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A METHOD FOR DETERMINING THE COLOR OF AGRICULTURAL PRODUCTS
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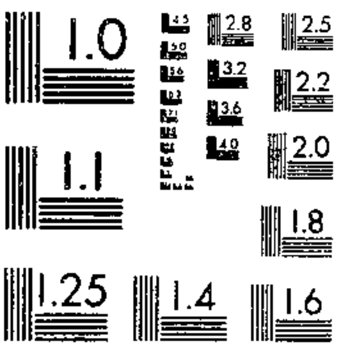

MICROCOPY RESOLUTION TEST CHART
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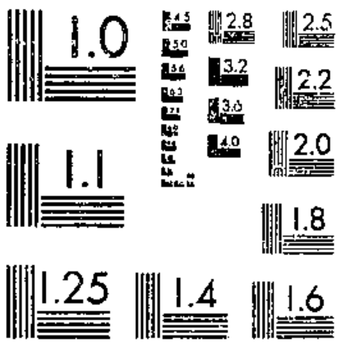

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TECHNICAL BULLETIN No. 154 DECEMBER, 1929

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

A METHOD FOR DETERMINING THE COLOR OF AGRICULTURAL PRODUCTS

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CONTENTS

METHOD OF APPROACH TO A COLOR PROBLEM

There are two distinct methods for measuring color. By one method the stimulus of any color may be completely specified in terms of intensity at each wave length or frequency, or partially specified in terms of secondary standards. By the other method colors may be matched by the use of secondary standards and specified in terms of color, not in terms of the stimulus.

According to the report of the colorimetry committee of the Optical Society of America for 1920–21 (*9*),[2,3] color is "the general name for all sensations arising from the activity of the retina of the eye and its attached nervous mechanisms, this activity being, in nearly every case in the normal individual, a specific response to radiant energy of certain wave lengths and intensities." The report says, further, that color "is fundamentally a psychological category," which means that we can not see wave lengths but that we can see color. To measure color we must deal with it psychologically—in terms of what we see, not in terms of the wave-length stimulus.

Color may be completely specified in terms of three attributes: Hue, brilliance, and chroma. Hue is the attribute which permits colors to be classed as reddish, yellowish, greenish, or bluish; brilliance is the attribute by which a light color is distinguished from a dark color; and chroma is the attribute by which a strong color may be distinguished from a weak color. Each of these attributes may be measured on a scale of psychologically equal steps.

[1] The author wishes to acknowledge indebtedness to C. F. Welsh, Bureau of Agricultural Economics, whose assistance in setting up and calibrating the various instrumental units used in this study was invaluable.

[2] This report is doubtless the best reference guide for a general study of color science that is available. The bibliography is excellent. Reprints may be obtained from the secretary of the Optical Society.

[3] Italic numbers in parentheses refer to "Literature cited," p. 32.

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The report of the colorimetry committee (*9*) defines these attributes as follows:

Hue is that attribute of certain colors in respect of which they differ characteristically from the gray of the same brilliance and which permits them to be classed as reddish, yellowish, greenish, or bluish.

Brilliance is that attribute of any color in respect of which it may be classed as equivalent to some member of a series of grays ranging between black and white.

Chroma [4] is that attribute of all colors possessing a hue, which determines their degree of difference from a gray of the same brilliance.

Regarding the measurement of color:

The three attributes of color can be treated as quantities and specified numerically, if all discriminable colors are conceived to be arranged into a system such that neighboring members differ from one another in each of the three attributes by just noticeable degrees. Such a system is necessarily three-dimensional, and three ordinal values representing the positions of a given color in the several dimensions are needed to define the color.

With such a definition of color and its attributes, and with a method of measurement so obvious in its simplicity, it would seem that any colorimetric method of measuring color to be employed in standardizing and studying a series of colors should be based on measurements of hue, brilliance, and chroma.

Both spectrophotometric and colorimetric measurements may be made in different ways. Circumstances may make one type of color measurement preferable to any other. Therefore before a method is chosen the problem should be carefully studied. If the problem concerns the specification of colors already produced, so that one can record what they look like, or if it concerns colors which are not to be combined to produce new colors, then it is probable that descriptive color measurements are desirable—that is, measurements in terms of hue, brilliance, and chroma. But if the problem concerns the stimulus of the color, how it is produced, which wave lengths are most highly reflected, and how the colors will combine to produce new colors, then stimulus measurements are desirable—that is, measurements in terms of intensity at each wave length or group of wave lengths. The question to be decided in any color problem is this: Are color measurements or color-stimulus measurements the thing wanted?

COLOR PROBLEMS IN AGRICULTURE

The element of color is an integral grading factor in numerous standards established for agricultural products. Cotton, for instance, is sold according to grade and staple. The grade factor consists of three variables: Color, leaf and trash, and preparation or ginning. Hay is graded on color, foreign material, and condition. Color is an important element in grading fruits and vegetables; it is a part of the specifications for cotton-linters standards; it plays a part in grading rice, honey, meat, grains, breads, mayonnaise, and innumerable other agricultural products, or products made from those of agriculture, often with direct correlation in protein content, diastatic activity, or money value.

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[4] "Saturation" is the term the report uses, with "chroma" given as a synonym. "Chroma," by definition, carries no other meaning, whereas "saturation" is often used to mean freedom from mixture with either white or black. See Webster's Dictionary, "Color", also Century Dictionary. (It has been suggested that chroma be used to cover those colors which exhibit hue, to contrast the term chroma with gray, or neutral colors—grays and chromas, for instance—but this use is very limited. For discussion of the subject see (*9, footnote p. 551*).

Since color is an important grading factor, it is necessary that a measure be made of color itself. Standards may thus be kept constant from year to year, the real importance of color as a factor of utility may be determined, and the intervals at which color gradations are fixed in the standards may be specified according to such determinations.

The aim of this bulletin is to describe a method of measuring color in agricultural products; to set forth the reasons for using this method, and to give needed illustrations of its use. The purpose is to aid others who have color-measurement problems to determine whether this method is fitted to their use and if so to give them an adequate description to indicate how it may be adapted and how it should be limited.

METHOD OF WORKING OUT A COLOR PROBLEM

ISOLATION OF COLOR PROBLEM IN COTTON STANDARDIZATION

The measurement of cotton has been chosen as a definite example of how this method may be applied, and will be used as such throughout this study except in so far as additional information may be brought out by other products. This does not mean that all of the work has been done on cotton alone. Considerable work has been done on hay color, and a satisfactory set of tables has been developed for determining grade from the color readings. In fact, the work on hay is the pioneer work of the method described.[5] Cotton, however, has been subjected to several methods of color measurement, and more phases of the subject of color and its application to color problems in agriculture can be illustrated in this bulletin by using cotton as the example.

The purpose of the study of cotton color is to isolate and measure the color factor in grading cotton, in order: (1) To insure constancy of the color element in the standards for grade (*a*) by making it possible scientifically to detect any variations which may occur, and (*b*) by making possible a series of exact color specifications for the various grades. (2) To determine the relationship between color in raw cotton and the color of yarns and fabrics in their "gray," bleached, dyed, and mercerized states. (3) To lay a foundation of fact material under item 2 upon which to determine how great emphasis should be given to color as a factor in the utility of raw cotton and whether fewer or more gradations of color in the standards would be desirable from a practical standpoint. (4) By an examination of properly selected samples of the crops of cotton actually produced from year to year to determine the limits of color variation in American cotton and the colors of most frequent occurrence, thereby providing a fund of statistical data from which to determine with accuracy how the standards for color should be pitched.

In approaching this problem there are factors peculiar to cotton which must be taken into consideration. There is, for instance, a very narrow range of color from the high to the low grades, and an exceeding fineness of differentiation which is ordinarily made by the cotton classer. Then, too, the cotton surface exhibits considerable leaf, trash, spots, and stains which must be integrated in order to

[5] Initiated in 1924 by E. C. Parker, K. B. Seeds, and W. H. Hosterman.

make possible the measurement of a sufficiently large sample to be representative.

The physical standards, known officially as the universal standards for American upland cotton and adopted for use by all of the principal international cotton exchanges, consist of nine grade boxes of White cotton. There are also 5 grades of Yellow Tinged, 3 of Blue Stained,

FIGURE 1. -Practical form of the universal standards for the grade of Middling White cotton. A photograph is shown inserted in the cover of the box to verify the preparation of the cotton and the position of the leaf. At the bottom of the photograph appears the seal of the Department of Agriculture and the certificate and signature of the Secretary of Agriculture. Standards for the other grades and colors are represented in the same manner

and 5 recently established for Extra White. Copies, or what are known as practical forms, rather than the standards themselves, were used in the color work described in the following pages. Figure 1 illustrates the form of the standards. The relationship of the grades is shown in Figure 2. In each grade box there are 12 samples which represent the extreme variation allowable in that grade. The colors vary for each grade and for each position within the grade; yet each is definite and must be matched in all copies of the practical forms (*6*).

GRADE NUMBER AND ABBREVIATIONS	EXTRA WHITE*	BLUE STAINED (B)	GRAY DESCRIPTIVE (G)	WHITE	SPOTTED DESCRIPTIVE (S.P.)	YELLOW TINGED (T.)	LIGHT STAINED DESCRIPTIVE (L.S.)	YELLOW STAINED (S.)
1 OR M.F.				MIDDLING FAIR				
2 OR S.G.M.				STRICT GOOD MIDDLING		STRICT GOOD MIDDLING		
3 OR G.M.	GOOD MIDDLING	GOOD MIDDLING	GOOD MIDDLING	GOOD MIDDLING	GOOD MIDDLING	GOOD MIDDLING	GOOD MIDDLING	GOOD MIDDLING
4 OR S.M.	STRICT MIDDLING	STRICT MIDDLING	STRICT MIDDLING	STRICT MIDDLING	STRICT MIDDLING	STRICT MIDDLING	STRICT MIDDLING	STRICT MIDDLING
5 OR M.	MIDDLING	MIDDLING	MIDDLING	MIDDLING	MIDDLING	MIDDLING	MIDDLING	MIDDLING
6 OR S.L.M.	STRICT LOW MIDDLING			STRICT LOW MIDDLING	STRICT LOW MIDDLING	STRICT LOW MIDDLING		
7 OR L.M.	LOW MIDDLING			LOW MIDDLING	LOW MIDDLING	LOW MIDDLING		
8 OR S.G.O.				STRICT GOOD ORDINARY				
9 OR G.O.				GOOD ORDINARY				

* THESE GRADES EFFECTIVE SEPTEMBER 1, 1928.

═ LIMITS OF TENDERABILITY FIXED BY CONGRESS MARCH 4, 1919.

▬ LIMITS FIXED BY SECRETARY OF AGRICULTURE BY CONSTRUCTION OF FIFTH SUBDIVISION OF SECTION, UNITED STATES COTTON FUTURES ACT.

●●● LIMIT FIXED BY SECRETARY OF AGRICULTURE BY CONSTRUCTION OF REPORT OF HOUSE COMMITTEE ON AGRICULTURE ON AMENDMENT OF MARCH 4, 1919.

FIGURE 2.—Grades and colors of the official standards for American upland cotton

EXPERIMENTS TO DECIDE UPON A METHOD OF MEASURING THE COLOR OF COTTON

In the first attempt to measure color, in the Division of Cotton Marketing, an investigation was made of various photometric methods and types of apparatus, using both reflected and transmitted light. A photometric method was developed [6] by which an average-reflection measurement might be made of each grade box. A Lummer-Brodhun photometer head was used, and the 12 cartons of the standard box were mounted in the form of a dodecahedron so that an average reading could be made of the whole. This method, however, had numerous disadvantages, since the measurement of brilliance is but a partial measurement of color and since readings for the individual samples are necessary, rather than average measurements for an entire

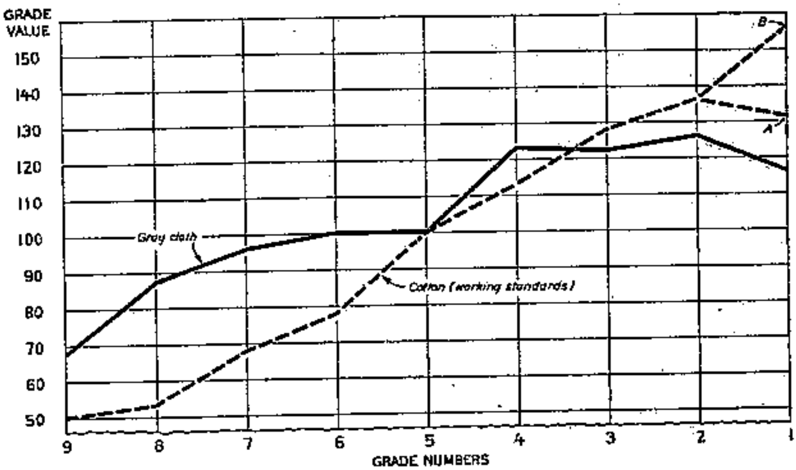

FIGURE 3.—Comparative brillance of cotton and cloth as determined by photometric readings, with grade No. 5, at 100, used as a basis. (Grade No. 1–A is taken from a box of the working standards, whereas grade No. 1–B is from a special sample of grade No. 1.) Note that the four high grades, Nos. 1 to 4, average about the same in the gray cloth, while Nos. 1 to 3 average about the same for the working standards. This is borne out by the brilliance measurements shown in Figure 12, which indicates that the average brilliance of grades 1 to 4 is approximately the same. (This graph is taken from Dept. Bul. 1488 (*10, p. 27*).)

grade box. Figure 3 shows graphically the results of some of these measurements, a box of Middling cotton being taken as a standard.

Later, after making a preliminary study of the situation, it was decided that measurements should be made by several methods before any one method was adopted.

SPECTROPHOTOMETRIC AND PHOTOMETRIC MEASUREMENTS

Two samples each of Middling Fair, Middling, Low Middling, Middling Gray, Good Middling Yellow Stained, Strict Good Middling Yellow Tinged, and Middling Blue Stained cotton were read spectrophotometrically. These same samples with 2 samples each of Good Middling and Strict Middling Yellow Tinged, Strict Middling Gray, and Good Middling Blue Stained, and 10 additional boxes of Middling White, were measured photometrically on the Munsell photometer.

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[6] By E. E. Chandler.

Table 1 is given with curves (fig. 4) for the spectrophotometric readings. They were made on a K & E Color Analyzer with a milk-glass standard for which a reflection factor of 0.731 is given. Four readings were taken at wave lengths 30 millimicrons (mμ) apart, from 700 mμ to 430 mμ, and these readings have been averaged and con-

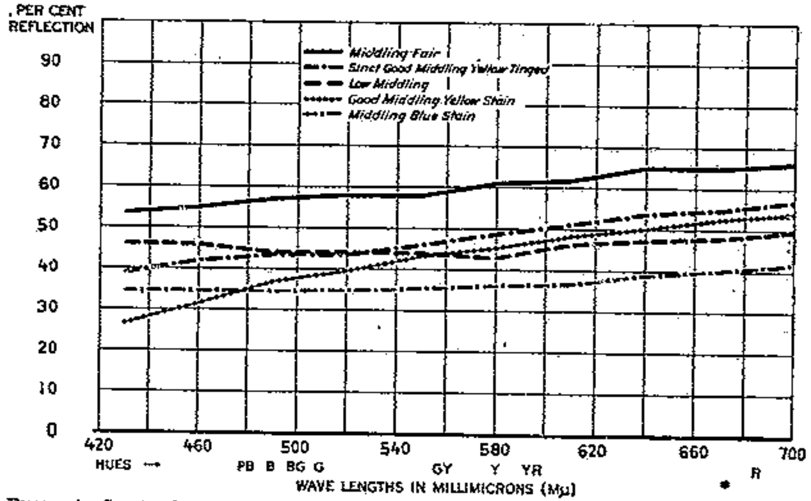

FIGURE 4.—Spectrophotometric curves of five grades of cotton. Readings were made for other grades and for other samples of the same grade. These five readings are sufficient, however, to show how difficult it would be to present graphically 12 variations for each grade from Middling Fair to Low Middling in such a way that each would stand out accurately and definitely

verted by adjusting for the reflection of 0.731 for the milk-glass standard used.

TABLE 1.—*Spectrophotometric measurements of cotton*

Wave lengths (mμ)	Per cent reflection of—													
	Middling Fair		Middling		Low Middling		Middling Gray		Good Middling Yellow Stained		Strict Good Middling Yellow Tinged		Middling Blue Stained	
	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2
700	66.1	62.6	57.0	65.4	49.6	55.2	------	49.3	54.0	45.3	57.0	65.4	41.7	44.7
670	64.9	63.5	54.6	63.6	48.0	53.9	------	47.4	52.6	45.2	55.0	63.7	40.1	42.4
640	65.1	62.9	53.3	60.7	47.3	52.5	------	45.1	50.1	42.1	53.7	64.2	38.9	42.3
610	61.8	60.0	49.6	59.2	46.3	49.8	------	46.9	48.2	40.0	51.1	60.7	36.6	39.3
580	61.0	59.1	49.1	57.7	42.8	48.8	------	45.3	45.3	36.2	48.7	60.9	36.2	39.4
550	57.9	56.9	48.4	57.7	43.8	49.3	------	45.0	43.1	34.9	46.0	58.8	35.4	37.4
520	57.9	58.4	47.5	58.1	44.0	47.7	------	44.7	39.5	32.5	43.4	55.9	34.7	36.5
490	56.9	55.9	47.7	57.7	44.0	47.7	------	40.8	36.8	30.8	43.3	55.6	34.4	36.3
460	54.8	52.0	45.8	57.9	45.8	43.5	------	42.8	31.4	29.9	42.0	53.4	34.5	37.3
430	53.4	48.7	44.5	56.7	46.1	40.9	------	41.5	26.6	28.1	38.0	49.7	34.4	36.6

Six readings each were made on the Munsell equality-of-brilliance photometer. The reflection for the milk-glass standard used in the instrument is 0.69. Averages of the six readings, adjusted for 0.69 reflection, are shown in Table 2. Flicker-photometer readings on seven of the samples were made at the same time.

TABLE 2.—*Readings made with an equality-of-brilliance photometer for cotton of different grades*

Grade	Identification No.	Reflection	Identification No.	Reflection
		Per cent		*Per cent*
Middling Fair	1	66	2	66
Middling	1	63	2	63
	3	64	4	64
	5	64	6	63
	7	64	8	64
	9	64	10	65
	11	65	12	60
Low Middling	1	60	2	59
Strict Good Middling Yellow Tinged	1	63	2	65
Good Middling Yellow Tinged	1	62	2	65
Strict Middling Yellow Tinged	1	59	2	60
Good Middling Yellow Stained	1	57	2	59
Good Middling Gray	1	64	2	61
Middling Gray	1	61	2	63
Good Middling Blue Stained	1	59	2	56
Middling Blue Stained	1	52	2	52

All of these readings were measurements of a part or the whole of the color stimulus, yet none seemed such that it could be used for a study of the entire color problem involved in the measurement of cotton. Photometric readings will not do because they are but a partial measurement. Spectrophotometric curves show real differences between grades, but because each sample of cotton is different from the next, with respect to the surface as well as to the color of fiber, because it is impossible to tell what a color looks like from such readings, and because it takes so long to make a careful reading,[7] spectrophotometric curves would not get the student far in studying or even measuring differences within a grade—the lack of precision would be too great. In addition, the surface area of cotton which could be measured in the color analyzer used was limited to a circle one-half inch in diameter. Only measurements over a large area could give results that would be representative of a surface with the variations that are shown by cotton.

COLORIMETRIC MEASUREMENTS

The next step was to measure the color itself, not the stimulus—to measure it in terms of what the eye sees, that is, in terms of hue, brilliance, and chroma.

Regarding the measurement of color, the colorimetry committee (*9*) reported that a 3-dimensional system, employing scales of hue, brilliance, and chroma, might be conceived to be arranged so that neighboring members differ from one another in each of the three attributes by just noticeable differences. The task of working out a theoretically and scientifically perfect system is one that will take time and specialized knowledge to accomplish. Meanwhile, an approach to such a system has been made which works well if one knows in which direction its limitations lie. It is the system worked out by the late A. H. Munsell (*5*) of Boston, examined by Priest and others (*8*). At that time neither science nor art clearly differentiated the three color attributes. Hue and brilliance were rather clearly

[7] To make a thorough spectral analysis of the stimulus of one color, as made at the Bureau of Standards, often requires an entire day.

defined, but chroma, or color intensity, remained vague and elusive. For purposes of illustration Munsell constructed a sphere by which to illustrate his idea that accurate scales of color could be made in any one attribute only when the other two attributes were held constant.

The vertical axis of the sphere illustrates an 11-step scale of brilliance from 0 to 10, black to white, each step equally distinguishable from the next. Hue varies about the circumference of the sphere in spectrum order, purple and red-purple connecting the red and purple-blue ends of the visible spectrum. Instead of having all the colors at full intensity on the surface of the sphere, the chroma scales are stepped off from 0, at the neutral center of the sphere, by five equidistant steps to the surface. In the blue and blue-green, five chroma

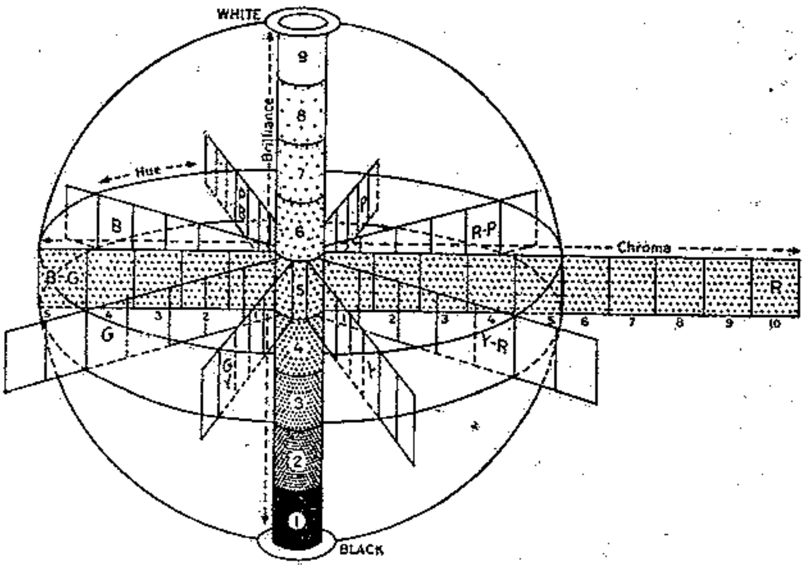

FIGURE 5.—The 3-dimensional relationship of color—color described by three attributes: Hue, brilliance, and chroma

steps make a maximally strong color, but in the red and yellow the fifth chroma step is not a maximum color. Accordingly, the sphere was enlarged to the form of a so-called color tree, the skeleton of a color solid, in which the branches could grow out as far as there are chroma steps to illustrate them. (Fig. 5.) In order that this concept of color might be useful, color charts were made that would illustrate it. The colors are made of permanent pigments carefully specified and measured so that the scales in any one direction approximate closely a series of equally perceptible hue, brilliance, and chroma steps.[8]

EXPLANATION OF COLOR NOTATION

The notation which has been built up around this color solid is, for the practical worker, as important as the 3-dimensional idea of color. (Fig. 6.). Five hues—red, yellow, green, blue, and purple—form the

[8] ATLAS OF THE MUNSELL COLOR SYSTEM, Baltimore, Md.

basis for the hue circle. Midway between them are the intermediate hues, yellow-red, green-yellow, blue-green, purple-blue, and red-purple, making a series of 10 hues, each equidistant to the eye from the next. The first letter of the name is used for the hue notation except when

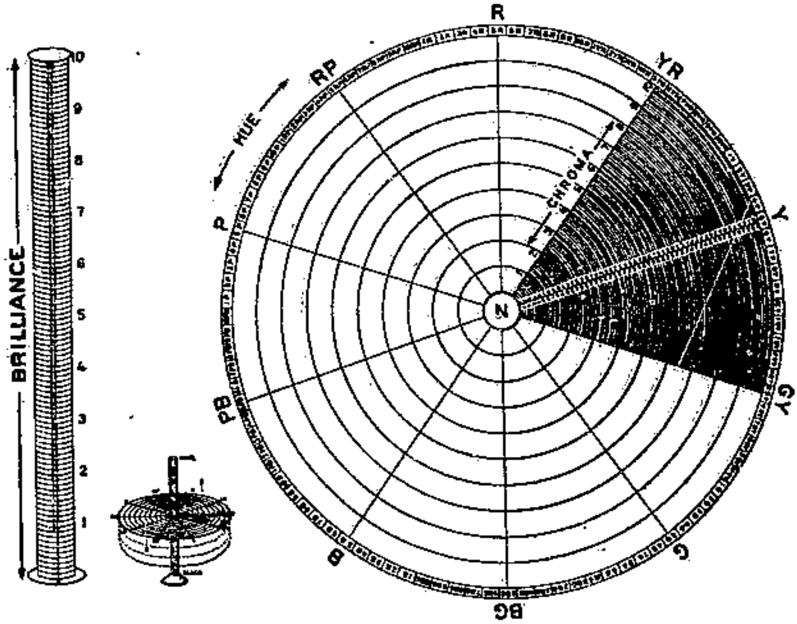

FIGURE 6.—Color notation in terms of both 10 and 100 steps each of hue, brilliance, and chroma

many more than 10 hues are to be used. Then a numerical notation may be substituted. The notation for a part of the hue circle is illustrated in Figure 7. Note that the standard red may be used as R, 5R, or 5, depending entirely upon the way in which one wishes to use it. When used without a hue letter the hue figure must be separated from those denoting brilliance and chroma. Subdivisions for

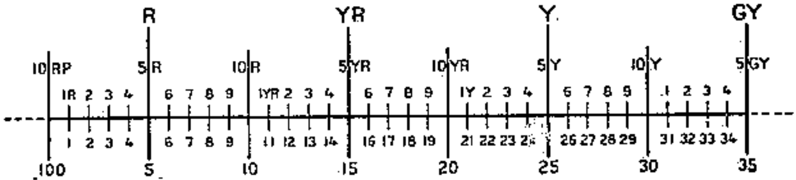

FIGURE 7.—Hue notation through a portion of the hue circuit, illustrating the numerical notation and that in which the letters of the hue names are employed

hue as fine as the eye can detect are made possible by the use of the decimal system.

The brilliance scale begins at 0, which is absolute black, and progresses through equal steps to a middle gray at 5, and from there to absolute white at 10. These steps may also be subdivided decimally to a degree as small as the eye can determine.

The notation for chroma begins at neutral gray, which is 0, and progresses through equal steps to as strong a color as is required. The end points vary for each brilliance and hue, with colors represented by pigments like vermillion and ultramarine extending as far as 10 in chroma. A weak color will have the notation of 1, 2, or 3, while strong colors may go out to 8, 9, 10, or even farther. Decimals may again be used for expressing finer differences.

The complete notation is always written in the following order: Hue, brilliance, chroma. For example, red, 4 in brilliance, and 10 in chroma is written as 5R 4/10. If the hue letter is omitted, the notation may be written as 5–4/10.

Colors of standard notation made from permanent pigments may be procured from commercial manufacturers or, if time and equipment are available, any colors may be standardized according to this notation and may be used for further work.

By the use of Maxwell disks (disks cut with a radial slit so that several may be slipped together with portions of each visible) and a motor on which to spin them at a speed great enough so that there is no flicker, any color which lies in the color solid within the region bounded by the colors used may be matched.

For cotton work it was found that Y 8/9, YR 6/8, N 9.4/, and N 7/, with the addition of N 6/ in a few of the lower grades, would measure the white grades.

It can be seen from Table 3 that the readings made on different days show considerable variation, but that the readings for both brilliance and chroma on the white cottons indicate a distinct trend, the lower grades becoming darker in brilliance and weaker in chroma. The spots, tinges, and stains become progressively stronger in chroma, whereas the extra whites, grays, and blues become weaker in chroma. The yellow stains are reddest in hue, whereas the so-called blue stains are yellow, sometimes slightly greenish yellow. In every case the average measurements on the cotton samples correspond with the "way they looked." It seems hardly necessary to state this fact if it is remembered that what is being measured is what they look like, and not the composition of the stimulus factors.

By a comparison of the results obtained from the methods experimented with—photometric, spectrophotometric, and colorimetric [9]—it seemed simplest and most satisfactory to adopt this last-described method in the color studies to be made regarding cotton, using disks of Munsell notation, with modifications in set-up that would permit more precise readings.

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[9] There are many colorimetric methods besides that which uses Maxwell disks—among them the Hess-Ives tintometer and the Eastman colorimeter. In all of them colors are matched, some by an additive and some by a subtractive effect, some matches being made through successive selective filters, some by varying proportions of standard wedges. Color matches may also be made by use of Lovibond glasses, which the Bureau of Standards will check in terms of their standard set of these glasses.

TABLE 3.—*Preliminary color readings on specified grades of cotton in terms of hue, brilliance, and chroma, made under a north skylight in June, 1927* [1]

Grade	Sample No.	Weather	Percentage of specified standard color disks used: YR 6/8	Y 8/9	N 9.4/	N 7/	Color notation: Hue-	Brilliance/	chroma
		Cloudy	4	22	58	16	4.0Y	8.75/	2.32
Middling fair	1	Gray	4	21.5	65	10.5	3.9Y	8.79/	2.25
		Bright	2	25.5	50	12.5	4.5Y	8.68/	2.45
		Cloudy	5.5	23.5	53.5	17.5	3.6Y	8.54/	2.55
Good middling	1	Gray	5.5	22.5	52	20	3.6Y	8.49/	2.47
		Bright	1.5	26.5	56.5	15.5	4.6Y	8.66/	2.60
		Cloudy	6.5	22	60.5	11	3.4Y	8.68/	2.50
	2	Gray	5	24	50	21	3.8Y	8.47/	2.56
		Bright	2	26.5	58	13.5	4.5Y	8.69/	2.54
		Cloudy	7	16.5	34.5	32	2.8Y	7.70/	2.05
Middling	1	Gray	3	18.5	43	35.5	4.0Y	8.27/	1.91
		Bright	3	21.5	53.5	22	4.1Y	8.54/	2.17
		Cloudy	5	18	35.5	31.5	3.8Y	7.75/	2.02
		Gray	3	19	40	38	4.0Y	8.20/	1.95
	2	Bright	2.5	19.5	60.5	17.5	4.2Y	8.68/	1.95
		Bright	2	20	55	23	4.4Y	8.57/	1.96
		Cloudy	3	14	24	59	3.8Y	7.77/	1.50
Low middling	1	Gray	2	16	20	62	4.2Y	7.68/	1.60
		Bright	1	18.5	32	48	4.6Y	8.00/	1.74
		Cloudy	3.5	14	16.5	66	3.6Y	7.56/	1.54
	2	Gray	3	16	26	55	3.8Y	7.83/	1.68
		Bright	1.5	18.5	38.5	41.5	4.3Y	8.17/	1.78
		Cloudy	3.3	14	16	66.7	3.7Y	7.55/	1.52
Good Ordinary	1	Gray	2.5	13.5	14	70	3.9Y	7.50/	1.42
		Bright	1	18	23	58	4.6Y	7.79/	1.70
		Cloudy	3	12.5	6.5	78	3.6Y	7.28/	1.36
	2	Gray	2.5	14.5	8.5	74.5	4.0Y	7.38/	1.51
		Bright	1.5	13.5	16.5	68.5	4.3Y	7.57/	1.30
		Raining	4.5	24.5	36	35	3.9Y	8.14/	2.56
Good Middling Spotted	1	Bright	4	30	51	15	4.2Y	8.43/	3.02
		Bright	1	30	59	10	4.2Y	8.73/	2.78
		Bright	5	28	56	11	3.9Y	8.64/	2.92
		Raining	5	24.5	40.5	30	3.7Y	8.18/	2.60
	2	Bright	2	28	51	19	4.5Y	8.54/	2.68
		Bright		31	55	14	5.0Y	8.67/	2.79
		Bright	2.5	32.5	55.5	9.5	4.5Y	8.70/	3.13
		Raining	5	21	28	46	3.7Y	7.91/	2.29
		Bright	2	23	34.5	40.5	4.4Y	8.10/	2.23
Strict Low Middling Spotted	1	Bright	1.5	25.5	37	36	4.6Y	8.19/	2.42
		Bright	5	23	46	26	3.8Y	8.36/	2.47

[1] This table demonstrates the extent of precision that can be expected under the best of natural daylight conditions. See Table 8 and compare standard deviations with Table 5.

MATCHING OF COLOR

The simplest method of color matching is to spin the color disks in juxtaposition to the sample, using a neutral mask with openings of equal size, one over the disks, the other over the sample (fig. 8), and to compare by eye the two fields.

A preliminary test was made by this method on a number of cottons, part of them listed in Table 3. The light used was that which comes through the north skylight in the cotton-grading room of the Division of Cotton Marketing, the glass being set at an angle of 20°. The cotton and the disks, with mask covering, are shown in Figure 8 as they were set up for this experiment. Three independent measurements were repeated on the same samples on following days.

The readings are made in percentages of the disks used to match each sample, and these readings are converted by formulas (to be described later) into terms of hue, brilliance, and chroma.

DEVELOPMENT OF APPARATUS

In order to make measurements in terms of hue, brilliance, and chroma, it is necessary to work out a convenient method for setting up the material always in the same way, for lighting it at a constant angle, for making the observations always from a single point, and for getting two similar fields for comparison. For the cotton work, a holder was built into which a single small sample carton might be slipped, the surface of the cotton to be as nearly as possible in the same plane with the disks used as standards, both at an angle of approximately 38° from the horizontal. A comparator eyepiece was developed [10] on specification which required that two fields approximately 2⅜ inches in diameter, separated by a small space, perhaps half an inch, should be brought into a single comparison field within an eyepiece. Only one-half of each of these fields is visible in the eye-

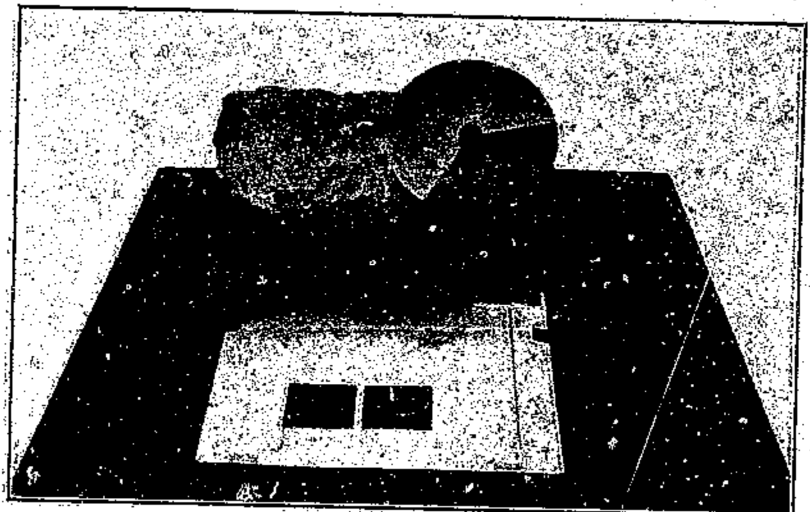


FIGURE 8.—Simple method of color matching. Color disks are spun in juxtaposition to the sample being measured, with a neutral mask in which openings of equal size are so cut that one may be placed over the disks, the other over the sample. The two fields are compared by eye

piece. The use of lenses and a prism puts the cotton surface sufficiently out of focus so that the result appears as one solid color, even though the cotton itself might have a very spotty appearance.

With this set-up Macbeth artificial-daylight lamps were used, measured for color temperature by the Bureau of Standards.* Their report on these lamps read in part as follows:

The incandescent lamps received with the daylight units were 200 watt, 110 volt, pear-shaped, frosted tip, gas filled lamps.

The daylight units—incandescent lamp, reflector, and daylight glass—were tested as received, the color temperature of the unit as a whole being determined in each case. The incandescent lamps were operated at 110.0 volts. Measurements were made at a distance of about 40 cm from the daylight glass and approximately along the axis of the light beam.

Values of color temperature were determined on the rotatory dispersion colorimetric photometer described in the J. O. S. A. & R. S. I., v. 7, p. 1175–1209; December, 1923. Two observers (D. B. J. and K. S. G.) made measurements with closely agreeing results. The average is reported. The following values of color temperature were thus obtained:

Lamp	*Color Temperature.*
A	7560° K
B	8100° K

[10] By Bausch & Lomb Optical Co.

The color match with the black body color was in both cases good (7, 8).

Daylight lamps were used in order that the best conditions under which cotton classers work might be duplicated. Their preference is light from a north sky, and the lamps used were selected after consultation with experienced classers who took samples of cotton and classed them under filters which gave a variety of color temperatures.

FIGURE 8.—First set-up for measuring the color of cotton using a comparator eyepiece. Note that the cotton is in juxtaposition to the color disks and that the lights are so placed as to give a definite angle on the desk surface. This set-up, modified as to the container for the sample, could be used for any other product that presents an even or a nearly even surface for measurement. The equipment has already been used for measuring the color of bread, cheese, condensed milk, and cotton cloth.

The lamps were marked so that they could always be set up in the same position, at the same angle, the light to fall on the samples at approximately 45°, possibly a little less. Figure 9 shows the entire equipment.

The colors chosen for standards are the four which, in combination, will match all but the very lowest grades of white cotton. They are Y 8/9, YR 6/8, N 9.4/, and N 7/. For a very few matches a slightly darker gray is necessary, and sometimes a green-yellow. These six colors were sent to the Bureau of Standards for measurement of spectral reflectance (Table 4), in order, as the report reads, to put on record data which are suitable and adequate to specify these colors, so that the reproduction of these present standards at some future time may be verified without depending upon the permanence of the color of these particular specimens.

For duplication of these data at any future time it is necessary that the samples be viewed normally under completely diffuse illumination; that is, under conditions identical with those of the original test. In this way a measurement is obtained which completely specifies the stimulus for these colors.

With this equipment, set up in a dark room, lighted only by artificial daylight, measurements were made on a series of 10 sets of practical forms of the standards, from No. 2, Strict Good Middling to No. 9, Good Ordinary. One box of No. 1, Middling Fair was measured.

TABLE 4.—*Spectrophotometric measurements on the six Munsell papers which are used in cotton measurements and which were submitted to the Bureau of Standards for testing* [1]

Wave length in millimicrons	YR 6/8	Y 8/9	GY 6/8	N 6/	N 7/ (37–N)	N 9.4/ (57–N)
380	0.0603	0.0563	0.0760	[2] 0.375	[2] 0.433	[2] 0.70
390	.0609	.0582	.0911	[2] .375	[2] .433	[2] .73
400	.0616	.0598	.0959	.375	.433	.765
410	.0626	.0612	.0981	.375	.433	.773
420	.0638	.0625	.0995	.375	.433	.787
430	.0655	.0640	.101	.375	.433	.799
440	.0683	.0662	.102	.375	.433	.811
450	.0728	.0719	.105	.375	.433	.821
460	.0790	.0832	.111	.375	.433	.829
470	.0879	.110	.121	.375	.433	.837
480	.100	.151	.137	.375	.433	.843
490	.113	.212	.168	.375	.433	.848
500	.128	.298	.225	.375	.433	.851
510	.148	.385	.306	.375	.433	.853
520	.172	.455	.408	.375	.433	.854
530	.201	.514	.502	.375	.433	.855
540	.243	.562	.541	.375	.433	.855
550	.297	.603	.535	.375	.433	.855
560	.361	.635	.504	.375	.433	.855
570	.430	.650	.465	.375	.433	.855
580	.494	.678	.427	.375	.433	.855
590	.554	.692	.398	.375	.433	.855
600	.609	.701	.370	.375	.433	.855
610	.650	.709	.346	.375	.433	.855
620	.679	.714	.325	.375	.433	.855
630	.698	.718	.308	.375	.433	.855
640	.710	.723	.294	.375	.432	.855
650	.721	.726	.283	.375	.431	.855
660	.730	.730	.274	.375	.430	.855
670	.737	.735	.266	.375	.429	.855
680	.745	.739	.261	.375	.428	.855
690	.753	.744	.257	.375	.427	.855
700	.760	.748	.254	.375	.425	.855
710	.766	.752	.251	.375	.422	.855
720	.773	.756	.249	.375	.418	.855

[1] $\frac{\text{Brightness of sample}}{\text{Brightness of MgO}} = Bx/Bo$, for completely diffused illumination and line of sight perpendicular to surfaces of sample and standard.

[2] Estimated. If zinc oxide (ZnO) is a principal constituent of these pigments, these estimated values will be greatly in error.

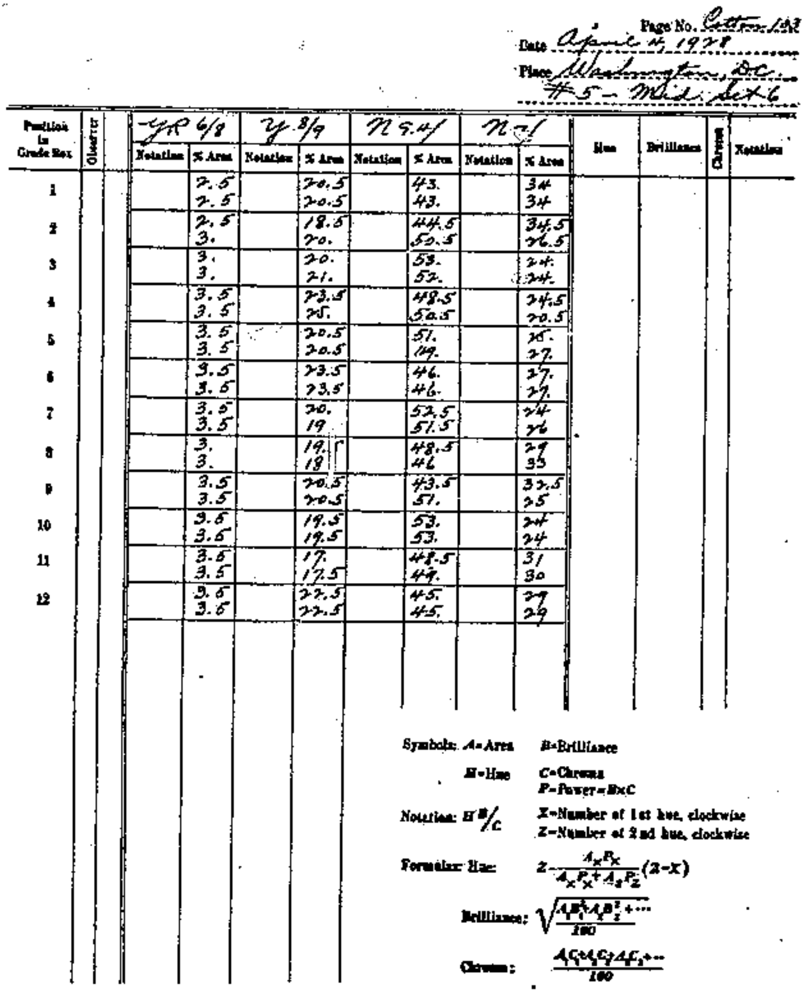
METHOD OF MEASUREMENT

The measurement is made by changing the areas of the disks until there is a match when viewed through the eyepiece. Since the lenses and prism of the color comparator are interposed between the eye and the sample, the color area is rid of all detail and presents a uniform field for measurement. It is easy, therefore, after short training for anyone with normal color vision [11] to make a color

[11] Qualitative tests for color vision—extremely important in all colorimetric work—may be made by the use of either or both of the following sets of charts: ISHIHARA, TESTS FOR COLOR BLINDNESS, and STILLING'S PSEUDO-ISOCHROMATIC PLATES FOR TESTING COLOR SENSE.

match. If a color measurement on a single sample is desired, several measurements should be made and an average taken, just as would be done in any other method of colorimetric or spectrophotometric measurement.

In making the readings on cotton an average was more important than readings on individual samples. For that reason only two read-



Page No. Cotton 1?3
Date April 4, 1928
Place Washington, D.C.
#5 – Mid. Set 6

Position in Grade Box	Observer		YR 6/8		Y 8/9		N 9.4/		N 2/		Hue	Brilliance	Chroma	Notation
			Notation	% Area	Notation	% Area	Notation	% Area	Notation	% Area				
1				2.5 2.5		20.5 20.5		43. 43.		34 34				
2				2.5 3.		18.5 20.		44.5 50.5		34.5 26.5				
3				3. 3.		20. 21.		53. 52.		24. 24.				
4				3.5 3.5		23.5 25.		48.5 50.5		24.5 20.5				
5				3.5 3.5		20.5 20.5		51. 49.		25. 27.				
6				3.5 3.5		23.5 23.5		46. 46.		27. 27.				
7				3.5 3.5		20. 19		52.5 51.5		24 26				
8				3. 3.		19. 18		48.5 46		29 33				
9				3.5 3.5		20.5 20.5		43.5 51.		32.5 25				
10				3.5 3.5		19.5 19.5		53. 53.		24 24				
11				3.5 3.5		17. 17.5		48.5 49.		31 30				
12				3.5 3.5		22.5 22.5		45. 45.		29 29				

Symbols: A = Area B = Brilliance
H = Hue C = Chroma
P = Power = $B \times C$

Notation: $H\,{}^{B}/_{C}$ X = Number of 1st hue, clockwise
Z = Number of 2nd hue, clockwise

Formulas: Hue: $Z - \frac{A_x P_x}{A_x P_x + A_z P_z}(Z - X)$

Brilliance: $\sqrt{\frac{A_1 B_1^2 + A_2 B_2^2 + \cdots}{100}}$

Chroma: $\frac{A_1 C_1 + A_2 C_2 + A_3 C_3 + \cdots}{100}$

FIGURE 10.—Record sheet used when making color measurements

ings were made on each of the samples, one on each side of the individual cartons. Thus, two areas were measured, each one-half of $2^{5}/_{16}$-inch-diameter circles. The two readings were averaged for each sample.

The readings are recorded by noting the percentage of the exposed area of each color. A calibrated disk (in terms of per cent) is used for this purpose. Figure 10 shows the form record sheet with readings made on Middling White cotton. This reading goes as far as most colorimetric methods do. It provides a record in terms of percentage of the area of each of the several standards used to make a match. For instance, an average color for Middling cotton may be established, the disks set up in the required areas, and samples of cotton set in, those that match being accepted as Middling, those that do not match being rejected. Yet this is but a part of the problem, for it is not enough to give an arbitrary match; the problem is to study the color relations within grades and between grades, possible only when the measurement is put on record in terms of hue, brilliance, and chroma, the three attributes by which color is described as it is seen.

FORMULAS FOR COLOR NOTATION

For converting the percentage area of standard colors into terms of hue, brilliance, and chroma, the Munsell system of notation is used. The following formulas, although used approximately at previous times, first became a matter of record when they were made a part of the record sheet of the Bureau of Agricultural Economics. There are one or two precautions that must be observed in using these formulas: (1) The hues selected should not be more than one-tenth of the hue circle apart; (2) the low brilliance steps, 1/ and 2/, should not be used if it is possible to use lighter colors; and (3) a single set of four disks should be used throughout any one piece of work wherever it is practicable to do so. The formulas will give satisfactory relative results just as long as a single set of colors is used. For instance, all cotton readings will be in relation, one to the others, as long as YR 6/8, Y 8/9, N 9.4/, and N 7/ are used. But should N 1/ be used instead of N 7/, it would still be possible to match the cotton; but since the square of brilliance is used in the formula, a slight error in the notation of the original color would be proportionally of more consequence in squaring 1 and 2 than in squaring 6 or 7.[12]

HUE

The hue notation is simply the proportion of one hue to the total. Instead, however, of using only the area proportion, the area is multiplied by its brilliance and its chroma, to give what may be called

[12] Since this bulletin was written, a new Book of Color has been published by the Munsell Color Co. It contains a set of charts revised and enlarged to give scales that are more consistent with the psychological data now available. The brilliance scale is corrected, and 20 hues, instead of 10, are included. Data regarding the brilliance scale may be found on page 42 of the new publication. It is hoped that data on the hue and chroma scales will be published. Since these new papers depart somewhat from the old, it is more important than ever in following the formulas given above to use a single set of colors throughout any one study so that the results may be in the proper relation. This does not mean the same disks, but disks of the same notation.

Ordinarily, a single investigator is interested chiefly in the results of his own problem, yet he may sometimes wish to convert the readings made of many different sets of colors into a relation that will hold more rigorously than the relative results to be obtained by the formulas described above. It is therefore suggested that the colorimetry committee report previously cited (*9*) provides, on pages 570 to 592, a method for reducing diverse color specifications to the common denominator apparently provided by the *elementary color excitations*.

the "power"[13] number of the color. The following formula is quite simple:

$$H = z - \frac{A_z P_z}{A_x P_x + A_z P_z}(z - x)$$

in which

x = number of first hue (clockwise on the hue circle). (Fig. 7.)
z = number of second hue (clockwise on the hue circle). (Fig. 7.)
A = area.
P = power number (brilliance × chroma).
H = hue resultant.

Working out the first reading on Figure 10 gives 2.5% of YR 6/8 and 20.5% of Y 8/9. The other two colors are neutrals; they have no hue and are therefore 0 (and thus disregarded) in the formula given. Since z, the second hue, is Y, it has a hue notation, in figures, of 25 (see fig. 7 for hue notation) while x, which is YR, is 15. The area of the first hue, A_x, is 2.5, and P_x, the power number of the first hue, is 6 × 8, that is, its brilliance times its chroma. A_z, the area of the second hue, is 20.5, and P_z, the power number of the second hue, is 8 × 9, its brilliance times its chroma. Substituting in the formula gives

$$H = 25 - \frac{2.5(6 \times 8)}{[2.5(6 \times 8)] + [20.5(8 \times 9)]}(25 - 15)$$

$$H = 25 - \frac{120}{1596}(10)$$

$$H = 25 - .75$$

$$H = 24.25$$

Translated into terms of Y by reference to Figure 7, this is 4.25Y, or, dropping the last figure, 4.2 or 4.3Y, the hue of the cotton matched.

More than one card of the same hue may be used, as in the yellow of the following match for alfalfa hay:

$$25 \text{ per cent YR } 4/5 + \begin{cases} 49 \text{ per cent Y } 3/3 \\ 26 \text{ per cent Y } 4/4 \end{cases}$$

The power (P) of each is multiplied by its respective area and added together to give a total for its hue, as follows:

$$H = 25 - \frac{25(4 \times 5)}{[25(4 \times 5)] + [49(3 \times 3) + 26(4 \times 4)]}(25 - 15)$$

$$H = 25 - \frac{500}{500 + 441 + 416}(10)$$

$$H = 25 - 3.68$$

$$H = 21.32, \text{ or } 1.32\text{Y}$$

[13] This term is perhaps more easily understood by reference to colors used in outdoor advertising: To be effective at any distance the power of the color must be great. A dark blue, although it might be quite strong (*PB* 4/10) can not compete with a brilliant yellow (*Y* 8/9) or a brilliant orange (*YR* 6/10). The power of the *PB* given in this example is but 40, while that of the *Y* is 72, and the *YR*, 60. As the blue is increased in brilliance or chroma, perhaps to *PB* 5/12, it begins to compete with the yellow and orange.

By referring to Table 6, it will be seen that the conversion in terms of per cent natural green color in alfalfa hay is 10.

The same thing may be done with more than two areas of a single hue, as in the following match for a greener sample of alfalfa hay:

$$17 \text{ per cent YR } 5/4 + \begin{cases} 32 \text{ per cent Y } 5/5 \\ 11 \text{ per cent Y } 5/4 \\ 40 \text{ per cent Y } 4/4 \end{cases}$$

$$H=25-\frac{17(5\times4)}{[17(5\times4)]+[32(5\times5)+11(5\times4)+40(4\times4)]}(25-15)$$

$$H=25-\frac{340}{340+1660}(10)$$

$$H=25-1.7=23.30, \text{ or } 3.30 \text{ Y}$$

The conversion in terms of "per cent natural green" alfalfa is 26.

BRILLIANCE

In working out the brilliance of any match, the area of each color is multiplied by the square of the brilliance. The square of brilliance is used since reflection under certain illuminations bears a relation to brilliance according to a square law. For instance, half black and half white mixed by means of disks do not produce a gray that looks half way between black and white.[14] Instead, the color looks nearer to three-quarters of the way towards white. When about one-quarter white and three-quarters black are mixed on disks, the result is very near to a middle gray. That means that 25 per cent white with 75 per cent black is approximately 5/ in brilliance, while 50 per cent white and 50 per cent black is nearer 7/ in brilliance. Brilliance scales made up of painted papers of equally perceptible steps will vary with illumination, and up to the present time no definite scale has been adopted. The Munsell scale was made to follow the square law (practical because a cat's-eye shutter is used in the Munsell photometer), but since the white used in the original photometer as a standard was not calibrated on the basis of total reflection, but was used as 10/, the highest brilliance step, the scale does not exactly follow this law. However, it closely approximates it, and will give readings that are relatively correct. Further work regarding this relationship has been done both by I. G. Priest, at the United States Bureau of Standards, and by the Munsell Research Laboratory.

The formula that is used is as follows:

$$B=\sqrt{\frac{A_1 B_1^2+A_2B_2^2+A_3B_3^2+\cdot\cdot\cdot\cdot\cdot}{100}}$$

when B = brilliance and the area is expressed in percentage. Working out the first reading on Figure 10, gives 2.5 per cent YR 6/8, 20.5 per cent Y 8/9, 43 per cent N 9.4/, and 34 per cent N7/—the square root of the sum of the different brilliance readings squared and multiplied

[14] This is in general accordance with the Weber law which states that the just appreciable increase of stimulus bears a constant ratio to the original stimulus. See Priest's discussion (*8, p. 20–31*).

by their respective areas, and the whole divided by 100, the total per cent area. In other words

$$B=\sqrt{\frac{(2.5\times 6^2)+(20.5\times 8^2)+(43\times 9.4^2)+(34\times 7^2)}{100}}$$

$$B=\sqrt{\frac{6867}{100}}=\sqrt{68.67}=8.29$$

The brilliance of this color match is 8.29.

CHROMA

The chroma of any color match is the proportion of the chromas used to the total, or 100 per cent of the area. The formula is simply the sum of the per cent area of each color multiplied by its chroma, as follows:

$$C=\frac{A_1C_1+A_2C_2+A_3C_3+\cdot\cdot\cdot\cdot}{100}$$

when C=chroma.

Working out the first reading of Figure 10 for chroma gives

$$C=\frac{(2.5\times 8)+(20.5\times 9)}{100}=2.05$$

It makes no difference whether two or many more colors are used, the formula remains the same so long as the colors are not more than one-tenth of the hue circle apart. For instance, solving the alfalfa reading gives 17 per cent YR 5/4, 32 per cent Y 5/5, 11 per cent Y 5/4, 40 per cent Y 4/4; substituting in the formula gives

$$C=\frac{(17\times 4)+(32\times 5)+(11\times 4)+(40\times 4)}{100}=4.32$$

INTERPRETATION OF COLOR MEASUREMENTS

It is highly important that careful analysis be made of the results of the color readings. For that reason the readings made in the cotton problem are analyzed and discussed in the following paragraphs, with statement as to what they may mean in terms of cotton.

The measurement of the first reading made on cotton in Figure 10 is, according to the solution presented, 4.3Y 8.29/2.05. Table 5 gives the measurement for the other readings in terms of hue, brilliance, and chroma. Those hues which are 4.3 and 4.4 are slightly more yellow in hue than 4.2, while 3.9 and 4.0 are slightly more reddish than 4.2. The highest brilliance readings indicate the brighter, lighter cottons; highest chroma readings indicate the creamiest of the cottons; the low chromas indicate the so-called "bluish" cottons.

It is interesting to discover that the term "blue," as applied to cotton, does not indicate a real difference in hue; it indicates lack of chroma in comparison with the creamy bales. According to the law of simultaneous contrast, each color affects every color with which it comes in contact. The slighter the differences are, the greater the relative differences appear. Black and white, for instance, offer the maximum of brilliance contrast for reflecting surfaces. Therefore any simultaneous contrast does not seem to affect these differences as much as it does two grays that are almost alike. Hold the grays apart and you may be unable to tell which is which; yet once they are put together the difference is magnified by simultaneous contrast; the lighter gray of the two appears still lighter, whereas the darker gray looks darker. For example, which of the grays in Figure 11 looks lighter? They are actually alike; yet the gray which is placed against the dark background looks much lighter than the gray against the white background.

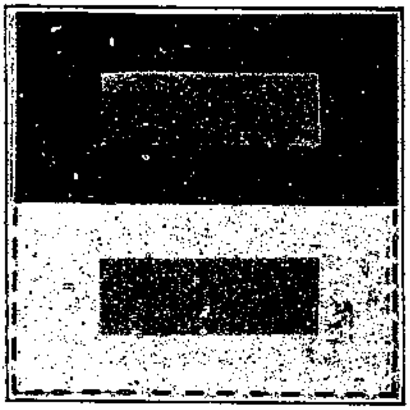


FIGURE 11.—Illustration of contrast as applied to light and dark areas. Chromatic areas present similar problems in contrast. The central rectangle surrounded by dark looks considerably lighter than the central rectangle surrounded by light; yet they are actually the same. Questions of contrast enter into many color problems

The averages of the measurements made on 10 sets of the practical forms of the cotton standards are given in Table 5, with standard deviations (σ) for brilliance and chroma which show the variations about the average. (Refer to Table 3; note descriptive title.) Hue varies so very little—only

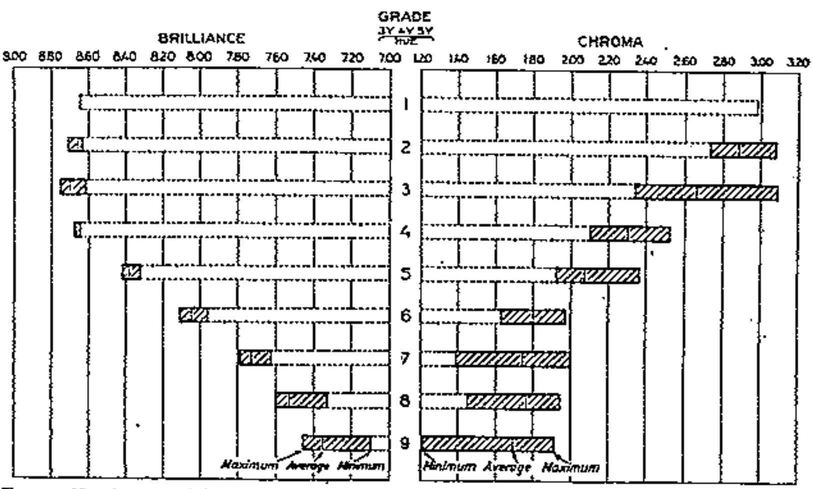


FIGURE 12.—Average of the grade and extremes for 10 sets of the practical forms of white cotton that have been measured for hue, brilliance, and chroma. The brilliance average for the four highest grades is nearly constant. Not very much tolerance from the high to low samples is represented in the grade box. From No. 4, Strict Middling, each grade becomes considerably darker, with a greater tolerance as between the lightest and darkest samples in the grade. Chroma measurements for the nine grades show considerable tolerance within each grade. The averages, however, progress gradually from the high grades in which the cottons are of a creamy color to a grayer cotton in the lower grades. From grade No. 6 to grade No. 9 thea verages for chroma are nearly constant

between 3 Y and 5 Y—that no standard deviation has been worked out for it. Brilliance and chroma measurements are charted in Figure 12.

TABLE 5.—*Average of color readings on 10 sets of practical forms of the standards in terms of hue/brilliance/chroma with standard deviations (σ) for brilliance and chroma*

Grade	Position 1	σ	Position 2	σ	Position 3	σ	Position 4	σ	Position 5	σ	Position 6	σ
1. Middling Fair	40Y 8.60/2.91		39Y 8.64/3.03		39Y 8.61/3.08		38Y 8.68/3.09		37Y 8.66/3.00		37Y 8.64/2.85	
2. Strict Good Middling	41Y 8.67/2.78	0.09/0.10	41Y 8.69/2.89	0.07/0.14	41Y 8.71/2.87	0.10/0.11	42Y 8.65/3.08	0.09/0.07	41Y 8.65/2.97	0.10/0.11	41Y 8.68/2.80	0.07/0.10
3. Good Middling	41Y 8.77/2.43	.10/ .10	42Y 8.68/2.79	.08/ .15	42Y 8.69/2.78	.08/ .09	42Y 8.65/3.09	.05/ .10	42Y 8.66/2.75	.06/ .08	42Y 8.77/2.42	.09/ .16
4. Strict Middling	41Y 8.65/2.12	.09/ .16	41Y 8.65/2.19	.09/ .09	42Y 8.66/2.28	.08/ .10	42Y 8.69/2.69	.09/ .17	42Y 8.68/2.41	.07/ .18	41Y 8.68/2.16	.05/ .13
5. Middling	41Y 8.35/2.15	.10/ .10	41Y 8.38/1.99	.11/ .08	40Y 8.41/2.01	.12/ .12	42Y 8.38/2.36	.09/ .08	41Y 8.36/2.02	.11/ .12	41Y 8.35/2.16	.13/ .13
6. Strict Low Middling	41Y 8.08/1.75	.13/ .09	41Y 8.11/1.72	.09/ .07	41Y 8.06/1.94	.12/ .13	41Y 8.06/1.97	.07/ .12	41Y 8.10/1.87	.11/ .06	40Y 8.07/1.73	.08/ .09
7. Low Middling	41Y 7.78/1.77	.17/ .12	40Y 7.74/1.65	.13/ .10	41Y 7.79/1.76	.08/ .14	41Y 7.75/2.00	.08/ .06	39Y 7.75/1.78	.08/ .08	41Y 7.74/1.75	.11/ .12
8. Strict Good Ordinary	41Y 7.60/1.79	.09/ .10	41Y 7.60/1.73	.08/ .10	41Y 7.60/1.83	.09/ .07	41Y 7.57/1.94	.09/ .09	41Y 7.57/1.78	.12/ .08	41Y 7.56/1.79	.09/ .07
9. Good Ordinary	41Y 7.36/1.65	.08/ .05	41Y 7.35/1.67	.08/ .08	42Y 7.41/1.85	.07/ .09	42Y 7.32/1.84	.09/ .13	41Y 7.46/1.84	.06/ .06	41Y 7.39/1.69	.05/ .07

Grade	Position 7	σ	Position 8	σ	Position 9	σ	Position 10	σ	Position 11	σ	Position 12	σ
1. Middling Fair	38Y 8.67/3.00		40Y 8.67/2.90		39Y 8.60/2.92		41Y 8.62/3.09		40Y 8.76/2.84		38Y 8.59/3.08	
2. Strict Good Middling	41Y 8.68/2.87	0.11/0.13	41Y 8.65/2.74	0.07/0.16	42Y 8.65/2.85	0.07/0.06	42Y 8.68/2.98	0.08/0.09	42Y 8.64/2.73	0.06/0.16	43Y 8.66/3.05	0.06/0.13
3. Good Middling	42Y 8.71/2.75	.08/ .15	42Y 8.78/2.38	.07/ .11	42Y 8.69/2.79	.16/ .12	42Y 8.62/2.72	.08/ .10	42Y 8.75/2.34	.10/ .09	42Y 8.65/2.70	.05/ .09
4. Strict Middling	42Y 8.66/2.22	.06/ .08	42Y 8.68/2.14	.06/ .13	42Y 8.67/2.89	.11/ .12	42Y 8.68/2.52	.09/ .18	42Y 8.66/2.10	.08/ .11	42Y 8.67/2.47	.11/ .16
5. Middling	41Y 8.42/2.07	.10/ .05	41Y 8.36/1.91	.13/ .06	41Y 8.38/2.04	.09/ .10	41Y 8.40/2.05	.13/ .09	41Y 8.40/1.92	.13/ .09	42Y 8.32/2.17	.09/ .13
6. Strict Low Middling	41Y 8.09/1.90	.08/ .10	41Y 7.96/1.63	.09/ .05	41Y 8.04/1.76	.09/ .05	40Y 8.04/1.71	.13/ .05	40Y 7.98/1.63	.11/ .10	41Y 8.02/1.95	.08/ .13
7. Low Middling	40Y 7.72/1.75	.08/ .13	40Y 7.61/1.41	.09/ .10	40Y 7.74/1.72	.09/ .05	41Y 7.74/1.85	.10/ .12	41Y 7.63/1.40	.06/ .08	41Y 7.74/1.98	.07/ .11
8. Strict Good Ordinary	41Y 7.59/1.83	.05/ .06	41Y 7.39/1.47	.14/ .05	41Y 7.54/1.79	.07/ .05	41Y 7.57/1.78	.10/ .07	42Y 7.33/1.45	.07/ .06	42Y 7.48/1.92	.09/ .08
9. Good Ordinary	41Y 7.34/1.83	.10/ .10	41Y 7.10/1.21	.11/ .10	41Y 7.38/1.70	.09/ .07	41Y 7.48/1.83	.07/ .07	43Y 7.19/1.26	.08/ .06	42Y 7.38/1.91	.09/ .09

Note how little brilliance variation there is in the high grades. The low grades have a greater variation, partly because minimum measurements are pulled down by the so-called "bluish" bales in the box. The brilliance averages for the four top grades are very nearly the same. Middling No. 5, Strict Low Middling No. 6, and Low Middling No. 7, drop considerably lower, the steps being fairly even, with a smaller brilliance drop for the two lowest grades, Strict Good Ordinary No. 8, and Good Ordinary No. 9. A great part of this brilliance change is due, doubtless, to the increasing quantity of leaf and trash present in cotton as the grades become lower.

Chroma shows a wider variation within each grade. In fact, it can be rather accurately stated that chroma differences, with the exception of the darker "bluish" bales in the low grades, are responsible for the color variations within each grade. Even in the "bluish" bales, chroma is more significant than brilliance. Chroma averages compared with grade are very nearly the reverse of those for brilliance; that is, the four top grades, instead of remaining constant as is the case with brilliance, decrease in fairly regular steps as far as No. 6, leaving the last four grades from No. 6 to No. 9, inclusive, with chroma averages which, instead of decreasing rapidly, remain very nearly constant.

Grade No. 3 is the only one in which both the brilliance and chroma measurements overlap. This is doubtless due to the increasing importance of leaf in this grade and to the fact that in certain of the samples there has been an offset of better color with more leaf. The average of the grade falls in line, but the extremes, that is, the maximum and minimum chroma, overlap, the maximum being as creamy as the maximum for grade 2, the minimum being almost as gray or weak in chroma as the average for grade 4.

In the lower grades, Nos. 7, 8, and 9, the wide chroma variation is caused by the "bluish" bales, for they are very much weaker in chroma than the average. Figure 13 shows the averages of the grades with brilliance (vertical) plotted against chroma (horizontal). About the averages are grouped the extremes, marked as to their position within the grade box. The other positions about the average may be put in by reference to Table 5. By this chart the color relation of the grades is most truly represented, although it is doubtless grasped more readily by reference to Figure 12.

Information obtained from measurements on any other product should be analyzed carefully as the foregoing analysis of the cotton measurements indicates.

IMPROVED EQUIPMENT

After these measurements were made and the results had proved them to be practicable the next step was to refine the method and equipment. A new instrument [15] has therefore been developed which has the advantage of eliminating the spinning of disks, making it easier to match the sample. When making measurements by means of this instrument, the eye need not be taken off the comparison field while the disk areas are being changed, a factor which is important in making readings easily and accurately. (See figs. 14 and 15, photographs of the instrument ready for use.)

[15] Built by Keuffel & Esser Co., Hoboken, N. J., on specification provided by this bureau.

MEASUREMENT OF COLOR IN OTHER PRODUCTS

Many other products besides cotton may be measured by this method.

The grading factor of color in the United States hay standards is based upon color measurements in terms of hue, for hue seems to be the color factor most closely correlated with grade. (With standard

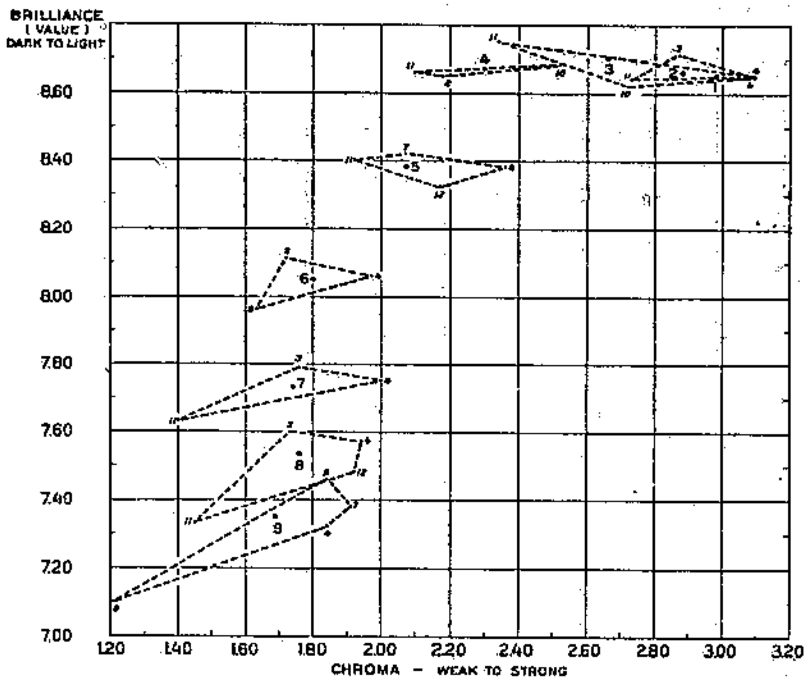


FIGURE 13.—Average readings on 10 sets of the practical forms of the standards, charted as to brilliance and chroma. The averages of the grades, together with the extremes (numbered to correspond with the position in the grade box), are shown. Note that position 4 shows in most cases the extreme amount of chroma for each grade, whereas 11 or 8 shows the least chroma. This means that in most of the grades position 4 shows the highest yellow (in the high grades by creaminess and in the lower grades by spot and sometimes slight stain) and that position 11 and 8 are the grayest bales in the grade (in the high grades the steely white bales and in the low grades the blue bales). Note that these extremes vary in their relation to the average. Whether the measurements be of cotton, flour, milk, or of anything else, the color relations indicated by a change in brilliance and chroma may be most clearly indicated by a chart of this kind

light, it is found that brillance may also be highly indicative in its relation to hue and grade.)

The first practical application to hay color work consisted of an apparatus in which the hay could be spun to get a composite color to be matched with standard cards. Figure 16 illustrates the most recent apparatus of this type.[16] This method can be used with many products, and may sometimes be advisable; but the use of a viewing unit, in which the material is put sufficiently out of focus to give a uniform color field, will accomplish the same purpose without the spinning.

[16] This machine was constructed by J. F. Barghausen, Agricultural Technologist, Bureau of Agricultural Economics.

In order to make "conversion tables" from which the grade might be read directly from a table of color readings (and this may often be advisable for many other products), a great many hay samples were graded by trained inspectors and then matched for color on the "color machine." The two sets of readings, those of the inspectors in terms of "per cent natural green color" and those made on the color machine in terms of hue, were then related in order that the

FIGURE 14.—Colorimeter developed for this work as it is set up for the measurement of cotton. The area within the black ring is measured at one time. Figure 15 shows the details of the apparatus

hue readings might be put into the inspector's language. (See Tables 6 and 7 and note that the same relations do not hold for different kinds of hay.) Equal hue differences may indicate dissimilar grade differences. Conversion tables in which two or three color factors vary may be prepared by handling the material by statistical methods of correlation.

An instrument similar to that used for cotton has been developed for hay. Note, however (fig. 17), that the field is larger in order to include a 14-inch diameter field of hay.

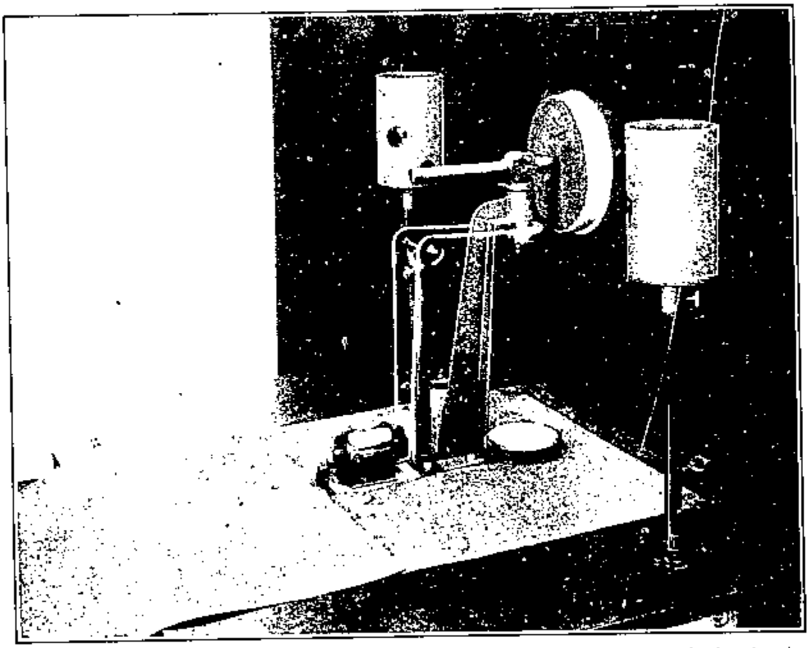


FIGURE 15.—Rear view of colorimeter, showing disks in a horizontal position. A spinning rhomb, mounted above the disks, is rotated by the pulley attached to the motor. Lamps are inclosed in the housings on either side. The black pan placed just behind the eyepiece saves the eyes from strain by enabling the observer to keep both eyes open while making readings without the chance that stray light will enter the unused eye

FIGURE 16.—The hay slug, placed in the machine, is ready to be spun in order that a color comparison may be made with the spinning disks. The disks are adjusted on a movable arm to a separate motor in order to avoid the necessity for stopping and starting the motor that keeps the hay slug revolving. When the disks are spun on a separate motor it is important that they run at the same number of revolutions per minute

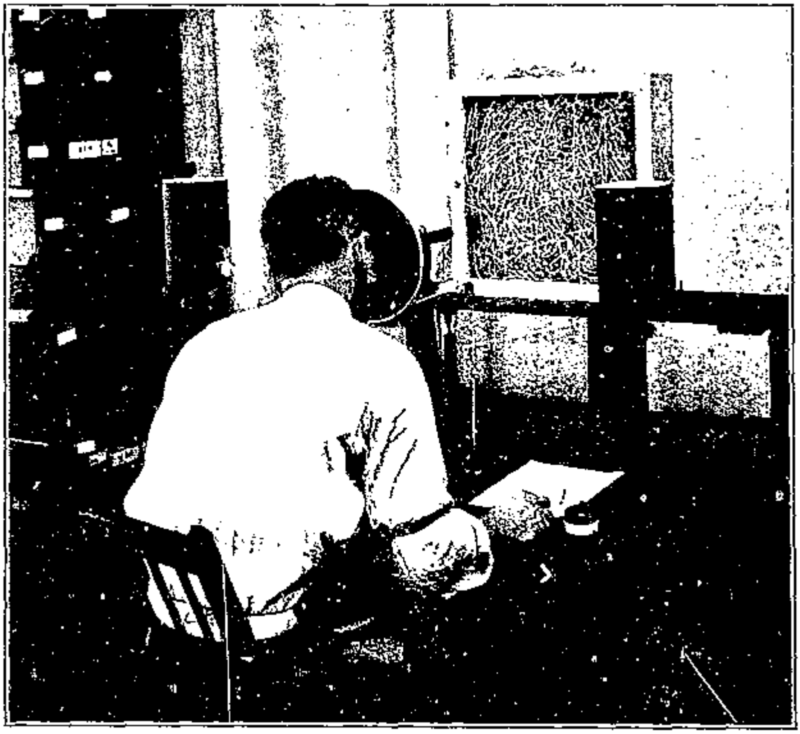


FIGURE 17.—A simplified instrument recently developed for measuring the color of hay. An area of the hay 14 inches in diameter may be measured at one time

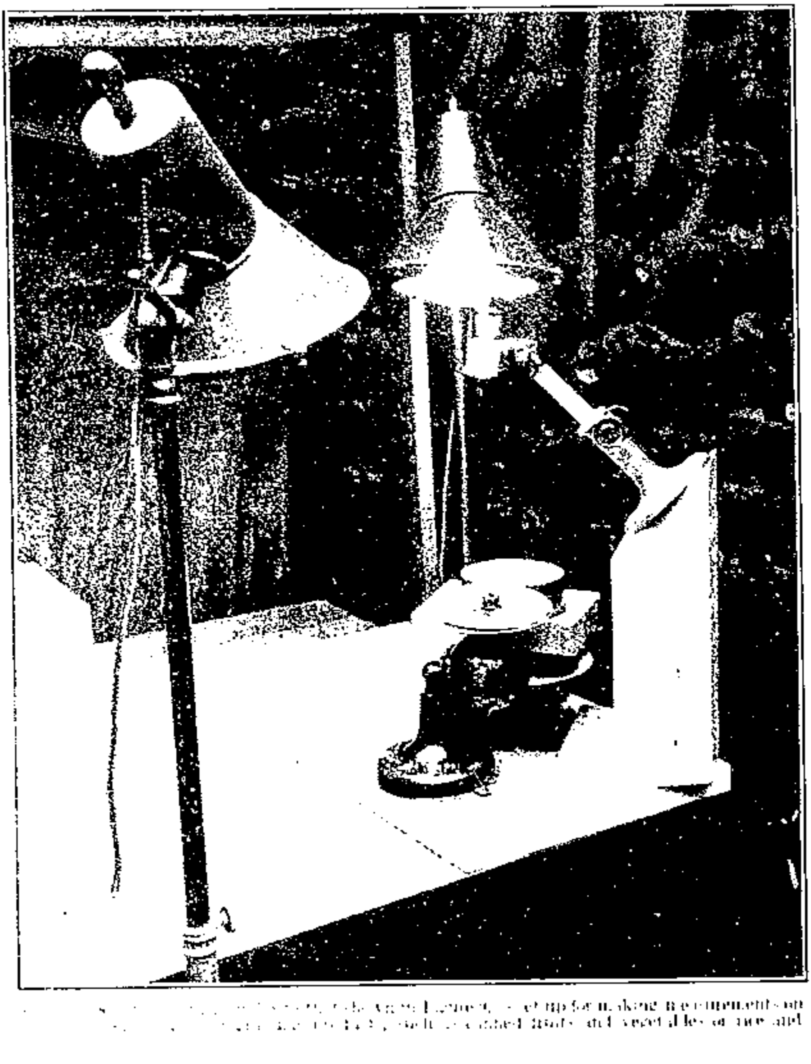
TABLE 6.—*Conversion table for alfalfa hay showing what is called "per cent natural green color" and the equivalent Munsell hue*

"Per cent natural green color"	Munsell hue	"Per cent natural green color"	Munsell hue	"Per cent natural green color"	Munsell hue	"Per cent natural green color"	Munsell hue
0	10.00 YR	30	3.75 Y	55	6.87 Y	80	10.00 Y
5	0.62 Y	35	4.37 Y	60	7.50 Y	85	0.62 GY
10	1.25 Y	40	5.00 Y	65	8.12 Y	90	1.25 GY
15	1.87 Y	45	5.62 Y	70	8.75 Y	95	1.87 GY
20	2.50 Y	50	6.25 Y	75	9.37 Y	100	2.50 GY
25	3.12 Y						

TABLE 7.—*Conversion table for clover hay showing what is called "per cent natural green color" and the equivalent Munsell hue*

"Per cent natural green color"	Munsell hue	"Per cent natural green color"	Munsell hue	"Per cent natural green color"	Munsell hue	"Per cent natural green color"	Munsell hue
0	7.25 YR	30	1.75 Y	60	4.25 Y	90	8.25 Y
5	8.97 YR	37	2.12 Y	65	4.75 Y	95	9.10 Y
10	[illegible].65 Y	40	2.50 Y	70	5.35 Y	100	9.95 Y
15	[illegible].92 Y	45	2.87 Y	75	5.95 Y		
20	[illegible].20 Y	50	3.25 Y	80	6.55 Y		
25	1.17 Y	55	3.75 Y	85	7.40 Y		

The sample of such products as can not be measured in a vertical or near-vertical plane, may be placed in a horizontal container and the equipment arranged so that the observer looks down through the eyepiece on to the sample. For instance, if any granular or semiliquid product is to be measured, such as rice or tomato pulp, a container of



[illegible] set up for making measurements on [illegible] such as canned fruits and vegetables or rice and [illegible]

the proper size should be selected and so placed that a portion of the area of the open top is visible through the eyepiece if an eyepiece is used. (Fig. 18.)

If the sample has a lustrous or semilustrous surface, the question of lighting is particularly important. Diffused lighting may give the best results, although for some work it is quite possible that, for comparison, studies should be made in both diffused light and in light at a definite angle.

It is not necessary that all color work have equally sensitive instruments with control of all environmental conditions. Just how the equipment should be set up depends upon the precision required for the work and the funds that are available. For preliminary work or for approximate studies, the simplest sort of apparatus may be used.

Ordinarily, four disks are enough for the work, the four chosen being those which, when spun, will include the extremes of the colors that are to be measured. The colors should include the two hues which are nearest to that which is to be matched, and a light and a dark neutral. For instance, in measuring tomatoes, first look at the color and decide upon the hues that must be used. Obviously one will be red, but will the other hue be a yellow-red (orange) or a red-purple? It depends upon which is the nearer to tomato coloring. Ordinarily, tomatoes will be yellowish-reds, rather than purplish-reds, so a yellow-red disk will be selected to use with the red one. Tomato colors are generally very strong in chroma, so the strongest available chromas should be selected. If there are not strong enough colors in the regular supply, then special, strong colors must be prepared.[17] It is also possible to spin either a light or a dark neutral disk before one side of the eyepiece in order that the tomato color and neutral may be alternately exposed, thus reducing or increasing the brilliance as may be necessary.

The neutrals that are selected will depend upon the brilliance of the colors which are to be measured. Tomatoes are medium to dark in brilliance. Therefore a N 1/ or 2/, nearly black, with a medium 5/ or 6/ may complete the selection of disks for tomato work.

For cotton, it is immediately evident that one hue will be yellow. The chroma of the cotton is so weak that it may not be possible to decide upon the second hue until both yellow-red and green-yellow have been tried. These hues are tried since a yellow, when departing from the standard yellow, must be either greenish or reddish. Trial will indicate that yellow-red and yellow are the hues to be used. Since the chroma of cotton is weak, a great deal of neutral color will be necessary in order to reduce the chroma of the disks, and part of that neutral will be dark, thereby reducing brilliance as well as chroma. This is not desirable, and for that reason the hues should have as strong a chroma as is possible in order to require a limited area of dark colors. Yellow has a maximum chroma of 9 on the 8 level of brilliance. Yellow-red has a maximum chroma of 8 on the 6 level of brilliance. Therefore the notation of the two hues for cotton will be Y 8/9 and YR 6/8. The neutrals to be used with these disks should contain one color which is as light as it is possible and practicable to get. This is necessary since the color of cotton is lighter than either of the disk colors selected, and a great deal of white may sometimes be necessary to counteract the darker brilliance of the yellow and yellow-red disks. The second neutral should be dark enough so that even the darkest of the colors to be measured may be included by a variation of the four disks.

Whenever it is practicable, hues of the same brilliance and chroma should be selected in order to eliminate a simultaneous change in several color factors which occurs with the change of a single area when there is a variation in the brilliance and chroma of each disk.

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[17] These may not prove permanent in color, but if care is taken in using them, and spectrophotometric curves are kept as a record, they may answer the purpose satisfactorily.

Using one neutral of the same brilliance as that of the hues will also simplify the process of matching. This, however, is not often possible when a range of colors is to be measured by disks limited in number to four or five.

This selection of disks, a motor on which to spin them, and a method of holding the sample in the same plane with the disks, are all that is necessary. A mask of neutral gray with two holes of equal size, one over the sample, one over the disks, will facilitate matching. (Fig. 8.) Light from a north sky, if daylight is used, is probably the most advisable. It is important that there be no red brick walls or other reflecting surfaces near by which may add their reflections to the daylight. Table 8 indicates, from readings made at this bureau in daylight (most of them made under a north skylight) about what variation may be expected in color readings made under these conditions. The average difference between high and low readings with the standard deviation of the average, is given in Table 8. Some of the readings were made a year or two years apart on the same sample. The readings on cotton and hay were made by different experienced observers, one observer for cotton and two for hay. (These readings should be compared with those of Table 5, which were made under constant light.)

TABLE 8.—*Average difference in readings of hue, brilliance, and chroma, made in daylight*

Commodity	Samples	Average color notation (Munsell)	Difference between high and low readings in terms of 100 hue steps, 10 brilliance steps, and 10 chroma steps, with standard deviations		
			Hue	Brilliance	Chroma
	Number				
Cotton	23	4.63Y 8.09/2.73	0.70±0.42	0.22±0.13	0.43±0.23
Alfalfa hay	44	5.36Y 4.21/3.67	.44± .37	.13± .12	.20± .18
Johnson hay	15	3.52Y 4.95/3.73	.80± .38	.28± .20	.19± .15
Prairie hay	17	4.45Y 4.81/3.25	.60± .44	.31± .17	.19± .16

This method, with equipment reduced to a minimum (a toy top may be used instead of an electric motor, if the top will spin the colors) may be used for field work, as is done in matching the color of soils (*3*) both by the Bureau of Chemistry and Soils and by members of the Soils Congress. For indoor work, with north skylight, this equipment may be set up for getting measurements on the varying colors of mayonnaise, as is done in the Food Research Division of that bureau.

The next refinement of method is to add a comparison eyepiece and standard artificial light. The eyepiece makes it easier to compare colors, and standard lighting conditions eliminate changes that occur when the light varies, for natural daylight will vary from day to day and from hour to hour. A number of measurements, many of a preliminary nature, have been made with this type of equipment on cotton, cotton linters, canned corn, Lima beans, tomatoes, pulp tomatoes, barley, rice, bread, both crust and crumb (*2*), and washed cloths being studied by the Bureau of Home Economics as part of a laundry problem. The Bureau of Animal Industry is also studying the color of meat by this method as a part of a cooperative correlation study of meat quality.[13]

[13] SHEETS, E. W., A STUDY OF THE FACTORS WHICH INFLUENCE THE QUALITY AND PALATABILITY OF MEAT. U. S. Dept. Agr., Bur. Anim. Indus. Natl. Coop. Proj., 48 p. [n. d.] [Mimeographed]; Sup. to Natl. Coop. Proj. 13 p. 1928. (Mimeographed.)

If color study is important enough to be a routine part of the daily laboratory work of establishing or maintaining standards, or if it is an important part of a large correlation project, equipment should be used that will allow color measurements to be made with the utmost ease, precision, and speed. For this work such equipment is advisable as that which has been developed for the measurement of hay and cotton in this bureau. (Refer to figs. 14, 15, and 17 for illustrations.) This method of color reading allows a truly representative area of any sample, whether that area be a circle 2 inches in diameter or 14 inches, to be brought into one field, the sample being thrown out of focus so that there is one uniform field to be matched, no spots visible.

Color measurements sometimes show that hue alone is the important grade factor; sometimes it is brilliance; at other times, chroma, or a combination of any two, or of the three. If a direct relation is not apparent, a multiple correlation (*1*) may exist. Or, it is possible that color may not be a factor; in that case much future labor will be avoided by a study which will indicate this fact conclusively, for it is possible to tell whether there is a color relationship and how far the relationship holds only after measurements have been made and correlated.

SUMMARY

Methods of color measurement may be principally referred to as methods of measuring color and methods of measuring the color stimulus. One method is psychological, the other is physical; and elements of the two may be combined in what may be termed psychophysical methods. The method used in the work described in this bulletin comes under the third head, but it is interpreted in terms of the first. All methods of spectrophotometry and many methods of colorimetry come under the second. In general, methods of colorimetry may come under any of the three heads.

Color measurement of agricultural products is a distinct necessity, not alone for purposes of standardization but for determining the importance of color as a factor of their utility and value and for correlations with other factors which are important.

Experiments made on cotton are used throughout this bulletin as an example of what may be done with other products. They include spectrophotometric, photometric, and colorimetric measurements. Those measurements which were made in terms of hue, brilliance, and chroma, gave the most satisfactory results. The measurements are expressed in terms of the Munsell notation, formulas for which are developed and explained.

In order to illustrate how these color readings may be translated into terms which may be used by nonscientific workers—inspectors, graders, and other field men—the development of hay conversion tables is described.

A method for setting up and measuring a sufficiently large sample to give a representative color has been worked out, and apparatus for making careful and accurate readings has been developed and improved.

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