions which take the form $\theta = KC^n$.

A number of "improved" forms of the basic θ function can be put into such a form; consequently even if the system does not obey the simple Kubelka-Munk equation, equally useful results are obtained. Under these conditions, a correction factor equal to n must be applied to the vertical displacement to obtain the true concentration differences.

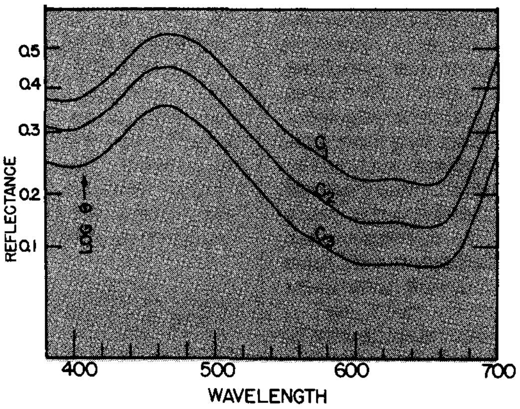

Fig. 2. Plot of log θ = log $(1-R)^2/2R$ vs. wavelength (nanometers) showing constancy of curve shape at different concentrations C_1, C_2, C_3.

The details of other methods (*25-27*) of solution of the required equations will not be considered in this paper, but it should be noted that any physical quantity proportional to θ can be used to obtain solutions. Since methods are widely available for accurately controlling and proportioning voltages, the electrical approach is appealing. The electrical analog approach has been extensively developed by Davidson (*28*) in experiments with analog simultaneous equation solving. These experiments culminated in the commercial production of a device called COMIC I, which permits the observation on an oscilloscope of the sixteen simultaneous equations.

While this device has been largely superseded by digital computers, some of its features are novel and worthy of mention. The 16 points displayed are redundant by 11. All that is needed to solve for the concentrations of five colorants are five simultaneous equations with θ_T or voltage V_T at five selected wavelengths. The redundancy is necessary to determine whether the correct colorants have been selected by checking the solution at the other 11 points and to permit calculation of tristimulus values. The oscilloscope display permits the simple determination of the best possible solution to 16 simultaneous equations when there is no exact solution. By the use of auxiliary equipment this "solution" can be made the best possible in a colorimetric sense.

The techniques discussed above and other similar methods permit the entire process (including measurement) of determining the dyes to be used and their proportions to be carried out in 15-20 min. At this point, it is important to re-emphasize we have a trial formulation, not a match on the material at hand.

Up until now we have only developed a solution for the special case where $R_a = R_b$ (or only slightly disagrees).

If such a solution is impossible because of other requirements such as fastness, price, dyeing process, etc., we must produce a metameric or conditional match. In this case the values of R_b must be adjusted by varying dye concentration and selection so that equality exists for a set of at least six integrals of the form (for X).

$$\int_{400\text{ nm}}^{700\text{ nm}} E_c R_a \bar{x} d\lambda = \int_{400\text{ nm}}^{700\text{ nm}} E_c R_b \bar{x} d\lambda \tag{17}$$

Similar equations exist for the tristimulus values Y and Z. If more than one illuminant is of interest, six equivalent integrals will be required for each light source.

The reason for the importance of the solution $R_a = R_b$ should be apparent. In practice we never really know the magnitude and spectral distribution of E or the observer's spectral sensitivity, thus, the only simple general solution possible is for $R_a = R_b$.

For a standard light source and a standard observer, it is possible by various methods to express the difference in tristimulus values ΔX, ΔY, ΔZ in terms of ΔR (*23, 27*). The fairly complicated mathematical operation of reducing ΔX, ΔY, ΔZ to a sufficiently small number by varying ΔR through the functional relation $\theta = f(R) = KC$, can be carried out by modern analog or digital computers using iteration methods. An elegant exposition of the mathematics involved in these methods has been given by Allen (*25*). Several computer programs have been developed along these lines.

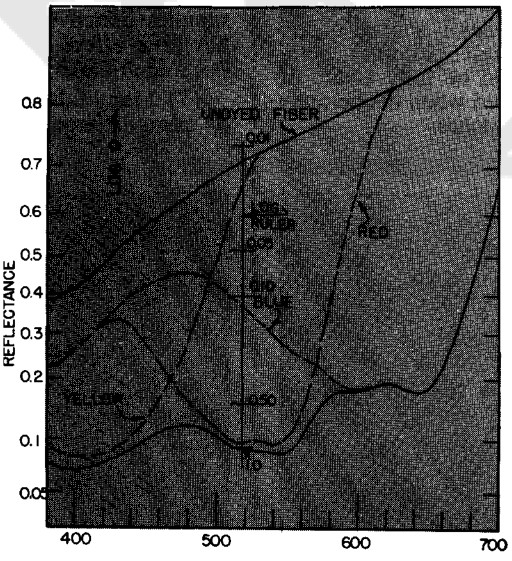

Fig. 3. The Pineo method of colorant formulation. Since log $\theta = (1-R)^2/2R$ is an additive function, the combination of yellow, red and blue necessary to match the standard (solid line) is readily determined. The relative concentrations of each dye is read directly from the transparent logarithmic nomographic scale. In principle, this is the same method used in the COMIC and digital computer methods where the solution $R_A = R_B$ nonmetameric match is desired.

By combining the various approaches outlined above, it is possible to obtain a formulation which satisfies the equations of a simple instrumental color match. (The results can be available within a few minutes after measuring the spectral reflectance or the sample.)

Almost any variety of modifications to the basic procedure can be introduced into this system. ΔX, ΔY, ΔZ can be calculated in a few illuminants, a "metameric index" (*25*) obtained, and the formulation altered to obtain the optimum value. A minimum cost formula can also be calculated. Fastness properties, compatability with the system and affinity can also be built into the combined computer and information retrieval system. The complexity of the calculations for four or more dyes transcends simple comprehension, but may be within the capability of modern high-speed computers.

In favorable cases, the results employing any of these methods are straightforward. First trials of computed formulations often produce matches (by visual examination) within at least three or four color difference units of the standard (i.e., for the Adams-Nickerson equation with a factor of 40, presently accepted terminology being AN-40).

The limitations that prevent 100% instrumental match formulation and subsequently a true visual color match by use of the simple methods outlined above are unfortunately fairly numerous and constitute a barrier to realizing the goal of color matching solely by reference to instrumental measurements and computation.

(1) Failure to obtain a reliable measure of reflectance is a problem due to the lack of correspondence of instrument geometry with visual viewing conditions, lack of sensitivity or accuracy of the instrument and the nature of sample with respect to size or texture.

(2) Failure of ΔX, ΔY, ΔZ, equal to zero by computation to be equal to zero visually is a problem related to metamerism and a number of less common problems.

(3) Because of variations in the dyeing process such as concentration errors, fiber variation and control of the dyebath pH and temperature, duplicate dyeings often vary by an amount which exceeds the matching tolerance. This leads to the problems illustrated in Figs. 4-6. When the first trial formulation is dyed it usually does not match the standard; therefore, a cor-

rection must be applied. Since the measured ΔX, ΔY, ΔZ are not the true values due to the variability of the process, the correction, no matter how mathematically precise, will produce a match only by chance. The probabilities associated with this chance are readily determined once the variances are known.

In addition to the variation of the dyeing process, one must consider the variation of the measuring process which, depending on the nature of the sample and the precision of the instrument, may be smaller or larger than the dyeing variation. With the use of a good instrument with a simple homogenous sample, this variance can be expected to be about 10% of the variance associated with the dyeing process. Some interesting observations on these matters have been made recently by Marshall and Tough (*29*). The importance of statistical considerations in all aspects of instrumental color measurement cannot be overemphasized. Fig. 6 shows the variation in repeat measurements on a piece of wool flannel. The improvement in variation from the mean obtained by the simple expedient of comparing the averages of two readings is clearly demonstrated and is somewhat better than theoretical improvement expected for a normally distributed sample. In practice, it is rarely worth making more than four readings on the same sample. The gain in precision is not sufficient to justify the extra time involved.

Attempts to produce matches within a smaller tolerance than the sum of the variances is not logical from a statistical viewpoint; however, it is necessary in practice. The color matcher must, by some means, obtain a match that suits the customer no matter how small his tolerance, therefore, he must know that such a match can actually be attained. Experience indicates that a formulation may produce a near, but unacceptable match. However, it may not be possible further to correct the formulation instrumentally to attain a better match.

(4) The greatest single cause of disagreement between customer and supplier regarding the quality of the match is the metameric or conditional match. The difficulty a visual color matcher encounters in attempting to produce a metameric match that satisfies the customer (whose spectral sensitivity function is unknown) in several light sources is evident from consideration of eq. (5).

Fig. 7 shows the results of a color matcher's attempt to produce a metameric match as compared to a nonmetameric match of the same color. The difficulty with the metameric match lies with his attempt to compromise several illuminants not just the illuminant C illustrated. In fact, he is not even matching in standard illuminant C, but rather by means of an artificial daylight lamp (MacBeth), whose spectral energy distribution differs considerably from illuminant C. This is not a factor in the nonmetameric case, but may be critical for the metameric match.

Instrumental color matching in the metameric case will produce more consistent results, since the instruments experience no such conflict of goals. However, correspondence between the instrumental match and a visual match will frequently be poor.

The preceding argument is not to be construed as indicating that metamerism should be avoided at all costs, however it is a major source of rejected material and customer complaints. One should be fully aware of the dangers involved when deliberately producing such matches.

It is often noted in the literature that the easiest method of insuring nonmetameric matches is to formulate with the same dyes or colorants as in the standard. If more than three dyes are used in the formulation, no insurance against metamerism is provided by this method. It can only be stated that under these conditions, it is possible to produce a nonmetameric match. It is also possible to produce a large number of metameric ones. This possibility increases rapidly with the number of colors involved.

(5) Some samples are difficult or impossible to measure. Intimate blends containing many colored fibers comprise one such class. Such blends produce interesting style effects, but matching such a mixture, where the spectral and colorimetric nature of the components is unknown, is extremely difficult. Usually, one has to resort to "microscope matching." Very small samples, i.e., portions of prints, mixed yarns or very small colored areas within a larger sample, are difficult to measure with reliability.

(6) Both instrumental and visual matching of fluorescent materials can be difficult, since in this case the reflectance (R) is a generally unknown function of the illuminant (E). Thus, it is not easily possible to measure reflectance under one light source and calculate the results in another, as in the simple color measurement equations where E and R are independent variables. The nature of this problem has been discussed in detail by Allen (*30*). One cannot expect the precision under these circumstances we have come to expect of nonfluorescent colorimetry. A new variable is introduced, and we have the possibility of fluorescent metamerism, wherein two samples match under a source which has little effect on reflectance but do not match under a more active source.

(7) Many fabrics contain two, three or more different fibers. Each of these

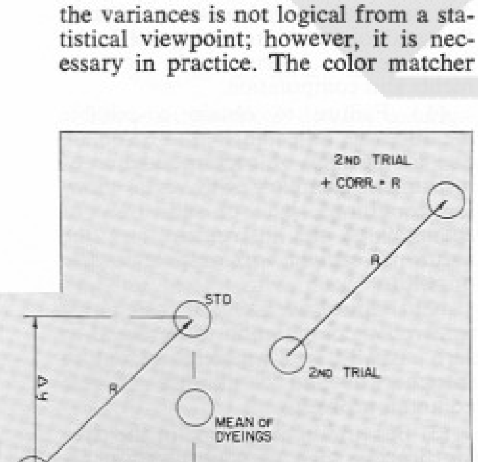

Fig. 4. Effect of reproducibility of dyeing and measurement process on predicted match.

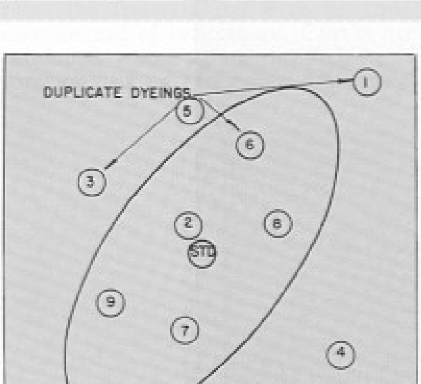

Fig. 5. Variation in dyeings. Dyeing 1-10 were made simultaneously by using the standard formula under carefully controlled conditions.

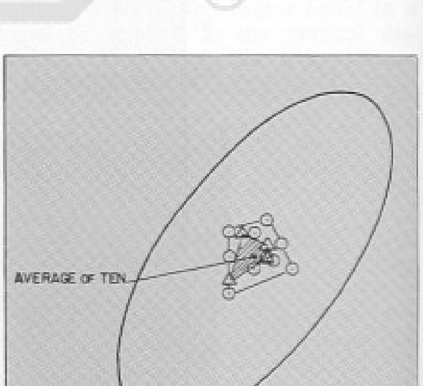

Fig. 6. Variation in repeat measurements on same sample removed and remounted. Comparison of single to means of two measurements: (○) single measurement; (△) mean of two measurements.

may be dyed with several different dyes. The ideal circumstance would exist if each set dyed only one fiber or one set dyed them all. Unfortunately, this is rarely the case, and each fiber displays its own relative affinity. This affinity depends on many things and is not independent of the quantity and type of other fibers present. Many practical cases become unbelievably complicated and again, one may have to resort to the microscope.

(8) The problem of visual effects outside the limits of the simple color measurement equations will not be discussed in detail, but it should be noted that common examples may be found in textile color and design of virtually every type discussed by Burnham (*8*) and Judd and Wyszecki (*9*). Some of the more common are: simultaneous contrast, spreading effects, area effects and surround and diffuse edge effects. In all of these cases, $(X, Y, Z)_A$ may be equal to $(X, Y, Z)_B$, but the samples or areas do not match. In order to produce the desired match, it is necessary to produce a ΔX, ΔY, ΔZ different from zero. Unfortunately, the functional relations are not generally available which would permit instrumental formulation of the proper difference to produce the desired color effect (*18*).

The functional relations and instrumentation are sufficiently developed at present to enable rapid calculation of formulations from basic data where one is given either reflectance or colorimetric data on the material to be matched. Thousands of calculations of this type have been made which indicate the validity of the underlying assumptions.

The formulations produced by these methods can be expected, in many cases, to produce initial matches within a few color difference units of the standard. Due mainly to variances inherent in the measurements and the basic data, it is unlikely that much greater precision can be expected. In addition, certain fundamental errors are involved in relating instrumental color measurement to visual results.

In the future, the complexity of any calculation will provide no deterrent to its usage. The basic data on various colorants will be stored in an easily retrievable state. Improved instrumentation and computational techniques based on the principles already proven will be available which will facilitate proper color matching. It appears, however, that the final arbiter will always be the color sensation produced in the eye and brain of the customer, despite McLaren's cogent arguments for the instrumental approach (*14*). If the homemaker, architect or designer does not see the color he desires he will never be happy with the fact that the calculated color difference from the standard was zero.

In considering the complexity of the color matching problem, it is not considered likely that the entire problem will be handled instrumentally in the foreseeable future. Rather, the color matcher will be trained in the use of spectrophotometry, colorimetry and computer methods. These aids will relieve him of the routine, simple matching tasks and enable him more intelligently to cope with the complex problem.

Principle Of Average Change

The value of quantifying and applying statistical techniques to colorimetric data is illustrated in Fig. 8. Starting with process 1 we have indicated the inherent variability by the ellipse. For example, this could be the color of a fiber blend. The next process introduces its own variations, which may be larger or smaller than the first. As an example, further blending would generally reduce the initial color differences. Following the colorimetric path of the material through to the final step where it is examined and compared to a suitable standard, one notes a series of vectors in the color space employed. Each sample follows some such path as it progresses through the various production steps. The result is a dispersion or scatter around the standard. If this total variation falls within the customers' tolerance the material will be acceptable, otherwise, some predictable percentage will be rejected.

If the vector relationships can be kept constant, on the average, within the limits indicated by the variability ellipses, the final material will fall within the customers' specification indicated by the last ellipse.

It will then be necessary only to determine the average change vector and begin at this point (process 1) and finish at the standard.

Two points are perhaps obvious, but worth mentioning: (1) if the entire process takes place within the tolerance ellipse, little concern for the individual steps is required; (2) the larger the average change vector, the greater control of the individual process vectors will be required in order to stay with final tolerance.

To this extent, it would appear we are on the verge of realizing the vision of the future expressed by Professor Hardy nearly 40 years ago.

Color Control

If color can be reliably measured or quantified with sufficient precision, then its control becomes a matter of straightforward application of well-

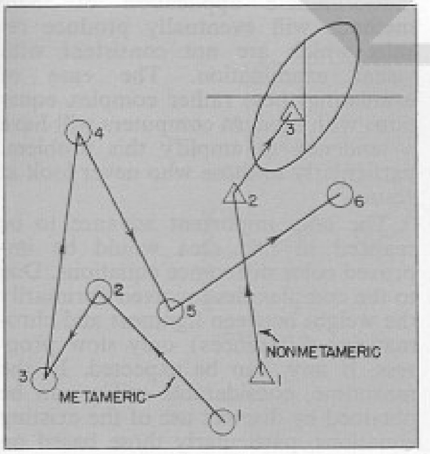

Fig. 7. Comparison of metameric and nonmetameric matching with respect to trials and difficulty of attaining match. Ellipse represents "target" match.

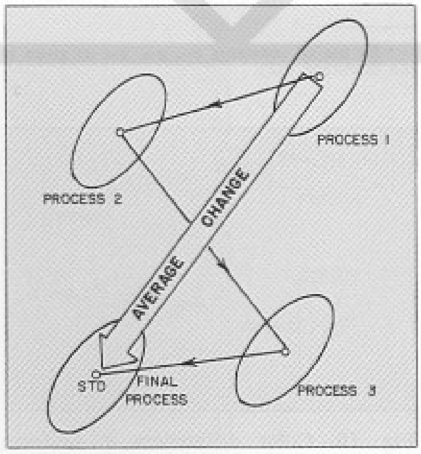

Fig. 8. Principle of average change vector in multiple stage process color control. See text for details.

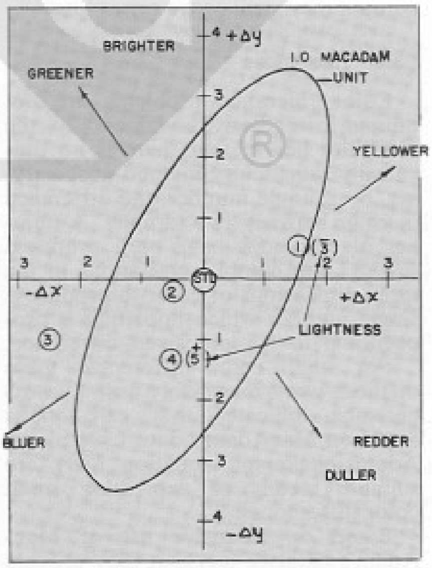

Fig. 9. Color quality control chart of the four production samples shown: (3) unacceptable for chromaticity (outside ellipse), (4) unacceptable for lightness (+5 in parenthesis); and (1) borderline. The units are Δx, Δy, $\Delta Y \times 1000$.

developed methods of statistical quality control.

Some sort of a control chart or color map (similar to that shown in Fig. 9) is usually employed. A number of ingenious and convenient plotting methods have been devised. Hundreds of thousands of instrumental color measurements are made each year for this purpose. Their success provides some confidence in the theory of color measurement. It may be useful to plot such data in a more uniform color space. This is readily accomplished by using modern computer techniques.

This concept has provided the basis for successful color control for millions of yards of cloth manufactured to the very close tolerances required by the U.S. government. The most important point is that it would be extremely difficult to apply this statistical technique visually. It is under such circumstances that colorimetry offers its greatest value—not in deciding whether a sample is redder or greener than the standard.

The limitations on instrumental color control are inherent in the theory of color measurements as discussed earlier. A further complication is difficulty of obtaining meaningful instrumental results on many colored materials of commercial importance.

The future in this area is well defined. One can expect a steady advance in the ease of data acquisition, storage and display. An increased awareness of the power of statistical methods, coupled with the ease of computation, will prove rewarding.

Color Tolerances

Color tolerance problems are not unique to textiles. Fundamentally, the difficulty lies in that there is no universally satisfactory method of specifying, by a single number, the difference in color between two samples. A number of equations have been proposed (*18, 31*) to combine variations in the three dimensions of color to produce a single number which hopefully is proportional to the perceived difference. For small color differences these methods work reasonably well. Our experience indicates that calculations based on MacAdam's data (*32*) or the Adams-Nickerson equation (*18*) are suitable means of expressing small color differences.

Based on extensive use of MacAdam's data we feel that they provide a reliable guide to the relative importance of chromaticity differences for small differences (5 CD or less).

The major problem appears to arise when one attempts to incorporate the lightness term: no simple constant ratio between the lightness difference and the chromaticity produces generally satisfactory results. I believe that there is an inherent problem here that is related to the experiences recently publicized by Land (*12*). The problem is graphically illustrated in Fig. 10.

The success of the Gray Scale method of evaluating color differences would seem to indicate the feasibility of equating a lightness difference to a chromaticity difference. Based on visual experience and examining the data on thousands of samples, it is our feeling that there exists a fundamental problem in that the relation is not constant. Again, for small differences (the smaller the better) this is not a major problem, and consistent results are obtained. Since we believe that chromaticity differences (ΔC) and lightness differences (ΔL) are fundamentally visually distinct, it is our practice to record these differences separately as well as combined in a "total" color difference (ΔE). Recent practice of fractionating the problem into red-green, blue-yellow differences in addition to lightness differences have good theoretical foundations in the color vision theories of Hering, Hurvich and Jameson (*33*) which seem to be gaining general acceptance. Hunter's *L, a, b,* scales (*34*) use this concept.

Due to the fact that the numerical results are not adequately normalized, i.e., the same value of color difference in the yellow and blue regions does not appear visually equal, it is difficult to generalize with respect to tolerances. An approximate guide for textile materials based on examining thousands of results in our laboratory is: for close tolerance chromaticity, 0.5-1.0 MacAdam's Units,* lightness 5%; commercial tolerance chromaticity, 1.0-2.0 MacAdam's Units,* lightness 10%.

It cannot be emphasized too strongly that these are only guidelines and will vary from one part of the chromaticity diagram to the other and with lightness level. One of the most sensitive areas of color discrimination occurs when the eye is adapted to the color being judged. In practice this occurs when examining large areas of cloth for area shade variations. Such differences produce a condition referred to in the trade as "shady," "cloudy," or "streaky" material.

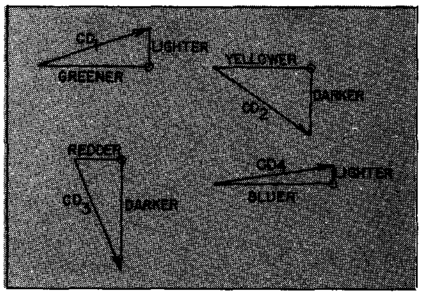

Fig. 10. Color differences in uniform color space. If plotted in truly uniform color space $CD_1 = CD_2 = CD_3 = CD_4$. Unfortunately, it has not been possible to find a completely satisfactory transformation, especially when considerable differences in the lightness terms are present (CD_3 and CD_4).

Some years ago we demonstrated an excellent correllation between the judgment of inspectors at the mill level and color difference measurements on samples of this type (*35*) This work was based on the application of the Adams-Nickerson color difference equation, but due to the small size of the differences, other equations will undoubtedly give satisfactory results.

The tolerances found were (using $f = 100$ in the CD equation): ΔE less than 1.0 (blues 0.80), acceptable; ΔE greater than 1.0, less than 2.0, slightly shaded; ΔE greater than 2.0, badly shaded.

Another difficulty with color tolerance specifications is that they may not represent a uniform relation to perception differences. Thus, due to preference, knowledge of the enduse, etc., certain directions in color space may be tolerated to a greater extent than one would predict based on perception data. For example, it is almost certain that the green tolerance in the cast of meat borders on the limits of perceptability, whereas almost any saturation or lightness variation would be tolerated. This problem led Professor A. C. Hardy to consider color tolerance specification in a general way to be impossible. He may be correct.

In closing these remarks on color tolerances, it should be emphasized that when used with care and knowledge, the reduction of colorimetric data to a single number "color difference" can be most useful. However, indiscriminate application of these methods will eventually produce results which are not consistent with visual examination. The ease of evaluating these rather complex equations with modern computers will have a tendency to amplify this problem, particularly to those who never look at results.

The only important advance to be realized in this area would be improved color difference equations. Due to the complexities involved (primarily the weight between lightness and chromaticity differences) only slow progress, if any, can be expected. In the meantime, considerable utility can be obtained by discreet use of the existing equations, particularly those based on MacAdam's work (*31, 36*).

Standards

Maintaining standards without recourse to physical samples has always

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* By use of constants g_{11}, g_{12}, g_{22} as given in the literature (*32*).

been of interest. If one wishes to specify a homogeneous colored textile by means of colorimetric data in order that its shade may be reproduced in the future, great care must be taken in the measurements.

We believe it is readily possible to specify a color on such a basis to within about three color difference units. However, this requires careful, well calibrated measurements.

With the aid of permanent standards as reference points, the samples should be reproducible within two color difference units. Again, the need for special care and the application of good measurement practice is emphasized if these goals are to be attained.

Color Faults And Their Evaluation

In the daily production of large quantities of colored textiles often consisting of several fibers, each dyed with several dyes, it is inevitable that faulty results should arise. It is the task of the colorist to determine the nature and cause of the problem as rapidly as possible. Spectrophotometry is an indispensable tool in many of these problems. Colorimetry, on the other hand, is of little value, since it adds nothing beyond what the eye can readily see. Spectrophotometric analysis, particularly with the aid of the log θ ordinate plot is in many cases the key to a correct and expeditious solution. One common example is shown in Fig. 11. This is the classic "blue fade" problem wherein the dulling of a light blue by adding orange appears as a loss of blue—that is, an increase in reflectance even though the measured lightness (Y) is lower.

A similar visual effect occurs when one adds a small amount of violet or blue to a yellow-white. The material looks whiter or lighter even though the Y value is lower. As in the case of the light blues above, this approach applies only within limited Y values.

Concluding Remarks

In 1900 Paterson, in the preface to his remarkable book (*37*) entitled *The Science of Colour Mixing,* stated, "Theoretical knowledge alone cannot make a successful color mixer, but it certainly proves of great value in explaining the true causes of failure and in directing the conditions which lead to success."

This statement is as true today as when written. The modern colorist must cope with an ever increasing number of new fibers, new dyes, and new finishes. The number of combinations of shade, fiber and finish becomes rapidly large. New demands on chemical stability or fastness places further restrictions on the available solutions. The increasing search by designers for styling and properties with new market appeal leads to evaluation of every conceivable combination.

Without the aid of instrumental color measurement, computer color formulation and computer information retrieval, the task facing the colorist or color mixer of the future would be formidable, if not impossible.

In order to realize the potential of instrumental methods we need more precise and reliable instrumentation, but more important, we need colorists thoroughly trained in the theory and practice of spectrophotometry, color measurement and color science as applied to the color of textile.

Acknowledgement

The present paper represents a distillation of thoughts and concepts that have evolved over a period of 25 years in innumerable discussions with some of the foremost color scientists of our time. In particular, the writer has been strongly influenced in his ideas by the writings and discussions of Dr. D. B. Judd, Dr. David L. MacAdam, Ralph Evans, Prof. A. C. Hardy, Hugh R. Davidson, Dr. Henry Hemmendinger and Dr. T. E. Atherton.

It will also be impossible to do justice to the many contributors who have brought color science to its present state. A comprehensive compilation of the present state of quantitative knowledge covering virtually all aspects of color science has been provided by Wyszecki and Stiles (*18*).

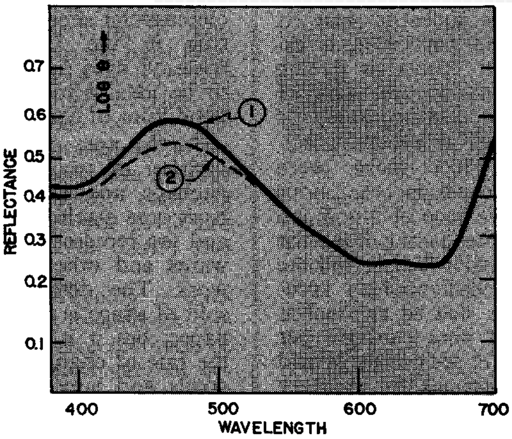

Fig. 11. The blue "fade" problem. If to a light blue (curve 1) is added an orange or yellow in order to produce curve 2, it will appear as if 10-20% of the blue has faded. Actually, there has been no loss of blue as shown in the 600-700 nm region.

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