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THE OPTICAL SOCIETY OF AMERICA

THE OPTICAL SOCIETY OF AMERICA was organized in 1916 "*to increase and diffuse the knowledge of optics in all its branches, pure and applied, to promote the mutual interests of investigators of optical problems, of designers, manufacturers and users of optical instruments and apparatus of all kinds and to encourage cooperation among them.*" It aims to serve the interests of all who are engaged in any branch of optics from fundamental research to the manufacture of optical goods.

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Editorial Comment

COOPERATION AMONG COLOR EXPERTS

THE papers on the Munsell Color System which appear in this issue will appeal on their own merits to all workers in the field of colorimetry. To others, the plan of simultaneous publication will be of interest as an example of an earnest effort, initiated by the authors, to advance scientific knowledge in an orderly manner. Colorimetry has always been a controversial subject. It is of importance to chemists, physicists, physiologists, and psychologists, each group having its own background and habits of thought. To confound the confusion, a term may connote different concepts in the different fields, or several terms may refer to the same concept.

Impartial evaluation of the Munsell Color System is especially difficult because the writings of A. H. Munsell include a discussion of two systems whose underlying concepts are fundamentally different. One set of concepts appeals to the instincts of the physicist, while the other seems more natural to the psychologist. As a practical matter the two systems may be much alike, and no useful purpose would be served if the importance of one system were exaggerated at the expense of the other. Realizing that this might occur if the papers in this series were published separately as individual contributions, the several authors have undertaken to forestall such a result by a free interchange of data, and by correspondence and conferences aimed at a reconciliation of opposing points of view. When a unified plan of publication had been evolved, the manuscripts were submitted to an associate editor of the Journal who was empowered by the authors to make such additional changes as were found necessary to present an impartial description of the work of A. H. Munsell in a language which is consistent throughout the series.

It is probable that the field of colorimetry will soon supply another example of cooperation among scientists on an even larger scale. In 1920, the Optical Society appointed a Committee on Colorimetry which published its report in the Journal two years later. This report was widely accepted and the supply of reprints was soon exhausted. As the subject of colorimetry became of greater importance and better data became available, a new committee was appointed which has been engaged for several years on the preparation of a report that will present the composite thoughts of a large group of experts who have often discussed the same phenomena in a variety of languages. In size and subject matter, this report is assuming the aspect of a treatise, and the care that is being taken in its preparation should endow it with a long and useful life. It is greatly to the credit of the individuals on this committee who have worked so assiduously, that they are willing and eager, purely for the sake of advancing the art, to relinquish the prestige that attaches to the publication of individual contributions, and to cooperate in an endeavor where the status of an individual member of the committee approaches complete anonymity.

The Munsell Color System

Foreword

AN obvious purpose is served by arranging this series of five papers on the Munsell Color System together as a unit. The various steps in the development of the ideas of the originator, Albert H. Munsell, may in this way be presented together with the technical data resulting from each step so that for the first time it is possible for a reader to trace this development in complete detail.

But there is a second, less obvious, though no less important purpose served by this series of papers. It arises from the fact that Mr. Munsell's original idea for color specification had two aspects: First, that the color notation should indicate color as perceived by the observer; second, that the assignment of the notations should be based upon an accurately reproducible system of measurement. That is, the ideal color notation should conform to a purely psychological requirement and at the same time enjoy a rigorous psychophysical definition.[1]

It is a common first impression of many students of colorimetry that this double requirement is easy to meet; in fact, it is often erroneously supposed by them that there is no need for the distinction between psychological and psychophysical systems. More thorough consideration reveals this error and often gives rise to the opinion that the two kinds of system are so utterly different in their concepts that there is no possibility of correspondence between them. To one who holds this opinion, Mr. Munsell's original idea seems to be based upon ignorance and impossible to fulfill.

There are possible, however, many psychophysical color systems. Some of them, such as the tristimulus system, yield variables having no obvious relation to the psychological attributes of color as perceived by the observer. Others, such as the dominant wave-length and purity system, yield variables having some degree of correspondence to them. Mr. Munsell knew well that the search for a psychophysical color system whose notation should correspond with what an observer sees is far from hopeless because he discovered a psychophysical system which fulfills this condition to a surprising degree, better than any yet found of comparable simplicity.

The second purpose of arranging these papers into a series is, therefore, to bring out the much misunderstood relations and distinctions between psychological and psychophysical color systems. The second paper of this series, that by J. E. Tyler and A. C. Hardy, analyzes the psychophysical color system discovered by A. H. Munsell. The third paper, that by K. S. Gibson and D. Nickerson, shows the degree to which the color standards of the 1915 *Atlas of the Munsell Color System* accord with this psychophysical color system. The fourth paper, that by J. J. Glenn and J. T. Killian, defines psychophysically the color system previously defined only by the material color standards of the 1929 *Munsell Book of Color*. The final paper of the series, "Preliminary report of the O.S.A. subcommittee on the spacing of the Munsell colors," by S. M. Newhall, Chairman, presents extensive data on which is to be based a psychophysical color system intended to fulfill as closely as possible the psychological ideal of A. H. Munsell.

D. B. JUDD, *Associate Editor*

[1] Color is defined as a psychophysical quantity in the report of the Committee on Colorimetry now in preparation. In this series of papers on the Munsell Color System, the psychological definition of color given in the 1922 report (J. Opt. Soc. Am. **6**, 531 (1922)) has, therefore, been superseded by a psychophysical definition.

History of the Munsell Color System and Its Scientific Application

Dorothy Nickerson
Agricultural Marketing Service, United States Department of Agriculture, Washington, D. C.

ALBERT H. Munsell was born in Boston, Massachusetts, on January 6, 1858 (1). Following a public school education, he studied art at the Massachusetts Normal Art School, and won a fellowship for foreign study. In Paris he attended Julien Academy where his work qualified him to take the examination for the Beaux Arts. There he won second prize in his first yearly competition, and, later, the Catherine de Medici scholarship which gave him another year abroad, this time in Rome. After his return, and until 1917, he kept a studio in the Back Bay section of Boston and there he painted, chiefly portraits. For his exhibitions in Boston, New York, Pittsburgh, and Chicago he was highly praised. His painting the "Ascension of Elijah," so far as we know, still hangs in the Beaux Arts in Paris. During his entire life, boats and the open sea held an unusual interest for him, as is witnessed by his many seascapes.

From 1881 to 1918 he taught drawing and painting from the antique figure and living model, composition, and artistic anatomy (1) at the Massachusetts Normal Art School, now the Massachusetts School of Art. He was loved and respected by his students to an unusual degree—they never fail to speak of him with admiration and affection.

Except for a few publications, chiefly *A Color Notation* (2) and the *Atlas of the Munsell Color System* (3), it is to a color diary (4) kept by Mr. Munsell from 1900 to 1918 that we owe most of our knowledge of the development of the Munsell system during its early history.*

It is important to recognize that Mr. Munsell's purpose in developing a system of color notation, illustrated by charts of measured colors, was to make the recording of color easy and convenient in order to provide a real aid in teaching color, particularly in teaching color to children. Because he believed that proper color training should begin with children, he spent much time in writing outlines for primary school grades and in conferences with art teachers and supervisors. It is evident that he felt that if children were properly taught, color would have more meaning and use for them all through life, and this became more important than ever to him when the early phases of development of his system were completed. The preface to the first edition of *A Color Notation* indicates that "the gist of these pages has been given in the form of lectures to students of the Normal Art School, the Art Teachers' Association, and the Twentieth Century Club . . . and . . . before the Society of Arts of the Massachusetts Institute of Technology." In the preface to the third edition in 1913, he adds: "Brewster's mistaken theory of color . . . still . . . gives children a false start with Froebel balls and a three-color box . . . but a fine color sense may be trained by decorative studies whose simple color relations permit the student to realize in what way and by how much he falls short of a definite standard. Plates II and III reproduce children's studies with measured intervals of color-light and color-strength, which so discipline their feeling for color balance that they may then be trusted to use even the strongest pigments with discretion." An introduction to the system, prepared as an aid in teaching children, was separately published as *Color Balance, Illustrated*. There is record also of several other articles written by Mr. Munsell (5).

In his introduction to *A Color Notation*, Professor H. E. Clifford, then Gordon McKay Professor of Electrical Engineering at Harvard University, states, "In the determination of his (Munsell's) relationships he has made use of distinctly scientific methods." In the same paragraph he acknowledges the chief purpose for which the system was built by stating that we

* A typewritten copy from the diary in Mr. Munsell's handwriting was made in the early 1920's by the Munsell Color Company. For the most part, charts and graphs were traced so as to represent the originals accurately. In 1939, the Inter-Society Color Council obtained permission of the Munsell Color Company, Mr. A. E. O. Munsell, and Mrs. J. E. O. Munsell (son and wife of A. H. Munsell) to have a bibliofilm record made and deposited with the American Documentation Institute of the typed copy of this diary so that it might be made available to research students. The original diary is contained in six volumes. The typed copy is contained in two volumes of approximately 250 pages each.

all appreciate the necessity for improvement in our ideas of color, and "the natural inference is that the training should begin in early youth."

The subtitle of *A Color Notation*, as published by A. H. Munsell in the "fourth edition, revised and enlarged," 1916, is "an illustrated system defining all colors and their relations by measured scales of hue, value, and chroma made in solid paint for the accompanying *Color Atlas*," the Atlas having been published in full in 1915.

Because they may help in understanding Mr. Munsell's exposition of his system and notation, the following definitions which he gave in *A Color Notation* are listed. These definitions appear in a glossary which accompanied the first seven editions of the book. This glossary is omitted in the 1936 edition (the definitions that still seemed applicable being incorporated in the text). In his book Mr. Munsell refers all discussion of hue, value, and chroma to these definitions.*

Color.—Objectively that quality of a thing or appearance which is perceived by the eye alone, independently of the form of the thing; subjectively, a sensation peculiar to the organ of view, and arising from the optic nerve (p. 108).
Hue.—Specifically and technically, distinctive quality of coloring in an object or on a surface; the respect in which red, yellow, green, blue, etc., differ one from another; that in which colors of equal luminosity and chroma may differ (p. 109).
Value.—In painting and the allied arts, relation of one object, part, or atmospheric plane of a picture to the others, with reference to light and shade, the idea of hue being abstracted (p. 112).
Chroma.—The degree of departure of a color sensation from that of white or gray; the intensity of distinctive hue, color intensity.
Scale.—A graded system, by reference to which the degree, intensity, or quality of a sense perception may be estimated.

Highlights from the Color Diary

The first entry in the A. H. Munsell color diary goes back to 1879: "Studied Rood's *Modern Chromatics*—made twirling model of two triangular pyramids. . . ." There is an entry dated 1892 when he and Denman Ross were sketching together in Venice. It says they talked over a "systematic color scheme for painters, so as to determine mentally on some sequence before laying the palette." In 1898 Munsell worked with rotary color mixture, having bought a child's globe for that purpose. It was about this time that the Munsell daylight photometer was built, a cat's eye shutter being used to cut down the amount of light entering the standard side of the instrument. Several of these instruments were built in 1900–1902. From the diary, it is evident that Munsell was quite familiar with the Fechner law, for there are many references to it during this period. The names of Rood, Bailey, Pickering, Cross (A. K. and C. R.), Clifford, Dolbeare, Ross, Pritchard, Abney, and Bowditch appear during this time, and with most of them he discussed his ideas and to most of them showed his sphere. It was in this early period that Mr. Wm. Filene asked to have the sphere shown to the Shopkeepers' Association in Boston.

In 1901 Munsell was still wondering whether to base his hue circuit on ten or on three colors. The decimal system was finally decided upon, and five principal hues were then determined by selecting colors which, when they appeared to have equal chroma, with values equal as determined by luminosity readings on the photometer, would spin together in equal proportions to give a neutral gray. As early as 1901 (April 11) he quotes Mr. Filene as saying "The retailers want a standard system fixed at all times—charts with numbers." In 1901 (April 29) appears the first mention of contact with the Bureau of Standards; Mr. Munsell wrote to Dr. Stratton "asking about color."

By January of 1902 *A Color Notation* and a *Color Atlas* were already being discussed and described. In 1903, on November 7, he describes the spinning of disks in the photometer, with value equalized by adjustments in illumination, in order to measure chroma. However, this method was dropped as unsatisfactory, for chroma scales were not finally decided upon until 1912, although charts were painted by visual estimates as early as 1901–02 in his studio by a Mr. Lyon who (evidently) prepared the original charts under Mr. Munsell's direction.

In 1904 Mr. Munsell met and talked with Jay Hambidge and notes that he was struck with points common to investigators of color and design. He lectured before many audiences, a number of them at the Massachusetts Institute of Technology, where during this early period he kept in close touch with Professor C. R. Cross

* These definitions are taken from the 4th edition, published in 1916.

and Professor Clifford, as well as with Professor Bowditch of Harvard.

During 1905 first mention is made of Arthur Howland who came to the studio and saw "all system but charts." Mention is also made of Arthur S. Allen, and of Wilhelm Ostwald. Dr. Ostwald was in Boston that year, with his son and daughter, to give a series of lectures at the Massachusetts Institute of Technology. Munsell and Ostwald had many conversations. Ostwald visited Munsell's studio, and at one of Ostwald's M.I.T. lectures he showed the Munsell color sphere and referred to the Munsell book.

About this time a first contract to supply enamels, charts, and crayons for school supplies to be used in teaching the Munsell system was made with Wadsworth-Howland & Company of Malden, Massachusetts.*

A Color Notation (2) was published in 1905, and during that year first contacts were made with Favor, Ruhl and Company through Charles W. Bidwell, manager of the Chicago branch.

In 1908 Christine Ladd-Franklin and her husband returned from abroad on the same ship with Mr. Munsell. They had several color discussions on shipboard, and later at the Munsell studio in Boston. In 1908 there was also discussed the matter of an understudy for Otto Anderson, who was in charge of painting papers for Munsell charts at Wadsworth-Howland & Company, and F. A. Carlson was decided upon. (We understand from Mr. Carlson that from the beginning he did all of the painting, Anderson being the shop supervisor.)

From 1908 to 1911 there were many lectures and talks, a series at Columbia, one in Boston for art supervisors, a lecture at the Harvard Psychological Laboratory. During this period the names of Professor Dow, Professor Yerkes, of Miss Patrick, and Professor Titchener, appear among those of a number of people Mr. Munsell met and talked or worked with in relation to his system and its application in the teaching field. In 1909 there is mention that in Mr. Drisco's laboratory at the Massachusetts Institute of Technology, spectrophotometric measurements of his five middle colors were tried—"by daylight and tungsten." No figures were given. In 1910 there is mention of receiving two copies of the new *Color Atlas* while cruising on his boat, the *Ahmed II*. These charts were evidently published first as a forerunner of the more complete Atlas, for a note from the ***Boston Journal***, December 22, 1910, describes this Atlas as containing at present two charts, chart A, the value scale, and chart B, chroma scales for 5 hues. In 1911 there is mention of meeting E. C. Andrews of Chicago when he and Arthur S. Allen visited the *Ahmed* off Annisquam, Massachusetts. Though they went sailing, the diary reads "discuss 'sequences' and E. C. A.'s color form."

In December of 1911 Mr. Munsell read a paper in Washington by invitation of the American Psychological Association, in which he described his system as "an experimental system built up with the aid of a new photometer, Maxwell disks, and the trained capacity of the painter—using a consensus of many individual decisions to gain the mean of color discrimination." At that meeting he met many of this country's leading psychologists, and they received his paper so well that he was asked to repeat it before the meeting was over. During this visit to Washington, Mr. Munsell visited the Bureau of Standards and met Dr. Nutting, in charge of colorimetry, where he left a Munsell photometer for test. On January 18, 1912 Dr. S. W. Stratton wrote that he would be pleased to examine a full set of the Munsell elementary color samples and look over the system of scales. A series of the five middle colors, and a sixth sample intended to be a neutral 5/ were sent to the Bureau, and the diary notes that report No. 10696, dated February 28, 1912, signed by P. G. Nutting, was received from the Bureau of Standards. It contained the information given in Table I.

There is no reference in the diary to the fact that Mr. Munsell was invited to present a paper on his system before the Physiological Congress held at Gröningen in 1913 (5). But it is recorded that he sailed on June 23, 1913, and that on August 30 he went to Gröningen. No mention is made of his report, but he does list about two dozen persons whom he met at the conference,

* Arthur Howland later developed a system based completely on disk mixture, known as the Howland system. It was limited to as few disks as possible, using sector disks of very strong colors spun against a hole in a black box which provided his black. Mr. Howland's Color Mixer was patented, and he was always on a search for new and stronger colors for his 4 to 7 standards that were used with a series of white sectors.

Dr. Edridge-Green among them. A few weeks later he spent some time with Sir William Abney in his studio, and records meeting Dr. Parsons and his assistants. Then back to Paris, and on to Naples, Capri and Palermo, before sailing for home on December 3. There is evidence that during this time there were numerous lectures and discussions regarding the Munsell color system.

In 1914 he returned to Europe at the request of persons who had been interested by his reports during the previous year, and again he spent about six months abroad, lecturing several times in Paris and Berlin. He was ill in London, yet he notes that the doctor permitted him to go by sea to Berlin, where his lecture was given before an audience of 300. From there he returned to London, where the notes say he was operated on by Dr. Heil on July 4, and that (I am) "remaining in Dr. Rowland's nursing home until I sail." In the early fall he was again at the Wadsworth-Howland factory, and resumed his teaching duties at the Normal Art School.

In 1915 the complete *Atlas of the Munsell Color System* (3) was published by Wadsworth-Howland & Company. From the diary it seems evident that the original charts were made by Lyon in the Munsell studio, and that the papers for the published Atlas charts were made at the Wadsworth-Howland factory, all colors being checked by Mr. Munsell. Disk mixture was used as a check for chroma and hue and all colors were measured for value in the Munsell photometer.

In 1915 suggestions regarding commercial developments of the Munsell idea became numerous, the Wadsworth-Howland representative reporting that "charts have been ordered by the Rockefeller Foundation, the Carnegie Institute, Heintz of Chicago, Dartmouth College, and others." There was much discussion during this year and the next regarding school supplies to teach the Munsell system, and of the means of producing and publicizing them by commercial groups.

In October, 1915, Cleland, Greenleaf, and Allen lunched with Mr. Munsell, then called on Miss Helen Dryden, indicating perhaps, that plans for *A Grammar of Color* (6) were then being formed. On November 6 of 1915 there is a record of "3 colors telegraphed (by Cooper) from California to New York, this is Cooper's answer to Stevenson's difficulty."

In the summer of 1916 a summer school course was held at Boothbay Harbor, Mr. Munsell delivering 12 lectures from July 25 to August 19. He returned in the fall to take up school duties again. In the winter of 1916–17 the notes say "confined to house by rheumatism."

On March 27 of 1917 there is the first mention of the Munsell Color Company, suggested to Mr. Munsell by Messrs. Allen and Greenleaf. In May he had an appendicitis operation, "not expected to survive, two nurses all summer." As a result of this illness, the studio at 221 Columbus Avenue, which he had occupied since 1901 was vacated. (It was taken over a few months later by John Singer Sargent.)

In February there is a brief note that papers for the A. H. Munsell Color Company, Inc., were "rewritten," and evidently filed at the State House, Boston, February 6, 1918.

As time went on, Mr. Munsell became somewhat dissatisfied with the handling of his materials by Wadsworth-Howland. One of the very last entries in the diary, dated February 13, 1918, tells of meeting with Judge Perkins (his lawyer) and Arthur Howland: "Discuss latter's interest in his photometer and possibility of avoiding unfair attitude toward my system. He tells of his belief in the scientific nature of his work—although I show that it ignores the fundamental law of sensation."* As a result the possibility was considered of having the New York office of the Munsell Color Company take over the educational interest as well as the industrial, leaving

Table I.

	Wave-Length Dom. Hue	% White	Refl. Coef.
Red	612	62	0.19
Yellow	585	50	0.23
Green	508	78	0.25
Blue	488	80	0.20
Lt. Purple	568[a]	31[b]	0.22
Dk. Purple*	568[a]	31[b]	0.08

[a] Wave-length of complementry hue.
[b] Percent of added hue to match white.
* In Mr. Munsell's handwriting the following note is added to the report: "(Dark purple a neutral gray N 5/)." It seems probable that a sample of P 3/5 was submitted by mistake instead of the intended N 5/.

* See asterisk footnote, page 577.

only manufacturing of materials to Wadsworth-Howland & Company.

The last entry in the diary is dated February 16, 1918.

Late Period in Life of A. H. Munsell

The color diary contains items that concern chiefly the development and use of the Munsell system and notation, and we do not realize from it that, after the 1914 trip, Mr. Munsell returned home more or less an invalid, unable to continue the active life he had previously led.

Despite physical handicaps, he was intensely interested in plans for *A Grammar of Color* (6) which was being prepared for publication by the Strathmore Paper Company. Through Mr. Allen, Mr. Munsell kept closely in touch with this work, he wrote an "Introduction to the Munsell Color System" for it (5), and approved the manuscript and much of the illustrative work that appeared later in this volume. It was for this volume that *T.* M. Cleland wrote *A Practical Description of the Munsell Color System* (7), which has been reprinted since and distributed widely, having become better known to many students as a description of the Munsell system than Mr. Munsell's own book.

In 1918 the Bureau of Standards was requested to make a spectrophotometric analysis of the Munsell Color System and for that purpose samples of the neutrals, and of the 3/5, 5/5, and 7/5 colors in five hues were supplied by the Munsell company. Whether this request was made for the company by Mr. Munsell, or by Mr. Allen is not entirely clear, but it certainly was with Mr. Munsell's complete approval. He speaks several times, particularly in letters to Mr. Allen, of hoping to meet Mr. Priest. Mr. Allen had already met Mr. Priest and had discussed the Munsell charts with him.

Mr. Munsell died on June 28, 1918.

1918–1921

From the diary, as well as other records, some of which have been made available by Mr. Allen from his old files of Munsell correspondence, a picture of the early period of the Munsell Color Company emerges.

The company was formed to carry on the business of handling publications of books and charts, of crayons, water colors, color spheres, colored papers, and other school supplies which had been developed for use in teaching the Munsell system.

Care was taken when forming the company to have the industrial and educational phases separated. The chief stockholders were Munsell (51 percent), Allen, and Greenleaf. All educational development was at first left in the hands of Wadsworth-Howland & Company, the western representatives for educational supplies continuing to be Favor, Ruhl and Company where Miss Harriet Taylor became associated with them about this time in order to handle Munsell work. The Munsell company opened an office in New York City on the same floor with the Ruxton Ink Company showroom. The company in New York, under Mr. Allen and Mr. Greenleaf, was to promote and handle industrial applications of the Munsell system. After Mr. Munsell's death D. E. Kennedy became president of the Munsell Color Company, and he opened an office in Boston to handle Munsell supplies for the educational field, work which had previously been handled by Wadsworth-Howland & Company. For a time both offices continued to function, but that did not prove very satisfactory and the company was finally reorganized as the Munsell Color Company, with complete control in the hands of Mr. Munsell's family.

In 1919, during this period, the Bureau of Standards made its report, "An examination of the Munsell Color System," published in 1920 as Technologic Paper No. 167 (8). In that report it was stated that "A revised edition of the Atlas and *A Color Notation*, based upon the best present-day methods of measurement and specification, would be a most important contribution to the science and art of chromatics generally." Five proposals were made. They are briefly summarized as follows: (a) Standardization should be made of the value scale; (b) each color should be specified in terms of physical measurement; (c) colorimetric and photometric specifications should accompany the Atlas; (d) value measurements should be made with reference to a standard white; and (e) general agreement in nomenclature should be obtained before issuing a revised publication.

Shortly after this, another and fundamentally important report on a comparison of the Fechner and Munsell scales of luminous sensation value was made by Elliot Q. Adams (9).

1921–1930

In July 1921, A. E. O. Munsell, son of A. H. Munsell, after one year of medical school and just out of the U. S. Army, encouraged by his father's friends, took over the active presidency of the Munsell Color Company. Headquarters were then at 220 Tremont Street in Boston. A few months later, J. J. Roy became business manager of the company. In October of 1921 the writer became associated with the company, and in November of 1921, F. A. Carlson joined the group in Boston.

Because New York seemed to be a center of educational activities, and because a program of expansion in the educational field was expected, the company, including on the staff the three mentioned above, moved to the Printing Crafts Building in New York City. There Milton E. Bond, artist, of Rochester, New York, was added to the permanent staff.

At this time, the business of the company consisted chiefly of sales of school supplies such as those already mentioned. Mr. Carlson's work was to copy those sheets of Atlas papers in which supplies ran low. There were, for example, more calls for the "maxima" and "middle" colors than for any others, so extra copies of these particular papers had to be made up so as to fill orders for the complete series of papers in the Atlas. The color chips were pasted on the charts by hand—in fact, they still are, the papers being painted in large sheets, then cut to the required size.

From his earliest days with the company, A. E. O. Munsell was influenced in his thinking by Irwin G. Priest, then chief of the colorimetry section of the Bureau of Standards. Mr. Munsell was neither a businessman nor an artist. His interests lay rather in scientific fields, and, from the beginning, he left the handling of much of the business of the company to others, while he concentrated on the scientific aspects of the Munsell work. The writer's first memory of A. E. O. Munsell is that of his enthusiasm upon his return from the 1921 meeting of the Optical Society of America where he had met and talked with I. G. Priest. It was at that meeting that he first heard of Carl W. Keuffel's development of a direct-reading spectrophotometer, later described before the Optical Society by Mr. Keuffel. One was ordered on the spot and was delivered in New York to the Munsell Research Laboratory during the next year.

During 1922, artist tempera colors were produced for a brief period for the company by Martini, well-known maker of high grade artist tempera colors.

More and more, the burden of handling the details of a school supply business irked Mr. Munsell. There were no profits, so there was little interest and incentive for keeping on a business manager. Therefore, during the spring of 1923, arrangements were completed whereby the making and handling of Munsell crayons was turned over to the Binney and Smith Company, and the purchase and sale of all other Munsell school supplies, water colors, drawing papers, etc., was turned over to Favor, Ruhl and Company. The entire stock of such materials was cleared out of the Munsell stock room in New York City. The only things that the Munsell company itself intended to continue handling were the production and sale of Atlas papers, charts, disks, and Munsell publications.

About this time, the Munsell Research Laboratory came into being, supported by funds contributed by A. E. O. Munsell, his mother, Mrs. J. E. O. Munsell, and his sister, then Margaret Munsell. It was founded as a memorial to A. H. Munsell to carry forward the application of his particular contribution, namely; "a simple and practical notation, or method of writing color." The employment of Milton E. Bond to produce posters, paintings, and other examples of Munsell-inspired works that could be used in art educational work, the purchase of a spectrophotometer, and of artificial daylighting, and the development of a small laboratory darkroom were all part of the research laboratory work. This work had only its beginning in New York City, for while there, all work that might be classified as "laboratory" was done by Mr. Munsell himself and by the writer, who, by way of being his secretary, was also his laboratory assistant.

Soon, however, a move to Baltimore was effected, to quarters that would afford space for laboratory work, within a reasonable distance from the Bureau of Standards, and near to The Johns Hopkins University where Mr. Munsell intended to do such graduate work in physics and psychology as might help to carry out the very general laboratory plans he was developing under Mr. Priest's guidance. This move was made in June of 1923, Munsell, Nickerson, Carlson, and Bond making the move with the company. The headquarters of the Munsell Color Company have been at 10 East Franklin Street in Baltimore since that time.

Not long after this move Blanche Robertson (Bellamy), in August 1924, and Genevieve Becker (Reimann), in January 1925, were employed by the company. Mrs. Reimann left the company in 1929 but has continued with work that has included color specification. Mrs. Bellamy at the present writing is manager of the Munsell Color Company.

Under the advice and inspiration of Irwin G. Priest, the Munsell Research Laboratory broadened its activities. During a three- to four-year period, it supported considerable research activity in its own laboratory, and in those of the Bureau of Standards.

Mr. Priest advised that a standard for "white light" must be adopted before color measurements, of Munsell or any other system, could be made most useful, and data for setting a standard were not available. Therefore, one of the first projects supported by the Munsell Research Laboratory at the Bureau of Standards aided in procuring fundamental data. In fact, a considerable part of the data used by Mr. Priest at the 1931 I.C.I. meeting, when a standard observer and standard illuminants were adopted, had been obtained during the course of work partially or wholly supported by the Munsell Research Laboratory.

Little of the work done either at the Bureau of Standards or at the Munsell Research Laboratory in Baltimore has been published, but the following reports of work supported by funds of the Munsell Research Laboratory have been read before the Optical Society (A designates abstract):

I. G. Priest, "Progress on the determination of normal gray light," (Oct., 1922, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **7**, 72A (1923).

I. G. Priest and C. L. Cottrell, "The effect of various conditions upon the determination of the normal stimulus of gray," (Oct., 1922, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **7**, 73A (1923).

I. G. Priest, "The colorimetry and photometry of daylight and incandescent illuminants by the method of rotatory dispersion," (Oct., 1922, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **7**, 75A (1923); **7**, 1175 (1923); Trans. I. E. S. **18**, 861 (1928).

I. G. Priest, "Preliminary data on the color of daylight at Washington," (Oct., 1922, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **7**, 78A (1923).

I. G. Priest, "Apparatus for the determination of color in terms of dominant wavelength, purity and brightness," (Oct., 1923, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **8**, 28A (1924); **8**, 173 (1924).

Priest, Gibson and Munsell, "A comparison of experimental values of dominant wavelength and purity with their values computed from the spectral distribution of the stimulus," (Oct., 1923, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **8**, 28A (1924).

Priest, McNicholas and Frehafer, "Some tests of the precision and reliability of measurements of spectral transmission by the Konig-Martens spectrophotometer," (Oct., 1923, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **8**, 30A (1924); **8**, 201 (1924).

Munsell, Priest and Gibson, "Specification of color in terms of dominant wavelength, purity and brightness," (Oct., 1924, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **10**, 291A (1925).

I. G. Priest, "Gray skies and white snow," (Feb., 1925, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **11**, 133A (1925); J. Wash. Acad. Sci. **15**, 306 (1925).

K. S. Gibson and F. K. Harris, "A spectrophotometric analysis of the Lovibond color system," (Oct. 1925, Meeting), J.Opt. Soc. Am. and Rev. Sci. Inst. **12**, 481A (1926); Sci. Pap. Bur. Stand. **22**, 1 (1927–28); S547.

I. G. Priest, "Standard artificial sunlight for colorimetric purposes," (Oct., 1925, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **12**, 479A (1926).

A. E. O. Munsell and P. Reeves, "Value sensitivity and value scales," (Oct., 1925, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **12**, 481A (1926).

D. B. Judd, "The computation of colorimetric purity," (Oct., 1925, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **12**, 482A (1926); **13**, 133 (1926).

I. G. Priest, "An experiment bearing on the adoption of a standard neutral stimulus in colorimetry: the choice as between 'sun' and 'equal energy'," (Feb., 1926, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **13**, 306A (1926).

I. G. Priest and F. G. Brickwedde, "The minimum perceptible colorimetric purity as a function of dominant wavelength with sunlight as neutral standard," (Feb., 1926, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **13**, 306A (1926); J. Opt. Soc. Am. **28**, 133 (1938).

I. G. Priest, "Blue sky and white snow, a note on sensation and perception," (Feb., 1926, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **13**, 308A (1926).

I. G. Priest and K. S. Gibson, "Apparatus for the determination of the visibility of energy and the fundamental scales of visual psychophysics," (Oct., 1926, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **14**, 136A (1927).

E. P. T. Tyndall, "Sensibility to wavelength difference as a function of purity," (Oct., 1926, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **14**, 137A (1927); J. Opt. Soc. Am. **23**, 15 (1933).

I. G. Priest and D. B. Judd, "Sensibility to wavelength difference and the precision of measurement of dominant wavelength for yellow colors of high saturation," (Oct., 1926, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **14**, 137A (1927).

A. E. O. Munsell and I. H. Godlove, "White glass photometric standards," (Oct., 1928, Meeting), J. Opt. Soc. Am. and Rev. Sci. Inst. **18**, 167A (1929).

I. H. Godlove, "Standardization of Munsell colors," (Feb., 1932, Meeting), J. Opt. Soc. Am. **22**, 429A (1932).

I. H. Godlove, "Comparison of Cobb's and Munsell Research Laboratory's data on neutral value scales and equations describing them," (Oct., 1933, Meeting), J. Opt. Soc. Am. **24**, 55A (1934).

I. H. Godlove, "Color blending computations in psychological terms," (Oct., 1934, Meeting), J. Opt. Soc. Am. **25**, 44A (1935).

As may be seen from the titles, and as might be expected by those who knew Mr. Priest and Mr. Munsell, there was no narrow restriction regarding what might be carried on as Munsell-supported investigations. Yet it may be seen that they all point to the development of needed information if the Munsell, or any other, color system were to be critically studied.

Among unpublished reports of Munsell-supported work at the Bureau of Standards are certain letters and reports made to the Munsell Laboratory, or to Mr. Munsell. The following three are the most important of these:

"Report on spectral reflectance of 70 representative colored cards from the Munsell color system," Bur. Stand. Test No. 46045 (September 14, 1926).

"Derivation of the trilinear coordinates specifying the colors of constant saturation," letter to Munsell Laboratory (April 13, 1927).

"Data on least perceptible purity, including Priest's memorandum on 'Relation between the Munsell chroma scale and the data of Priest and Brickwedde on least perceptible purity,'" and notes by Judd on the memorandum, transmitted to Mr. Munsell, (May 9, 1927).

Although the work supported by the Munsell Laboratory at the Bureau of Standards covered a wide field, most of the work in the Baltimore laboratory was aimed more directly toward the collection, under controlled conditions, of sufficient data to enable the Munsell Research Laboratory to specify an improved series of papers to represent, even more adequately than the Atlas papers, a psychologically sound series of equally stepped scales of hue, value, and chroma.*

Experiments regarding value were prolonged and three partial reports of this work were later published in this Journal. (10), (11), (12).

Although many experiments were made regarding chroma and hue scales, there is no published material. But there are available, as a result of this work, certain valuable papers made for special experiments: 100 equally stepped hues painted to represent constant value and chroma (at 5/5), 50 hues at maximum chroma, a series of 60-value papers closely stepped from black to white, and certain chroma scales of very small steppings.†

It may be of interest, and is important as a matter of record, to note that in addition to those already named as part of the Munsell staff, the following individuals have been employed at one time or another in the scientific work of the Munsell Research Laboratory.

In Baltimore	At the Bureau of Standards
Miriam E. O'Brien (Underhill), 1924–25	Casper L. Cottrell
Louise L. Sloan (Rowland), 1925–26	Irwin G. Priest
Geraldine Walker (Haupt), 1925–27	Deane B. Judd
I. H. Godlove, 1926–33	F. K. Harris
Carl Boechner (part time 1925)	F. G. Brickwedde
Prentice Reeves (summers of 1925, 1926)	E. P. T. Tyndall
Willard L. Valentine (summer of 1926)	W. Greenberg

In 1927 the investigative work came practically to a stop. Funds had been contributed up to that time, but the contributors felt that by this time some practical use should be made of the data. The research laboratory had obtained the data for a purpose: the company should now use it for this purpose. Therefore, a studied revision of the standard color papers was made, to follow essentially the newly derived scales—a

* His family, who supported the laboratory for this purpose, considered this "a goal consistently striven for by Mr. Munsell."

† All measured by Granville, Nickerson and Foss, reference 27.

revision first suggested by the Priest, Gibson, McNicholas report (8).

The result was the publication in 1929 of a book of charts known as the *Munsell Book of Color* (13), to distinguish it from the *Atlas of the Munsell Color System* (3) which it was intended to replace. The work of producing the charts was completed under the direction of Walter M. Scott, service director of the Munsell Color Company, 1928–30. For the *Book of Color*, F. G. Cooper wrote a foreword and explanation of color which has been reprinted separately as a *Manual of Color* (14).

Except to those who used Munsell papers for purposes of color measurement, the new papers were not different enough from the old ones to cause any difficulty. In general, teachers liked the form of the new charts (made available in a pocket-size edition as well as the larger $8\frac{1}{2} \times 12$ charts of the standard edition), and since the charts were used by them for teaching the relation of colors, rather than for matching colors, they were well satisfied.

The Munsell company, particularly during the period of research activity, had developed a certain amount of consulting business, chiefly in relation to the preparation of standard colors, and color scales for specific purposes. Thus there were prepared the Flagg-haemoglobinometer, and meat-grading scales for the Department of Agriculture, both washable, made on a clear celluloid base. The preparation of a color chart for use in advisory work by the Clothing Information Bureau of the Filene Company in Boston is another example. Applications of the Munsell system to the textile industry were made while Dr. Scott was with the company (15). Standards for soap colors, for scales to measure detergent power, to measure smoke deposit—all such problems, and many more, were handled during the 1921–30 period.

Although the trend of thinking in the company during those years was along scientific rather than art educational lines, the actual business of the company (it never has made a profit, nor has it ever employed a salesman) was in supplying art educational materials for teaching the Munsell system. And this field was not entirely neglected by the research activities of the laboratory, for Milton E. Bond, while he was with the company, produced many pieces of illustrative work; Byron G. Culver of the Rochester Art Institute completed the manuscript of a book for teaching color;* a summer school session was held under the leadership of Royal B. Farnum and Byron G. Culver in 1926; and *Color News* was published by the Research Laboratory for three years, 1924–27 (16).

After the publication of the *Book of Color* in 1929, Mr. Munsell, who felt that the chief object of the laboratory had now been accomplished, began to devote himself to other interests. Thus he withdrew more and more from color activities, until in 1933 a complete break was made of all formal connection with the company. Whenever near enough, he has been available for consultation by whomever has been in charge of the company, for he is still interested in the work although he prefers that it be a side line rather than a lifework.

In 1930 the Munsell Color Company attempted, for a time, to turn over the distribution of supplies to Universal Color Standards, Inc., a Baltimore company formed for that purpose. But the attempt was not successful, and the Munsell company soon resumed the handling of those supplies which they make or publish themselves.

About 1929 a new Munsell universal photometer was developed, and in the early 1930's, during the time that the late Walter T. Spry was manager of the company (1933–1938), new types of school charts were produced (17). Arrangements also were made to handle the sale of the Pfund instruments, thus adding color and paint measuring instruments to the color publications and special charts which previously had been the greater part of the Munsell business.

Since Mr. Spry's death in 1938, Blanche R. Bellamy has been manager of the company where she is continuing its scientific tradition by sup-

* Publication of this manuscript was never made by the Munsell company, but a handbook based upon the Munsell system arranged by Mr. Culver on the same basic material was used for many years in his classes on color theory at the Department of Applied Art of the Rochester Athenæum and Mechanics Institute. (Mr. Bond now teaches the courses on color theory, using his own unpublished material, including a large number of effective teaching charts.) From Mr. Culver, now supervisor of the Institute's newly established Department of Publishing and Printing, we understand that, in connection with the work on printing, a new handbook on color is about ready for publication.

plying assistance and material for use in studies of scientific color interest. She has continued the assistance given by Mr. Spry to the subcommittee of the Colorimetry Committee of this society on the smoothing of the Munsell data. And Mr. Carlson, without whose steady eye and hand it would be hard to imagine a satisfactory supply of all of the regular and special Munsell colors that have been made since 1912, is still painting Munsell colors, although from 1931 to 1939 he was not regularly employed for full time by the company. At the present time, Mrs. J. E. O. Munsell is making provision for the development of special colors which is helping to keep Mr. Carlson with the company. Only Mrs. Bellamy and Mr. Carlson now remain of the earlier group. But the fact should be noted that a large proportion of the others connected at one time or another with the Munsell work are now employed in a wide variety of color activities. Working with the Munsell company never narrowed one to the confines of a single "system"; rather it encouraged a broad outlook on the entire color field.

Developments Outside Munsell Headquarters

Applications of the Munsell system in scientific work have been made to a greater extent from outside the Munsell laboratories than from within.

In March, 1927, the writer was employed by the United States Department of Agriculture to develop and carry on certain adaptations of the Munsell system for purposes of color measurement that had been started in connection with hay standards and color scales for meat grading. The development of a disk type colorimeter followed, the actual spinning of disks being eliminated by spinning an optical rhomb or wedge in one side of the viewing beam. The first instrument, suggested by one made by Carl W. Keuffel as the answer to an early discussion by Priest, Munsell, and Keuffel as to whether a spinning optical part could be used for mixing colors (18), was developed for the Department of Agriculture through the cooperation of Mr. Keuffel, and a commercial model (19) of this instrument was made and sold by the Keuffel and Esser Company. About the same time an eyepiece for the observation of spinning disks in comparison with a sample such as cotton or hay was developed for work in the Department of Agriculture laboratories by the Bausch and Lomb Optical Company.* In 1933 this was followed by the manufacture of a simplified form of disk colorimeter, the Bausch and Lomb HSB Color Analyzer—HSB for 1922 Optical Society terms hue, saturation, and brilliance (20). When this instrument appeared, the Keuffel and Esser Company stopped making the larger type. A revised model of the Bausch and Lomb disk colorimeter is now completed, and it is hoped that the rush of optical work due to the present defense program will not unduly delay its commercial production.

In 1929 the disk method of color measurement, using Munsell disks as secondary standards, was described in a technical bulletin of the U. S. Department of Agriculture (21). Since that time, the method of disk colorimetry, using disks calibrated for measurement of particular products, has spread to many fields of work, sometimes with instruments, sometimes without. Three papers by the writer concerning this method have appeared in the *Journal of the Optical Society* (19), (22), (23) and other reports concerned with disk colorimetry have been published elsewhere (24). A technical paper to serve as a handbook on disk colorimetry is now in preparation by the Department of Agriculture.

Other developments outside of the Munsell laboratories consist chiefly of the 1935 Glenn-Killian data on the Munsell papers (25); the work of a subcommittee of the Colorimetry Committee of this society in reviewing the spacing of the Munsell system (26); measurements by Granville, Nickerson, and Foss of the more than 400 special Munsell papers (in addition to those which appear on the regular charts) (27); a report by Tyler and Hardy at the October, 1939, O.S.A. meeting (28); a report by Nickerson and Granville in the April, 1940, *Journal of the Optical Society* (29); preparation of I.C.I. values for the

* Members of the Optical Society might have been amused could they have been with W. B. Rayton and the writer in 1927 on a trip in downtown Rochester to find a hay dealer with enough hay in stock to demonstrate whether the idea of obtaining the average color of a hay sample by a series of out-of-focus lenses would work!

Bureau of Standards 1926 measurements of Munsell papers (30); the adoption in 1939 of a system of standardized color designations by the Inter-Society Color Council, the limits being defined in terms of the Munsell notation (31); the measurement of a master set of Munsell papers at the National Bureau of Standards; the conversion of the colors of the Maerz and Paul *Dictionary of Color*, the color standards of The Textile Color Card Association of the United States, Inc., and of other standard color data, into Munsell notation.

Certain of this work is already partially or wholly available, certain of it appears in the four reports which follow and the rest will be made available as it becomes ready for publication.

Final

From this review it is hoped that the reader will be able to recognize the vitality of a color system that has grown so much in usefulness since first proposed in the early 1900's. That we should know in exact detail the various plans of the originator is now more interesting than important. His simple notation for color and the descriptions and charts made available for practical work, not only for teaching and understanding color, but for color measurement and coordination, have been an outstanding contribution to color knowledge. For this contribution the science of colorimetry is truly indebted to Albert H. Munsell, artist and art teacher.

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An Analysis of the Original Munsell Color System

JOHN E. TYLER AND ARTHUR C. HARDY
Massachusetts Institute of Technology, Cambridge, Massachusetts

IN 1919, the Munsell Color System was subjected to a spectrophotometric examination by Priest, Gibson, and McNicholas,[1] who determined the spectral reflection characteristics of fifteen chromatic standards and nine neutral standards of the system. These spectrophotometric data have now been integrated in accordance with the 1931 I.C.I. standard observer and Illuminant *C*. The resulting tristimulus values and trichromatic coefficients are listed in Table I.

The instructions given by Professor Munsell for making a pigment color-solid are so complete that the entire color system can be constructed, given any five chromatic colors of the system which are unrelated in the sense that no two have either the same hue or complementary hues. The definitions of *hue*, *value*, and *chroma* are unambiguously established by the operations involved in constructing the system by means of additive mixtures on a Maxwell disk.[2] The hue, value, and chroma of such a mixture are related to those of the components of the mixture as follows:

Hue.—When a chromatic color is mixed additively with a neutral (white, gray, or black), the *hue* of the mixture is the same as that of the chromatic color.

Value.—When two colors whose values are V_a and V_b occupy relative areas a and b on a Maxwell disk, the *value* of the mixture is given by the equation $V^2 = aV_a^2 + bV_b^2$.

Chroma.—When two complementary colors occupy areas on a Maxwell disk which are inversely proportional to the product of value by chroma, a neutral gray results.

By comparison of these quantities with the corresponding quantities in psychophysical systems, it is evident that *hue* is synonymous with dominant wave-length, that *value* is the square root of luminous apparent reflectance, Y, expressed in percent, and that, for a given hue and value, *chroma* is proportional[3] to colorimetric purity in psychophysical systems.

When tristimulus specifications have been assigned to five unrelated colors in the Munsell system, the calculation of the tristimulus specifications for all other colors in the system involves no more than a hypothetical repetition of the procedure employed originally by Professor Munsell. In other words, the disk mixtures of Professor Munsell can be made hypothetically by the I.C.I. observer under carefully standard-

TABLE I. *Tristimulus specifications (X, Y, Z) and trichromatic coefficients (x, y) of 15 Munsell Atlas colors computed from spectrophotometric data (1919) on the basis of the I.C.I. standard observer and coordinate system and for I.C.I. Illuminant C.*

Munsell Notation	X	Y	Z	x	y
R 7/5	0.4951	0.4399	0.4305	0.3626	0.3221
5/5	.2678	.2140	.1713	.4101	.3276
3/2	.0977	.0878	.0809	.3667	.3295
Y 7/4	.4661	.4869	.2625	.3835	.4006
5/5	.2605	.2662	.1024	.4141	.4232
3/2	.0950	.0974	.0708	.3611	.3700
G 7/4	.4173	.4860	.4688	.3041	.3542
5/5	.1811	.2454	.1982	.2899	.3928
3/2	.0766	.0933	.0952	.2888	.3519
B 7/4	.4325	.4827	.6573	.2750	.3070
5/5	.2246	.2595	.4385	.2434	.2813
3/2	.0822	.0904	.1412	.2620	.2881
P 7/3	.5162	.4978	.6613	.3081	.2972
5/5	.2773	.2448	.4187	.2948	.2602
3/2	.0981	.0921	.1553	.2838	.2667

TABLE II. *Tristimulus specifications (X, Y, Z) and trichromatic coefficients (x, y) of the five principal Munsell colors taken from Table I, each set of tristimulus specifications being multiplied by a factor to make Y=0.2500.*

Munsell Notation	X	Y	Z	x	y
R 5/5	0.31298	0.25000	0.20018	0.4101	0.3276
Y 5/5	.24459	.25000	.09613	.4141	.4232
G 5/5	.18454	.25000	.20198	.2899	.3928
B 5/5	.21634	.25000	.42235	.2434	.2813
P 5/5	.28326	.25000	.42761	.2948	.2602

[1] Tech. Paper No. 167, Bur. Stand. (1919).

[2] These operations are partly described in Chapter V of *A Color Notation*, by A. H. Munsell (Ellis, Boston, 1907), and the description is completed in the *Atlas of the Munsell System* (Wadsworth-Howland, Malden, Massachusetts, 1915).

[3] During his early work, Professor Munsell defined chroma in such a manner that when a chromatic color is mixed with a neutral on a Maxwell disk, the chroma of the mixture is less than that of the chromatic color in proportion to the fraction of the area of the disk occupied by the neutral. The type of color system to which this definition leads is discussed in a bachelor's thesis by John E. Tyler on file in the Library at the Massachusetts Institute of Technology.

TABLE III. *Tristimulus specifications (X, Y, Z) and trichromatic coefficients (x, y) computed for 260 Munsell designations according to instructions by Professor Munsell for making a pigment color-solid. These computed specifications are based upon the five principal Munsell colors specified in Table II.*

Munsell Notation	X	Y	Z	x	y
R 8/6	0.7598	0.6400	0.5569	0.3883	0.3271
4	.7185	.6400	.6013	.3666	.3266
2	.6771	.6400	.6459	.3449	.3260
7/8	.6315	.4900	.3729	.4226	.3279
6	.5953	.4900	.4118	.3977	.3273
4	.5591	.4900	.4507	.3728	.3267
2	.5229	.4900	.4896	.3480	.3261
6/10	.5128	.3600	.2215	.4686	.3290
8	.4817	.3600	.2549	.4393	.3283
6	.4507	.3600	.2882	.4101	.3276
4	.4197	.3600	.3216	.3811	.3269
2	.3886	.3600	.3550	.3522	.3262
5/14	.4293	.2500	.0751	.5690	.3314
12	.4034	.2500	.1029	.5334	.3308
10	.3776	.2500	.1307	.4979	.3297
8	.3517	.2500	.1585	.4627	.3288
6	.3259	.2500	.1863	.4276	.3280
4	.3000	.2500	.2141	.3927	.3272
2	.2742	.2500	.2419	.3579	.3263
4/12	.2830	.1600	.0392	.5869	.3318
10	.2624	.1600	.0614	.5423	.3307
8	.2417	.1600	.0836	.4980	.3297
6	.2210	.1600	.1059	.4539	.3286
4	.2003	.1600	.1281	.4101	.3276
2	.1796	.1600	.1503	.3666	.3266
3/10	.1670	.0900	.0137	.6169	.3325
8	.1515	.0900	.0304	.5572	.3311
6	.1359	.0900	.0470	.4980	.3297
4	.1204	.0900	.0637	.4393	.3283
2	.1049	.0900	.0804	.3811	.3269
2/6	.0708	.0400	.0098	.5868	.3317
4	.0604	.0400	.0209	.4979	.3296
2	.0501	.0400	.0320	.4100	.3276
YR 8/6	0.6972	0.6400	0.3966	0.4021	0.3691
4	.6767	.6400	.4945	.3736	.3534
2	.6562	.6400	.5924	.3475	.3389
7/8	.5585	.4900	.1863	.4523	.3968
6	.5405	.4900	.2719	.4150	.3762
4	.5226	.4900	.3574	.3814	.3577
2	.5047	.4900	.4430	.3510	.3408
6/8	.4190	.3600	.0951	.4794	.4118
6	.4037	.3600	.1684	.4331	.3862
4	.3883	.3600	.2417	.3922	.3636
2	.3730	.3600	.3150	.3559	.3435
5/8	.2996	.2500	.0252	.5211	.4350
6	.2868	.2500	.0864	.4602	.4012
4	.2740	.2500	.1475	.4080	.3724
2	.2611	.2500	.2086	.3628	.3474
4/6	.1896	.1600	.0260	.5048	.4259
4	.1794	.1600	.0749	.4330	.3862
2	.1692	.1600	.1237	.3735	.3533
3/4	.1047	.0900	.0238	.4793	.4119
2	.0971	.0900	.0604	.3922	.3636
2/2	.0449	.0400	.0187	.4332	.3862
Y 8/12	0.6214	0.6400	0.0241	0.4834	0.4979
10	.6238	.6400	.1353	.4458	.4574
8	.6262	.6400	.2459	.4141	.4233
6	.6286	.6400	.3572	.3866	.3937
4	.6310	.6400	.4685	.3627	.3679
2	.6333	.6400	.5790	.3419	.3455
7/10	.4762	.4900	.4272	.4720	.4856
8	.4783	.4900	.1399	.4316	.4422
6	.4804	.4900	.2370	.3979	.4058

Munsell Notation	X	Y	Z	x	y
Y 7/4	0.4825	0.4900	0.3342	0.3693	0.3750
2	.4846	.4900	.4314	.3447	.3485
6/8	.3504	.3600	.0552	.4578	.4702
6	.3522	.3600	.1384	.4141	.4232
4	.3540	.3600	.2217	.3783	.3847
2	.3558	.3600	.3050	.3486	.3527
5/6	.2438	.2500	.0614	.4391	.4503
4	.2453	.2500	.1308	.3919	.3993
2	.2468	.2500	.2003	.3541	.3586
4/6	.1554	.1600	.0060	.4834	.4978
4	.1565	.1600	.0615	.4140	.4232
2	.1557	.1600	.1171	.3628	.3680
3/4	.0876	.0900	.0138	.4577	.4702
2	.0885	.0900	.0554	.3783	.3847
2/2	.0391	.0400	.0154	.4140	.4234
GY 8/6	0.5687	0.6400	0.3871	0.3564	0.4011
4	.5910	.6400	.4882	.3438	.3723
2	.6134	.6400	.5892	.3329	.3473
7/8	.4088	.4900	.1747	.3808	.4565
6	.4283	.4900	.2631	.3625	.4148
4	.4478	.4900	.3526	.3470	.3797
2	.4673	.4900	.4401	.3344	.3507
6/8	.2906	.3600	.0850	.3950	.4895
6	.3073	.3600	.1608	.3711	.4347
4	.3241	.3600	.2366	.3520	.3910
2	.3409	.3600	.3125	.3364	.3552
5/6	.2064	.2500	.0801	.3848	.4660
4	.2204	.2500	.1433	.3592	.4074
2	.2344	.2500	.2065	.3393	.3619
4/6	.1254	.1600	.0210	.4094	.5222
4	.1366	.1600	.0715	.3711	.4346
2	.1478	.1600	.1221	.3438	.3722
3/4	.0726	.0900	.0212	.3950	.4897
2	.0810	.0900	.0591	.3520	.3911
2/2	.0342	.0400	.0179	.3711	.4346
G 8/6	0.5133	0.6400	0.5608	0.2995	0.3734
4	.5541	.6400	.6039	.3082	.3559
2	.5949	.6400	.6471	.3161	.3401
7/8	.3438	.4900	.3769	.2840	.4047
6	.3796	.4900	.4148	.2955	.3815
4	.4153	.4900	.4527	.3058	.3608
2	.4510	.4900	.4906	.3150	.3423
6/8	.2351	.3600	.2583	.2755	.4218
6	.2657	.3600	.2908	.2899	.3928
4	.2964	.3600	.3233	.3025	.3675
2	.3270	.3600	.3558	.3136	.3452
5/10	.1207	.2500	.1343	.2391	.4950
8	.1463	.2500	.1614	.2623	.4484
6	.1718	.2500	.1884	.2815	.4097
4	.1973	.2500	.2155	.2977	.3772
2	.2228	.2500	.2426	.3115	.3495
4/10	.0568	.1600	.0642	.2022	.5692
8	.0773	.1600	.0859	.2391	.4951
6	.0977	.1600	.1076	.2674	.4381
4	.1181	.1600	.1292	.2899	.3928
2	.1385	.1600	.1509	.3082	.3560
3/8	.0282	.0900	.0321	.1874	.5990
6	.0435	.0900	.0484	.2391	.4950
4	.0588	.0900	.0646	.2755	.4218
2	.0741	.0900	.0808	.3025	.3675
2/6	.0091	.0400	.0106	.1518	.6702
4	.0192	.0400	.0215	.2388	.4954
2	.0295	.0400	.0323	.2898	.3929

Table III.—*Continued.*

Munsell Notation	*X*	*Y*	*Z*	*x*	*y*
BG 8/4	0.5530	0.6400	0.7792	0.2804	0.3245
2	.5944	.6400	.7348	.3019	.3250
7/6	.3782	.4900	.6452	.2499	.3238
4	.4144	.4900	.6063	.2743	.3244
2	.4506	.4900	.5674	.2988	.3249
6/6	.2645	.3600	.4884	.2377	.3235
4	.2956	.3600	.4550	.2661	.3242
2	.3266	.3600	.4216	.2947	.3248
5/10	.1191	.2500	.4086	.1531	.3215
8	.1449	.2500	.3808	.1868	.3223
6	.1708	.2500	.3530	.2207	.3231
4	.1966	.2500	.3252	.2548	.3239
2	.2225	.2500	.2974	.2890	.3247
4/10	.0555	.1600	.2837	.1112	.3205
8	.0762	.1600	.2615	.1531	.3215
6	.0969	.1600	.2393	.1953	.3225
4	.1176	.1600	.2170	.2377	.3235
2	.1383	.1600	.1948	.2804	.3245
3/10	.0119	.0900	.1805	.0420	.3188
8	.0274	.0900	.1638	.0973	.3201
6	.0429	.0900	.1471	.1531	.3215
4	.0584	.0900	.1304	.2094	.3228
2	.0739	.0900	.1137	.2661	.3242
2/6	.0087	.0400	.0765	.0695	.3196
4	.0191	.0400	.0653	.1532	.3215
2	.0294	.0400	.0542	.2377	.3235
B 8/4	0.5948	0.6400	0.8861	0.2804	0.3018
2	.6153	.6400	.7882	.3011	.3132
7/4	.4509	.4900	.6996	.2749	.2987
2	.4688	.4900	.6140	.2981	.3115
6/6	.3116	.3600	.6082	.2434	.2813
4	.3269	.3600	.5349	.2676	.2946
2	.3422	.3600	.4616	.2941	.3093
5/10	.1843	.2500	.5751	.1826	.2477
8	.1972	.2500	.5140	.2051	.2601
6	.2099	.2500	.4529	.2300	.2739
4	.2227	.2500	.3918	.2576	.2892
2	.2355	.2500	.3307	.2886	.3063
4/10	.1077	.1600	.4169	.1574	.2337
8	.1180	.1600	.3680	.1826	.2477
6	.1282	.1600	.3192	.2111	.2634
4	.1385	.1600	.2703	.2434	.2813
2	.1487	.1600	.2214	.2805	.3018
3/8	.0587	.0900	.2437	.1496	.2294
6	.0664	.0900	.2070	.1827	.2476
4	.0741	.0900	.1704	.2215	.2691
2	.0817	.0900	.1337	.2676	.2946
2/6	.0244	.0400	.1165	.1348	.2212
4	.0295	.0400	.0920	.1826	.2477
2	.0346	.0400	.0676	.2434	.2813
PB 8/4	0.6405	0.6400	0.9135	0.2920	0.2917
2	.6382	.6400	.8014	.3069	.3078
7/4	.4910	.4900	.7228	.2882	.2876
2	.4889	.4900	.6257	.3047	.3054
6/6	.3630	.3600	.6382	.2667	.2645
4	.3612	.3600	.5549	.2830	.2821
2	.3594	.3600	.4716	.3018	.3023
5/10	.2558	.2500	.6167	.2279	.2227
8	.2543	.2500	.5473	.2419	.2377
6	.2528	.2500	.4779	.2578	.2549
4	.2513	.2500	.4084	.2763	.2748
2	.2498	.2500	.3391	.2978	.2980
4/10	.1649	.1600	.4501	.2128	.2064
8	.1637	.1600	.3946	.2279	.2227
6	.1625	.1600	.3391	.2456	.2418
4	.1613	.1600	.2836	.2667	.2645
2	.1601	.1600	.2281	.2921	.2918
PB 3/10	0.0939	0.0900	0.3052	0.1920	0.1840
8	.0930	.0900	.2637	.2082	.2015
6	.0921	.0900	.2220	.2279	.2227
4	.0912	.0900	.1804	.2522	.2489
2	.0903	.0900	.1387	.2831	.2821
2/6	.0416	.0400	.1270	.1993	.1918
4	.0410	.0400	.0987	.2280	.2226
2	.0403	.0400	.0709	.2667	.2644
P 8/4	0.6804	0.6400	0.8924	0.3075	0.2892
2	.6581	.6400	.7914	.3150	.3063
7/4	.5258	.4900	.7063	.3053	.2845
2	.5063	.4900	.6170	.3138	.3037
6/4	.3911	.3600	.5400	.3030	.2788
2	.3744	.3600	.4641	.3124	.3004
5/10	.3182	.2500	.5856	.2758	.2167
8	.3042	.2500	.5224	.2826	.2322
6	.2902	.2500	.4592	.2904	.2501
4	.2763	.2500	.3960	.2996	.2711
2	.2623	.2500	.3328	.3104	.2958
4/10	.2148	.1600	.4253	.2684	.2000
8	.2036	.1600	.3748	.2758	.2167
6	.1924	.1600	.3242	.2844	.2365
4	.1813	.1600	.2737	.2948	.2602
2	.1701	.1600	.2231	.3075	.2892
3/10	.1314	.0900	.2868	.2586	.1771
8	.1230	.0900	.2488	.2664	.1949
6	.1146	.0900	.2109	.2759	.2166
4	.1062	.0900	.1730	.2877	.2438
2	.0978	.0900	.1350	.3030	.2788
2/6	.0565	.0400	.1190	.2622	.1857
4	.0509	.0400	.0937	.2757	.2167
2	.0453	.0400	.0684	.2948	.2602
RP 8/4	0.7174	0.6400	0.7766	0.3362	0.2999
2	.6766	.6400	.7335	.3300	.3122
7/6	.5940	.4900	.6422	.3441	.2839
4	.5582	.4900	.6043	.3378	.2965
2	.5225	.4900	.5664	.3309	.3104
6/6	.4494	.3600	.4857	.3470	.2780
4	.4188	.3600	.4533	.3399	.2922
2	.3882	.3600	.4208	.3321	.3080
5/10	.3759	.2500	.4050	.3646	.2425
8	.3504	.2500	.3779	.3582	.2555
6	.3249	.2500	.3509	.3510	.2700
4	.2994	.2500	.3238	.3429	.2863
2	.2739	.2500	.2967	.3337	.3047
4/10	.2610	.1600	.2809	.3719	.2279
8	.2406	.1600	.2592	.3646	.2425
6	.2202	.1600	.2376	.3564	.2590
4	.1998	.1600	.2159	.3470	.2779
2	.1794	.1600	.1942	.3361	.2998
3/10	.1659	.0900	.1783	.3821	.2073
8	.1506	.0900	.1620	.3741	.2235
6	.1353	.0900	.1458	.3646	.2425
4	.1200	.0900	.1296	.3536	.2650
2	.1047	.0900	.1133	.3399	.2922
2/6	.0703	.0400	.0756	.3781	.2152
4	.0601	.0400	.0648	.3646	.2426
2	.0499	.0400	.0540	.3470	.2780
N 9	0.8046	0.8100	0.8737	0.3234	0.3255
8	.6358	.6400	.6903	.3234	.3255
7	.4868	.4900	.5285	.3234	.3255
6	.3576	.3600	.3883	.3234	.3255
5	.2483	.2500	.2697	.3234	.3255
4	.1589	.1600	.1726	.3234	.3255
3	.0894	.0900	.0971	.3234	.3255
2	.0397	.0400	.0431	.3234	.3255
1	.0099	.0100	.0108	.3234	.3255

TABLE IV. *Maximum Munsell chromas producible by real pigments.*

Hue	Value 2	Value 3	Value 4	Value 5	Value 6	Value 7	Value 8
R	7.7	11.6	15.4	17.8	16.8	13.5	9.6
YR	3.5	5.5	7.1	8.9	10.6	12.4	12.4
Y	3.7	4.0	7.0	8.0	10.0	12.4	13.4
GY	3.5	4.9	5.0	8.4	10.2	12.0	13.5
G	7.2	10.6	13.9	16.6	19.2	20.3	19.2
BG	6.6	9.5	12.0	13.6	14.7	14.7	13.3
B	9.1	12.9	14.0	17.5	18.6	15.3	10.0
PB	19.1	28.9	36.7	25.3	18.9	15.2	12.2
P	64.6	52.2	39.5	28.3	21.4	15.0	9.5
RP	17.3	23.5	27.2	26.2	24.3	19.6	12.8

ized conditions. The procedure need not be included here, since it is discussed in detail by Gibson and Nickerson in the paper[4] following this one.

If Priest, Gibson, and McNicholas had investigated only five chromatic colors instead of fifteen, there would have been no choice in the selection of data upon which to base these calculations. However, since an arbitrary choice of data must be made, it seemed appropriate to select the five principal colors R5/5, Y5/5, G5/5, B5/5, and P5/5. Use is also made of the rule that a mixture of the five principal colors in equal proportions yields N5/, which according to this definition is nearly but not quite the color of a nonselective surface.

Reference to Table I will disclose the fact that the five principal colors are not precisely of value 5 as intended by Professor Munsell. Instead, Y varies from a minimum of 0.2140 to a maximum of 0.2662. In view of the difficulties involved in heterochromatic photometry, which were more serious then than now, it seemed reasonable to multiply each set of tristimulus specifications by a factor that would bring each principal color accurately to value 5. This procedure does not alter the hue of the principal colors, and it makes only a trifling change in the chroma. After this adjustment, the basic data relative to the principal colors are as listed in Table II.

The data in Table III indicate what the Munsell Atlas of Color would have been if, starting with the five basic colors as defined in Table II, the extension of the system had been entrusted to the standard I.C.I. observer working under Illuminant *C*. The first column indicates the Munsell designation. This is followed by three columns giving the corresponding tristimulus specifications. Columns 5 and 6 list the trichromatic coefficients, x and y.

Professor Munsell devoted much attention to speculations concerning the shape of the color solid that results from the representation of hue, value, and chroma in cylindrical coordinates. His speculations had, perforce, to be based on the color gamut obtainable with pigments that were then available, and he was obviously unable to predict what new pigments might result from chemical research. By application of the work of MacAdam on "The maximum visual efficiency of colored materials,"[5] it is now possible to establish the limits of the Munsell color solid which newly discovered pigments may approach but will never exceed. This gamut is expressed most conveniently in terms of the maximum chroma corresponding to a given hue and value, as in Table IV.

Since the *Munsell Book of Color*, which appeared in 1929, was intended to supplant the original *Atlas of the Munsell Color System*, it is not immediately obvious that the publication of this paper serves, at this time, a useful purpose. We believe that its publication is justified on the ground that it calls belated attention to the remarkable scientific insight of Professor A. H. Munsell. At a time when there was little to suggest such a procedure, he formulated rules for the construction of a psychophysical color system that could be used today without apology. We believe also that the publication of this paper may call attention to the fact that the psychophysical definitions of the terms hue, value, and chroma given in the Atlas of the original Munsell Color System differ from the purely psychological definitions used since the death of Professor Munsell.

The writers are indebted to Mrs. Blanche Bellamy, Manager of the Munsell Color Company, Inc., Baltimore, Maryland, for the loan of Professor Munsell's Diary; to Dr. Walter Scott for valuable suggestions; and to Mrs. Arthur Howland for permission to review correspondence between her late husband and Professor Munsell. Miss Dorothy Nickerson has extended most gracious assistance in connection with the calculations.

[4] J. Opt. Soc. Am. **30**, 591 (1940).

[5] D. L. MacAdam, J. Opt. Soc. Am. **25**, 361 (1935).

An Analysis of the Munsell Color System Based on Measurements Made in 1919 and 1926

Kasson S. Gibson* and Dorothy Nickerson†

Introduction

THREE reports have been made by the National Bureau of Standards on papers representative of the Munsell color system: First, a very early report (No. 10,696) dated February 28, 1912, from P. G. Nutting to A. H. Munsell, giving dominant wave-length, percent white, and the reflection coefficient on six cards, which included the principal hues at 5/5, submitted to the Bureau by Mr. Munsell (1)‡; second, report No. 23,998 dated June, 1919, to the Munsell Color Company (later published as Bureau of Standards Technologic Paper No. 167 by Priest, Gibson, and McNicholas) (2) giving spectrophotometric data on nine neutral grays and three samples of each of the five principal hues; and third, report No. 46,045 (1), dated September 14, 1926, on "The spectral reflection of 70 representative colored cards from the Munsell color system." This third report was made to the Munsell Research Laboratory as a part of the cooperative work then being carried on between the two laboratories under the supervision of I. G. Priest, at that time chief of the Colorimetry Section, National Bureau of Standards, and A. E. O. Munsell, Director of the Munsell Research Laboratory.

The first report is not based on spectrophotometric data, and was made before publication of the complete *Atlas of the Munsell Color System* (3), but it is noted here because it indicates that from a very early date A. H. Munsell was intent upon standardization, particularly of the five basic "middle colors" around which his system was built. The second report has been published (2) and is therefore a matter of record. The data of the third report, obtained in 1926, are published for the first time in this paper.

For this 1926 test 70 samples were selected by A. E. O. Munsell for measurement, and submitted, not only as an exemplification of the Munsell system as it existed in 1926 but as an exemplification, as far as it was then possible, of the original system developed by A. H. Munsell. The samples were either the original paintings which had been kept unexposed in the files, or, where such were not available, duplicates that had been made to match the originals as accurately as possible whenever the supply of an original color was nearly exhausted. The samples were submitted in sheets 8 by 8 inches square, and were representative of the most highly saturated colors of the system as it then existed.** Their Munsell notations are given in Table I.

* Chief, Colorimetry and Spectrophotometry Section, National Bureau of Standards, Washington, D. C.

† Color Technologist, Agricultural Marketing Service, United States Department of Agriculture, Washington, D. C.

‡ Figures in parentheses, sometimes followed by a page number, refer to literature cited.

Methods of Measurement in 1926 Test

Three instruments were used to obtain the spectrophotometric data given in the 1926 report, all of the values being expressed relative to freshly prepared magnesium oxide.

Diffuse illumination, normal reflection, visual method

The König-Martens spectrophotometer with auxiliary equipment (4) was used to obtain data under these conditions. Measurements were made at every 20 mμ from 420 to 720 mμ. In

Table I. *Notations of the 70 Munsell Atlas samples measured at the National Bureau of Standards in 1926, NBS test 46,045.*

Hue		Value and Chroma V/C						
Name	Symbol							
Red	R	2/4	3/7	4/10	5/10	6/8	7/6	8/4
Yellow-red	YR	2/1	3/4	4/5	5/7	6/8	7/7	8/5
Yellow	Y	2/1	3/3	4/5	5/7	6/7	7/8	8/9
Green-yellow	GY	2/1	3/3	4/5	5/6	6/8	7/7	8/6
Green	G	2/1	3/4	4/7	5/7	6/7	7/7	8/5
Blue-green	BG	2/2	3/4	4/5	5/5	6/5	7/5	8/3
Blue	B	2/4	3/5	4/6	5/6	6/5	7/4	8/2
Purple-blue	PB	2/2	3/9	4/10	5/8	6/6	7/4	8/2
Purple	P	2/3	3/6	4/6	5/6	6/4	7/3	8/2
Red-purple	RP	2/2	3/6	4/6	5/6	6/4	7/4	8/2

** In 1929 the papers of the *Atlas of the Munsell Color System* were replaced with papers of the *Munsell Book of Color* in accordance with suggestions made in the Priest, Gibson, McNicholas 1919 report, reference 2. See reference 1 for details.

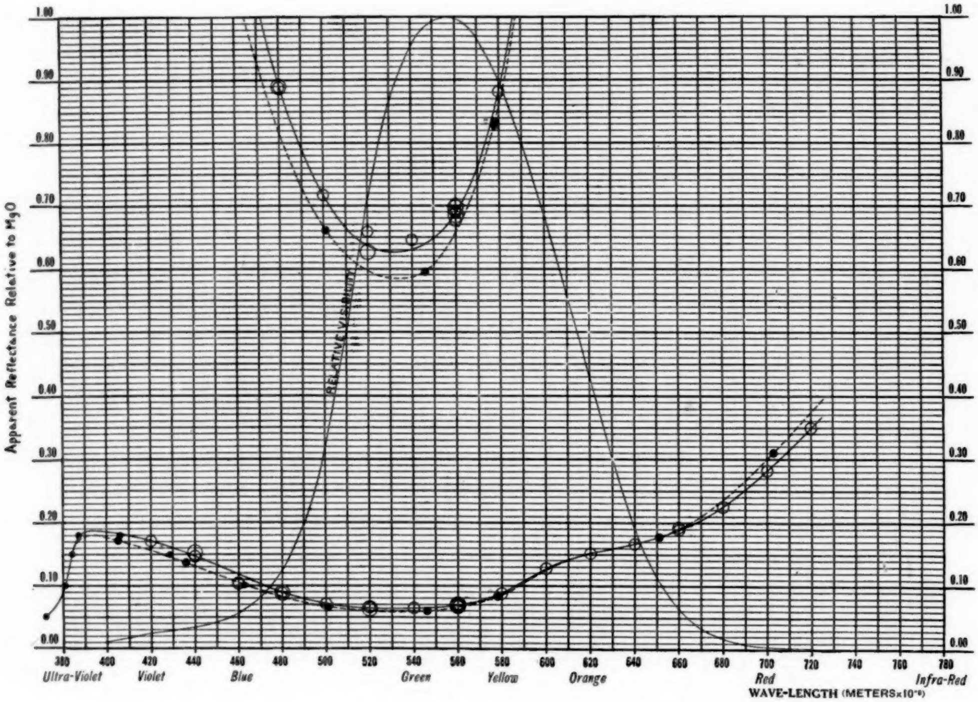

FIG. 1. Work sheet of spectrophotometric data and adopted values for Munsell Atlas sample RP 3/6, as used in National Bureau of Standards Test No. 46045 (1926 data). This is typical of the work sheets used for each of the 70 samples of that test. Key: open circles, diffuse-normal visual data; larger closed circles, 45°-normal visual data; smaller closed circles, 45°-normal photographic data; continuous line, adopted diffuse-normal data; dashed line, adopted 45°-normal data: values below 0.10 are also magnified by 10.

addition to the usual precautions to eliminate stray-light, wave-length, and slit-width errors, the order of wave-lengths chosen for measurement was such as to detect any change in the sample during measurement, so that if such change occurred the data could be corrected to apply as nearly as possible to the sample as it was at the start of the measurements. For these measurements and for those with the other instruments, small samples were cut for measurement from the large 8×8-inch sheets. A complete set of measurements was made on each of the 70 samples by W. Greenberg, research associate placed at the Bureau for this purpose by the Munsell Research Laboratory. Check measurements were later made by other observers, H. J. McNicholas, P. Rudnick and W. Greenberg, on different samples cut from the same large sheets. Such checks were made particularly for samples which changed during the first set of measurements.

45° illumination, normal reflection, visual method

The Martens photometer with filters was used with improvised equipment to obtain these data. Two light sources were used. The first was a quartz-mercury arc, with filters isolating in turn the light at 578 (577.0+579.1), 546.1, 435.8, and 405 (404.7+407.8) mμ. The efficiency of the filters was such that the light transmitted by the filter from the next most luminous line was not more than one percent of the light nominally being used. In addition, the red light from the arc was absorbed by a blue-green glass where the filter would otherwise transmit this. Plate glass prevented radiant energy of wave-length less than 320 mμ from reaching the sample. The second source was an incandescent lamp with

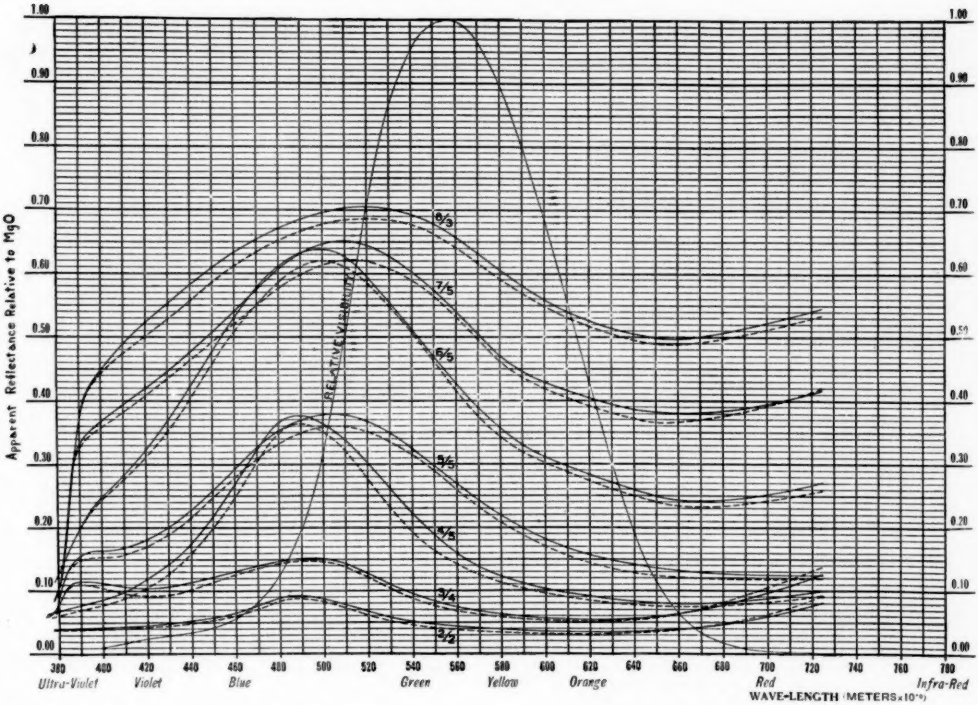

FIG. 2. One of ten figures given in the report on National Bureau of Standards Test 46045 (1926 data) showing adopted diffuse-normal (continuous lines) and 45°-normal (dashed lines) data for the eight samples of each of the ten hue designations of the Munsell Atlas colors. This illustration is for the eight samples of the blue-green (BG) series.

filters isolating spectral regions centering at 501, 651, and 703 mμ for a white surface. The data obtained in this way, while meager with respect to wave-length, had the advantage of yielding values applying to 45°-normal illuminating-viewing conditions, and of being free from errors caused by fading during measurements. Polarization errors were eliminated by proper orientation of the Martens photometer, the plane of the sample, and the direction of illumination. Measurements were made by P. Rudnick and K. S. Gibson.

45° illumination, normal reflection, photographic method

Inasmuch as zinc oxide was understood to be an important constituent of many of the pigments of the Munsell samples it seemed desirable to obtain data from 380 to 420 mμ, rather than to estimate over this range solely on the basis of the values at 405 mμ, since the reflectance of zinc oxide was known to vary strongly between 405 and 365 mμ (5). Accordingly, measurements were made photographically on most of the samples,* using the Hilger sector-photometer equipment (6) adapted to reflection measurements with incandescent lamps as source. All of the photographic measurements were made by H. J. McNicholas.

Reduction of the 1926 Spectrophotometric Data

All of the data obtained by the above methods, to quote the 1926 report, "were plotted as a function of wave-length. A separate curve sheet was used for each sample. Values of R_x/R_0 (apparent reflectance of the sample relative to that of MgO) less than 0.10 were also magnified by 10 in plotting. . . .

* On all of the BG, B, PB, P, and RP samples and on the 2/, 4/, 6/, and 8/ value samples of the other colors.

TABLE II. *Trichromatic analysis of Munsell Atlas colors, 1919 data. Values computed from spectrophotometric data in Bureau of Standards Technologic Paper No. 167 (B.S. test report 23,998) on the basis of the I.C.I. standard observer and coordinate system and for I.C.I. Illuminant C.*

Munsell Notation	Tristimulus Specifications			Trichromatic Coefficients		Dominant Wave-Length*	Excitation Purity*
	X	Y	Z	x	y	Λ	P_e
R 7/5	0.4951	0.4399	0.4305	0.3626	0.3221	605	15.7
5/5	.2678	.2140	.1713	.4101	.3276	604	29.8
3/2	.0977	.0878	.0809	.3667	.3295	597	18.8
Y 7/4	.4661	.4869	.2625	.3835	.4006	575.7	42.2
5/5	.2605	.2662	.1024	.4141	.4232	577.3	56.7
3/2	.0950	.0974	.0708	.3611	.3700	577.0	28.2
G 7/4	.4173	.4860	.4688	.3041	.3542	542	9.0
5/5	.1811	.2454	.1982	.2899	.3928	534	16.3
3/2	.0766	.0933	.0952	.2888	.3519	513	7.5
B 7/4	.4325	.4827	.6573	.2750	.3070	487.7	13.8
5/5	.2246	.2595	.4385	.2434	.2813	484.4	27.8
3/2	.0822	.0904	.1412	.2620	.2881	483.5	20.5
P 7/3	.5162	.4978	.6613	.3081	.2972	555 *c*	7.2
5/5	.2773	.2448	.4187	.2948	.2602	562 *c*	19.6
3/2	.0981	.0921	.1553	.2838	.2667	453	16.8

* Reference point (heterogeneous stimulus): I.C.I. Illuminant *C*.

"Smooth average curves were then drawn through the values obtained on the König-Martens spectrophotometer with diffuse illumination, the relative shape of the curves in the violet being influenced by the photographic data.

"With a relative shape following as closely as possible the curves for diffuse illumination just described, dotted curves were then plotted through the values obtained on the Martens photometer with approximately 45° illumination. . . . In some cases in the violet the shape of the curves was determined primarily by the Martens photometer values instead of by the König-Martens spectrophotometer values.

"In addition to the plotted values obtained photographically, the plates themselves were in most cases examined and the shape of the curves in the violet finally determined . . . from all of the data available. In general no attempt was made to keep the curves for diffuse and 45° illumination separated at 380 and 390 (mμ) where the reflection is varying rapidly.

"Values of R_x/R_0 were read at every 10 mμ from the curves as thus plotted."

These values are tabulated in the original report, and the colorimetric data which follow are based upon them. It seems unnecessary to give these spectrophotometric data here in

TABLE III. *Trichromatic analysis of Munsell Atlas colors, 1926 data, diffuse illumination. Values computed from spectrophotometric data given in Bureau of Standards Test Report 46,045 on the basis of the I.C.I. standard observer and coordinate system and for I.C.I. Illuminant C.*

Munsell Notation	Tristimulus Specifications			Trichromatic Coefficients		Dominant Wave-Length*	Excitation Purity*
	X	Y	Z	x	y	Λ	P_e
R 8/4	0.6796	0.6311	0.6388	0.3486	0.3237	599	12.1
7/6	.5356	.4522	.4130	.3824	.3228	606	21.0
6/8	.4347	.3368	.2726	.4164	.3226	609	30.1
5/10	.3218	.2137	.1316	.4824	.3203	613	47.1
4/10	.2543	.1563	.0894	.5086	.3126	620	52.2
3/7	.1224	.0846	.0591	.4600	.3179	615	40.5
2/4	.0543	.0439	.0435	.3831	.3100	640	18.0
YR 8/5	.6334	.6015	.3992	.3876	.3681	583.2	34.5
7/7	.4999	.4567	.2535	.4131	.3774	584.8	44.0
6/8	.4397	.3677	.0962	.4866	.4069	586.8	71.5
5/7	.2637	.2253	.0920	.4539	.3878	587.4	57.5
4/5	.1927	.1598	.0656	.4610	.3822	589.1	58.2
3/4	.1028	.0937	.0622	.3972	.3623	586.5	35.8
2/1	.0530	.0528	.0515	.3372	.3354	582.5	12.5
Y 8/9	.5478	.5717	.1222	.4411	.4604	576.3	73.8
7/8	.4697	.4841	.1052	.4435	.4572	576.8	73.5
6/7	.3523	.3627	.0970	.4339	.4467	576.9	68.2
5/7	.2345	.2382	.0815	.4231	.4298	577.6	60.8
4/5	.1719	.1714	.0639	.4220	.4210	578.5	58.1
3/3	.0943	.0967	.0626	.3720	.3812	576.9	34.0
2/1	.0544	.0556	.0503	.3393	.3470	577.0	16.1
GY 8/6	.5138	.6034	.3121	.3595	.4222	567.8	41.7
7/7	.4058	.5004	.1844	.3721	.4588	567.0	55.0
6/8	.3313	.4131	.1440	.3730	.4650	566.5	57.0
5/6	.1676	.2009	.1062	.3531	.4232	566.2	40.1
4/5	.1565	.1902	.0811	.3659	.4445	567.0	49.5
3/3	.0935	.1056	.0729	.3439	.3881	567.8	28.3
2/1	.0463	.0498	.0477	.3220	.3464	566.0	11.2
G 8/5	.5505	.6259	.6157	.3072	.3493	546	8.3
7/7	.4208	.5241	.4650	.2984	.3718	538	12.3
6/7	.3141	.4160	.3243	.2979	.3945	542	18.4
5/7	.1812	.2873	.2118	.2663	.4224	523	20.5
4/7	.1332	.2033	.1555	.2708	.4132	523	18.8
3/4	.0792	.0946	.0964	.2931	.3501	518	6.8
2/1	.0450	.0493	.0500	.3118	.3419	554	7.5
BG 8/3	.5836	.6383	.7236	.2964	.3298	504	4.5
7/5	.4596	.5359	.6168	.2851	.3324	499	8.4
6/5	.3611	.4454	.5773	.2610	.3219	492	17.8
5/5	.2119	.2726	.3227	.2625	.3378	496	16.4
4/5	.1394	.1920	.2840	.2265	.3120	490	31.5
3/4	.0741	.0875	.1477	.2396	.2828	485	29.3
2/2	.0429	.0506	.0751	.2543	.3003	488	22.0
B 8/2	.6362	.6730	.8941	.2887	.3054	484.6	9.0
7/4	.4840	.5341	.7490	.2739	.3023	486.3	14.7
6/5	.3891	.4308	.7340	.2504	.2772	482.5	26.0
5/6	.2431	.2824	.5431	.2275	.2643	483.0	35.5
4/6	.1459	.1705	.3751	.2110	.2466	482.0	43.6
3/5	.1054	.1161	.2676	.2154	.2374	480.2	43.0
2/4	.0429	.0475	.1061	.2182	.2417	480.5	41.6
PB 8/2	.6433	.6589	.8758	.2954	.3025	478.4	7.0
7/4	.4449	.4619	.7333	.2713	.2816	479.0	17.9
6/6	.3845	.3966	.6989	.2598	.2680	478.1	23.7
5/8	.2650	.2697	.5749	.2388	.2430	477.0	34.5
4/10	.1865	.1797	.5388	.2060	.1986	475.3	51.5
3/9	.1020	.0881	.3240	.1984	.1713	472.0	58.3
2/2	.0458	.0444	.1072	.2319	.2252	474.7	39.5
P 8/2	.6343	.6197	.8163	.3064	.2993	560 *c*	6.0
7/3	.5398	.5223	.6626	.3130	.3028	537 *c*	6.0
6/4	.4248	.3948	.5721	.3052	.2837	558 *c*	12.2
5/6	.2843	.2536	.4230	.2958	.2640	562 *c*	18.3
4/6	.2115	.1799	.3159	.2990	.2543	559 *c*	23.0
3/6	.1325	.1090	.2324	.2796	.2300	565 *c*	29.0
2/3	.0540	.0461	.0893	.2850	.2435	565 *c*	24.7
RP 8/2	.6718	.6510	.7869	.3185	.3086	503 *c*	4.7
7/4	.6142	.5594	.6765	.3320	.3024	499 *c*	9.8
6/4	.4276	.3829	.4934	.3279	.2937	508 *c*	12.5
5/6	.3055	.2597	.3438	.3361	.2857	506 *c*	17.0
4/6	.2020	.1603	.2375	.3368	.2673	515 *c*	24.6
3/6	.1179	.0884	.1509	.3301	.2475	532 *c*	31.3
2/2	.0545	.0466	.0686	.3211	.2748	534 *c*	19.0

* Reference point (heterogeneous stimulus): I.C.I. Illuminant *C*.

TABLE IV. *Trichromatic analysis of Munsell Atlas colors, 1926 data, 45° illumination. Values computed from spectrophotometric data given in Bureau of Standards Test Report 46,045 on the basis of the I.C.I. standard observer and coordinate system and for I.C.I. Illuminant C.*

Munsell Notation	Tristimulus Specifications			Trichromatic Coefficients		Dominant Wave-Length*	Excitation Purity*
	X	Y	Z	x	y	Λ	P_e
R 8/4	0.6807	0.6318	0.6419	0.3483	0.3233	599	12.1
7/6	.5399	.4598	.4122	.3824	.3256	603	22.0
6/8	.4406	.3430	.2697	.4183	.3256	606	31.5
5/10	.3224	.2114	.1277	.4874	.3195	614	48.2
4/10	.2536	.1557	.0844	.5138	.3153	617	54.1
3/7	.1215	.0841	.0552	.4659	.3225	612	43.2
2/4	.0518	.0420	.0385	.3914	.3175	615	22.0
YR 8/5	.6345	.6059	.4038	.3859	.3685	582.8	34.1
7/7	.5026	.4616	.2480	.4146	.3808	584.5	45.2
6/8	.4478	.3787	.0973	.4848	.4099	586.3	71.8
5/7	.2666	.2273	.0880	.4581	.3906	587.2	59.8
4/5	.1956	.1652	.0660	.4582	.3871	587.8	58.8
3/4	.1002	.0920	.0578	.4009	.3680	585.5	38.0
2/1	.0496	.0484	.0466	.3434	.3345	586.2	13.8
Y 8/9	.5514	.5833	.1199	.4395	.4649	575.7	74.4
7/8	.4678	.4898	.1067	.4396	.4602	576.2	73.4
6/7	.3524	.3673	.1000	.4299	.4481	576.3	67.5
5/7	.2329	.2408	.0807	.4201	.4343	576.6	61.2
4/5	.1681	.1688	.0612	.4223	.4240	578.2	59.2
3/3	.0919	.0947	.0590	.3742	.3857	576.5	35.9
2/1	.0519	.0532	.0492	.3365	.3446	576.5	14.7
GY 8/6	.5060	.5953	.3018	.3606	.4243	567.8	42.6
7/7	.4010	.4952	.1750	.3743	.4623	567.1	56.5
6/8	.3260	.4111	.1424	.3707	.4674	566.1	57.0
5/6	.1615	.1929	.0991	.3562	.4253	566.6	41.8
4/5	.1519	.1887	.0767	.3640	.4521	566.0	51.0
3/3	.0868	.0982	.0666	.3449	.3902	567.8	29.2
2/1	.0444	.0468	.0450	.3260	.3435	570.8	11.5
G 8/5	.5395	.6179	.5985	.3072	.3519	546	9.0
7/7	.4129	.5181	.4600	.2968	.3725	536	12.2
6/7	.3067	.4082	.3218	.2959	.3938	534	17.7
5/7	.1782	.2862	.2080	.2650	.4256	523	21.2
4/7	.1261	.1944	.1428	.2722	.4195	526	20.3
3/4	.0748	.0900	.0902	.2934	.3529	520	7.2
2/1	.0424	.0459	.0473	.3128	.3385	556	6.8
BG 8/3	.5594	.6229	.6971	.2977	.3314	507	4.1
7/5	.4476	.5213	.5939	.2864	.3336	500	7.8
6/5	.3489	.4343	.5531	.2611	.3250	493	17.8
5/5	.2003	.2603	.3058	.2613	.3396	497	16.4
4/5	.1272	.1748	.2637	.2249	.3089	490	32.2
3/4	.0696	.0823	.1382	.2398	.2838	485	29.2
2/2	.0391	.0457	.0709	.2512	.2935	486	23.9
B 8/2	.6321	.6679	.8731	.2909	.3074	485.1	7.9
7/4	.4722	.5217	.7294	.2740	.3027	486.4	14.7
6/5	.3778	.4202	.7241	.2482	.2761	482.7	26.9
5/6	.2317	.2731	.5203	.2260	.2664	483.5	36.0
4/6	.1437	.1661	.3646	.2131	.2463	481.7	42.9
3/5	.0977	.1076	.2493	.2150	.2367	480.1	43.4
2/4	.0398	.0447	.0981	.2180	.2448	480.9	41.3
PB 8/2	.6417	.6546	.8702	.2962	.3022	477.2	6.8
7/4	.4477	.4621	.7350	.2722	.2809	478.6	17.6
6/6	.3800	.3894	.6988	.2588	.2652	477.5	24.5
5/8	.2616	.2653	.5699	.2385	.2419	476.8	34.7
4/10	.1796	.1773	.5248	.2038	.2011	476.1	52.1
3/9	.0993	.0859	.3191	.1969	.1703	472.2	59.0
2/2	.0430	.0430	.0972	.2347	.2348	476.1	37.0
P 8/2	.6272	.6161	.7907	.3084	.3029	556 *c*	5.0
7/3	.5324	.5110	.6536	.3137	.3011	535 *c*	6.7
6/4	.4245	.3936	.5650	.3069	.2846	556 *c*	12.1
5/6	.2785	.2480	.4076	.2982	.2655	561 *c*	18.2
4/6	.2080	.1727	.3124	.3001	.2492	558 *c*	25.0
3/6	.1271	.1022	.2216	.2819	.2266	564 *c*	30.9
2/3	.0509	.0436	.0856	.2826	.2420	565 *c*	24.7
RP 8/2	.6710	.6525	.7599	.3221	.3132	494 *c*	3.5
7/4	.6029	.5508	.6600	.3324	.3037	498 *c*	9.5
6/4	.4223	.3776	.4834	.3291	.2942	506 *c*	12.5
5/6	.2968	.2509	.3263	.3396	.2871	504 *c*	17.2
4/6	.1991	.1555	.2311	.3399	.2655	513 *c*	26.0
3/6	.1134	.0850	.1337	.3414	.2559	516 *c*	30.2
2/2	.0514	.0436	.0606	.3302	.2802	514 *c*	18.3

* Reference point (heterogeneous stimulus): I.C.I. Illuminant *C*.

TABLE V. *Average values of Y for samples in 1919 and 1926 tests. These values are computed from the data of Tables II, III and IV, except for the neutral samples, for which the values are taken from Bureau of Standards Technologic Paper No. 167.*

Munsell Value	1919		1926	
	Chromatic Samples	Neutral Samples*	Chromatic Samples: Illumination at 45°	Chromatic Samples: Illumination at Diffuse
	Y	Y	Y	Y
9/		0.772		
8/		.602	0.6248	0.6274
7/	0.4787	.465	.4991	.5031
6/		.343	.3923	.3947
5/	.2460	.234	.2456	.2503
4/		.161	.1719	.1763
3/	.0922	.090	.0922	.0964
2/		.041	.0457	.0487
1/		.018		

* Computed for noon sunlight. The value of Y for neutral 9/, which is the most selective of the neutral samples, is 0.763 for I.C.I. Illuminant *C*. Difference in illuminant therefore will not account for the differences between the values of Y for the neutral samples and the average values of Y for the chromatic samples.

detail, but Figs. 1 and 2 are shown to illustrate the nature and extent of the work.

Figure 1 shows the working plot for RP 3/6. It includes the diffuse-normal, König-Martens spectrophotometric data, with some check points; the 45°-normal Martens photometer (with filters) data; the 45°-normal photographic data, 370 to 460 mμ, showing the absorption from the ZnO below 400 mμ; the plotting to a 10-times scale of values below 0.10; and the smooth curves drawn through the diffuse-normal and the 45°-normal data. The final judgment as to the true course of all of the curves (representing the adopted values) was made by the senior author of the present paper.

Figure 2 is one of the ten illustrations in the original report which show the deviations between the data as adopted for the diffuse-normal and the 45°-normal conditions. These blue-green samples have been selected for illustration because they show the greatest variation in dominant wave-length. Figure 2 also illustrates the general tendency for the apparent reflectances for the diffuse-normal conditions to be higher than those for the 45°-normal conditions.

Colorimetric Computations

Colorimetric computations were not made in 1919 nor in 1926, but have been completed during the past year, computations of the 1926

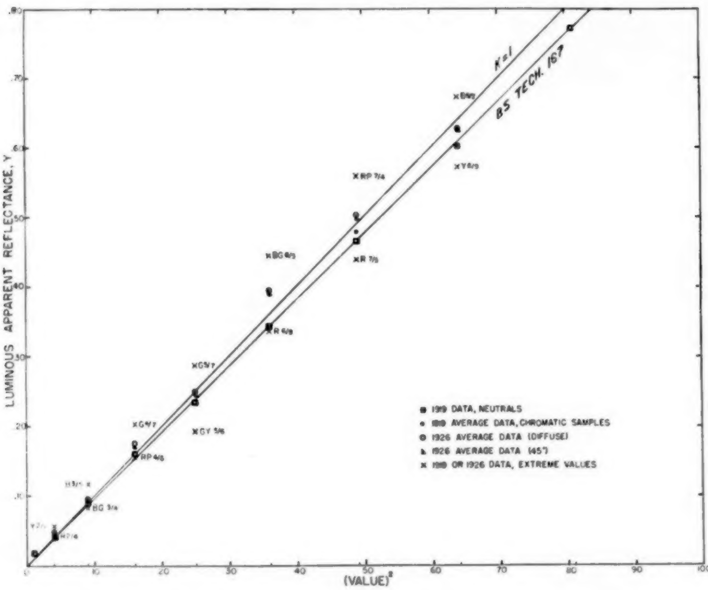

FIG. 3. These data show the relation between luminous apparent reflectance (relative to magnesium oxide) and the square of Munsell value, as obtained in the 1919 and 1926 measurements on the Munsell Atlas samples.

data being made for both the diffuse-normal and the 45°-normal conditions. These computations were made on the basis of the 1931 I.C.I. standard observer and coordinate system and for I.C.I. Illuminant *C*. The weighted ordinate method was used, summations being taken at every 10 mμ. Values of dominant wave-length (Λ) and excitation purity (P_e) have been read from the charts of the Hardy *Handbook of Colorimetry* (7). Values of X, Y, Z, of x, y, of Λ, and of P_e are given in Tables II, III and IV.

It will be recalled that the values of Y represent the luminous apparent reflectances relative to MgO. Table V gives the average values of Y for the respective Munsell samples in Tables II, III and IV, and for the neutral samples given in the 1919 report (2).

Tests for Conformity of the 1919 and 1926 Data to the Psychophysical System Described by A. H. Munsell

A. H. Munsell left two representations of his system, first, the charts of his Atlas, and second, statements concerning the method by which they might be tested. Without doubt he intended the charts to exemplify the laws of color sensation by illustrations of equally stepped scales of hue, value, and chroma. Also without doubt he intended these as "measured scales," and described them as having been measured, value by the photometer, and chroma by matches made on Maxwell spinning disks. The rule used for measuring chroma is that colors of complementary or opposite hue balance to gray in areas that are in inverse proportion to the products of their values and chromas.

The Munsell color system was based upon five color standards so chosen as to appear to be of the same lightness, the same saturation, and equally separated in hue. From these five standards chosen to fulfill the purely psychological requirement of appearance, it is possible by application of the psychophysical rules given in the *Atlas of the Munsell Color System* to derive a whole system of color standards. This aspect of the original Munsell color system has been analyzed by Tyler and Hardy (11). It is probable that Mr. Munsell believed that a color system derived by these psychophysical rules would also conform to psychological requirements analogous to those met by the five basic standards, but we now know that the conformity is not exact. We propose therefore to inquire whether the papers measured in 1919 and 1926 represent more nearly the psychological system described by Mr. Munsell when he said (9) in 1911, "The solid having been built up by equal and decimal steps of sensation . . ." or the psychophysical system which he implies in other places. To this end we shall compare the color specifications computed from the 1919 and 1926 measurements both with the psychophysical system and with the psychological system represented by the most adequate data that are available.

Relation between Munsell value and apparent reflectance

The value scale was the first of the three "color dimensions" to be developed by Mr. Munsell; and because he found early in his studies the relation between reflectance and value (8), he developed the Munsell daylight photometer on which value was thereafter always measured in making up the Munsell Atlas papers. He selected the cat's-eye form of shutter because it meant that a psychologically satisfactory scale could be read directly on the photometer scale.* The amount of light (the photometric scale) of the Munsell photometer varies in proportion to the square of the diagonal of the diaphragm opening and, since Munsell Atlas papers were all measured on this photometer, it is to be expected that V^2 will equal $k(100\ Y)$ where V is Munsell value, Y is the luminous apparent reflectance relative to MgO (hereafter termed simply the reflectance), and k is a constant close to unity. This was demonstrated in the 1919 report (2) and is also pointed out by Tyler and Hardy (11).

To test this relation further we have plotted in Fig. 3‡: A straight line with value of $k=1$; the straight line given in Bureau of Standards Technologic Paper No. 167 as representative of the relation derived from the nine neutral samples therein described; the average values of Y for Munsell values 3/, 5/, and 7/, as derived from Bureau of Standards Technologic Paper No. 167 in accordance with Table II of the present paper (1919 data); the average values of Y for the respective Munsell values from 2/ to 8/, for both diffuse-normal and 45°-normal conditions, 10 values of Y entering into each of the average values of Y for each of the two illuminating-viewing conditions, these data taken from Tables III and IV (1926 data); and the extreme individual values of Y for the respective Munsell values, taken from Tables II, III or IV.

From Fig. 3 we may draw several conclusions: The relation $V^2=k(100\ Y)$ is followed approximately by both the 1919 and 1926 data, although particular samples show large deviations. Both the 1919 and 1926 data indicate that Y has a small positive value (0.005 to 0.01) when the Munsell value is zero; black, in the Munsell Atlas, therefore corresponds to a luminous apparent reflectance of 0.5 to 1.0 percent. While the straight line representing the neutral samples of the 1919 data falls under the line $k=1$, a majority of the points representing the chromatic samples of the 1926 data fall above this line, and it is obvious that a straight line passing through the point $Y=0.007$, $V^2=0.0$ and the point $Y=1.0$, $V^2=100.0$ is well representative of the data as a whole. The fact that this line passes through the point $Y=1.0$, $V^2=100$ indicates that white, in the Munsell Atlas, is represented by fresh magnesium oxide. There are slight indications that individual values of Y for any given Munsell value may be high or low as a group. The data for $V=6$ are the most definite in this respect. The data also show that the colors of certain hues are uniformly different from others in Munsell value.

Relation between Munsell hue and dominant wave-length

If the samples representing the Munsell color system conform to the simple psychophysical definition of hue by disk mixture, the points representing all samples of the same Munsell hue designation and its complementary will plot on the Maxwell triangle along a straight line passing through the neutral point (11). To test

* In the Atlas there is a statement on several charts, to which Priest called attention in 1919, that is in error. It says in effect that a sample of value 5/ reflects 50 percent "of the luminosity of white," one of value 6/ reflects 60 percent, and so on. In footnote 17 of the Priest paper, reference 2, certain other excerpts from Mr. Munsell's writings are quoted. From later reference to the diary, reference 10, and to other Munsell sources, reference 17, it is evident that during the development of the value scale, and the photometer, Mr. Munsell was entirely aware of the relation between value and reflectance. The wrong statement in the Atlas would seem to have been an oversight.

‡ The authors are indebted to Marion A. Belknap for the preparation of Figs. 3 to 8.

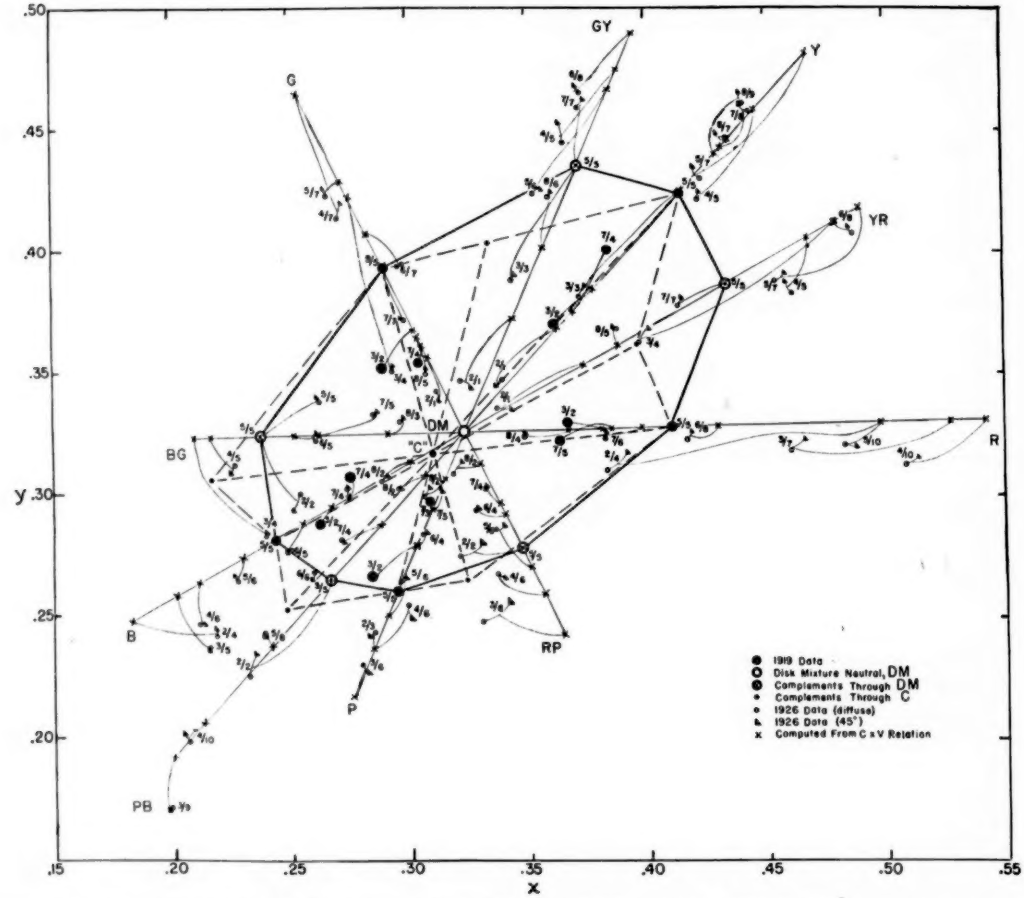

FIG. 4. Trichromatic coefficients (trilinear coordinates) of Munsell Atlas samples as obtained from measurements made in 1919 and 1926. Also shown in this figure are the complements of the 5/5 R, Y, G, B, and P colors derived from Eqs. [5], both with I.C.I. Illuminant C as the neutral point and with the disk-mixture (DM) color as the neutral point. Note the regularity of the ten-sided figure (continuous lines) resulting from use of the DM point as compared with that (dashed lines) based on C. Each pair of points representing the experimental data is connected to a point (×) on the line joining the DM and the respective 5/5 points, these ×-points being computed by Eqs. [5] and [6] for the given values of V/C.

this relation all of the 1919 and 1926 data for the chromatic samples have been plotted on the (x, y)-diagram shown in Fig. 4. To assist in an evaluation of any consistent or erratic differences among the data two straight lines are plotted for each Munsell hue designation: First, a dashed line passing from the 5/5 point for each of the five principal hues through the point representing I.C.I. Illuminant C and on to the complementary; and second, a continuous line passing from the same 5/5 point through the point (DM) which results from disk mixture of these five principal hues in equal proportions.†

To assist the reader to correlate the plotted points representing the experimental data with the proper pair of these dominant wave-length lines, each pair of points (45° and diffuse illumination) is connected by a light continuous line to the respective line of dominant wave-length, using the lines through DM for this purpose. The points chosen for the contact of the line

† Having first multiplied each (X, Y, Z)-triad by factors to make $Y=0.25$, as suggested by Tyler and Hardy, reference 11.

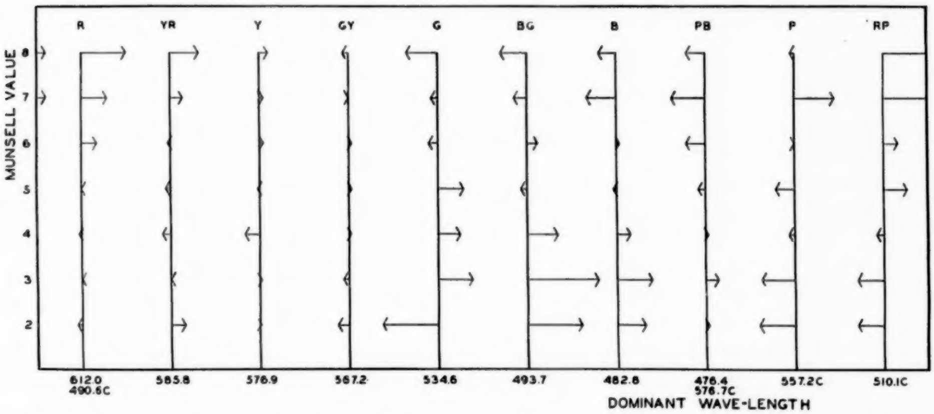

FIG. 5. In this figure is shown the degree to which the dominant wave-length of each Munsell Atlas sample (1926 data) departs from the average dominant wave-length for all samples of that hue designation, as derived from Tables III and IV. In each case, the arrow shows the direction of the departure and its length indicates the proportional part of the dominant wave-length interval to the adjacent hue. It illustrates the relative constancy of the dominant wave-lengths of, for example, the yellow samples and the shift of dominant wave-length for the blue-green and red-purple samples from value 8/ to value 2/. These dominant wave-lengths are all derived with I.C.I. Illuminant *C* as the reference point; the results would in some cases be importantly different if DM (Fig. 4) were used as the reference point.

connecting the experimental data with the lines of dominant wave-length, designated by crosses in Fig. 4, were determined on the basis of the psychophysical system described below and are taken from Table III of the Tyler-Hardy paper.

The 1926 data of Fig. 4 are plotted in different form in Fig. 5 in order to discover whether such variations as there may be in the relation between hue and dominant wave-length are random differences, or whether there may be some regularity in the pattern of variation. Each arrow point, at the value plotted, indicates the direction and magnitude of the difference between the dominant wave-length of that sample and the average dominant wave-length of all the samples of that hue designation, the length of arrow indicating the proportional part of the whole Λ interval. These average dominant wave-lengths were computed from Tables III and IV.

From an examination of Figs. 4 and 5 and reference to Tables II, III and IV, we may conclude that there are many deviations from dominant wave-length constancy among the samples for a single hue and its complementary. Some of the deviations are obvious from inspection of the samples, others are not. The hue which has the most constant dominant wave-length is yellow; the hue exhibiting the least constant dominant wave-length is blue-green, the deviation for this hue being nearly enough to extend to the average dominant wave-length of Munsell blue. In addition there is a very definite trend in some of the hues for the dominant wave-lengths of the samples of high Munsell value to be greater than those for the lower values. For example, with the blue-green samples, from values 8/ to 2/, dominant wave-length progresses from 506 through 500, 492, 496, 490 to 485 and 487 mμ. A reverse progression holds for the red series, the samples of high Munsell value being shorter in wave-length than those of low value, the progression being from a dominant wave-length of 599 mμ at value 8/ to 615 (or 640) mμ at value 2/. Such progressions are suggestive of the Bezold-Brücke phenomenon (12), the change in hue produced by an increase in luminance, but it must be recalled that the samples of each Munsell hue represented by Fig. 5 differ in purity as well as in luminous apparent reflectance. So the more or less regular departures from constant dominant wave-length shown in Fig. 5 for all but the yellow and green-yellow hues may exemplify the hue change by admixture of achromatic light (19) as well as the Bezold-Brücke phenomenon, and indeed the latter phenomenon would seem to be secondary for Munsell red and yellow-red because the direction of the departures from dominant wave-length constancy indicated in Fig. 5 for those hues is such as to accentuate the hue difference ascribable to the Bezold-Brücke phenomenon instead of compensate for it. Although detailed analysis by comparison with the Newhall (15) data has yet to be made, preliminary comparisons indicate that in general the departures shown in Fig. 5 are such as to make the samples of more nearly constant hue than they would be by keeping dominant wave-length constant.

On the other hand it is clear from Fig. 4 that most of the hues may be represented by lines, whether straight or slightly curved, which pass somewhere between the neutral gray point represented by Illuminant *C* and that represented by the disk mixture of the five principal hues. It is particularly noticeable that for the greens and complementary red-purples, and for the purples and complementary green-yellows, straight lines passing through the illuminant point do not properly represent the respective data, but that straight lines running through the point of disk mixture (DM) represent them more closely. The data for the yellows and complementary purple-blues may be represented by straight lines passing through either of the two neutral points, which themselves differ nearly in the yellow to purple-blue direction. Further discussion of the relative significance of these two neutral points is given in the following section.

Relation between Munsell chroma and colorimetric purity

In the constant hue charts of the Munsell Atlas we find statements such as the following, which is taken from the red and blue-green chart: "Any chosen steps of red and blue-green upon this chart may be balanced by noting their symbols: Thus light blue-green (BG 8/3) balances dark red (R 2/3) when the areas are inversely as the product of the symbols, *viz.*—six parts of light blue-green and twenty-four parts of dark red." Similar statements with illustrations may be found on the other charts.* The general rule is stated by Tyler and Hardy (11) as follows: "When two complementary colors occupy areas on a Maxwell disk which are inversely proportional to the product of value by chroma, a neutral gray results." The consequences of this psychophysical relation may be evaluated by the well-known laws of additive combination of colors by Maxwell disks (7, p. 30). This evaluation has been made easier than might have been supposed by writing out, in accord with suggestions by Dr. Judd hereby gladly acknowledged, the equations which by this relation connect the tristimulus specifications of color V/C (Munsell value, V, Munsell chroma, C) with those of color 5/5 of the same hue and of color 5/0 (Munsell N 5/).

The first step is to derive the equations for the complementary color $V/-C$. Let the tristimulus specifications of the two complementary colors be (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2), respectively, and let (X_n, Y_n, Z_n) be those of the neutral gray resulting from their combination in the proportions, a_1 and a_2, respectively. From the Munsell psychophysical relation:

$$a_1 = C_2V_2/(C_1V_1 + C_2V_2),$$

and

$$a_2 = C_1V_1/(C_1V_1 + C_2V_2). \quad [1]$$

From the laws of additive color combination (7, p. 30):

$$\begin{aligned} a_1X_1 + a_2X_2 &= X_n \\ a_1Y_1 + a_2Y_2 &= Y_n \\ a_1Z_1 + a_2Z_2 &= Z_n. \end{aligned} \quad [2]$$

From the definition of Munsell value, we have the relation:

$$Y_{V/C} = V^2/100,$$

and, in particular,

$$Y_{5/0} = Y_{5/5} = 25/100. \quad [3]$$

And from the fact that all Munsell neutral grays are taken as having identical trichromatic coefficients, we may write:

$$X_n/X_{5/0} = Y_n/Y_{5/0} = Z_n/Z_{5/0}. \quad [4]$$

* The authors have been unable to find any statement made by A. H. Munsell which definitely says that the color standards of the Atlas were chosen on the basis of this relation. After the system was partially completed, he found that colors used in areas inversely proportional to the product of their V and C numbers, often gave a neutral. Evidently he believed this relation to apply more rigorously than it may, for he notes it in several places. But the system was already well established, with chroma relations on a single value level being tested by disk mixture, before he found that this $V \times C$ relation seemed to exist.

Now if the first color be 5/5, and the second be $V/-C$, then: $V_1=5$, $C_1=5$, $V_2=V$, $C_2=C$,** and we have from Eq. [1]:

$$a_1=CV/(CV+25); \qquad a_2=25/(CV+25).$$

By substituting these values in Eq. [2], and eliminating X_n, Y_n, Z_n through Eqs. [3] and [4], we may solve explicitly for $X_{V/-C}$, $Y_{V/-C}$, and $Z_{V/-C}$:

$$X_{V/-C}=\frac{V}{5}\left[\frac{(V+C)}{5}X_{5/0}-\frac{C}{5}X_{5/5}\right]$$
$$Y_{V/-C}=\frac{V}{5}\left[\frac{(V+C)}{5}Y_{5/0}-\frac{C}{5}Y_{5/5}\right] \qquad [5]$$
$$Z_{V/-C}=\frac{V}{5}\left[\frac{(V+C)}{5}Z_{5/0}-\frac{C}{5}Z_{5/5}\right].$$

Equation [5] expresses the color $V/-C$ in terms of the neutral 5/0 and of the complementary 5/5 color. A similar derivation for the color V/C in terms of the 5/5 color of the same hue shows that it is necessary only to change the algebraic sign of C, thus:

$$X_{V/C}=\frac{V}{5}\left[\frac{(V-C)}{5}X_{5/0}+\frac{C}{5}X_{5/5}\right]$$
$$Y_{V/C}=\frac{V}{5}\left[\frac{(V-C)}{5}Y_{5/0}+\frac{C}{5}Y_{5/5}\right] \qquad [6]$$
$$Z_{V/C}=\frac{V}{5}\left[\frac{(V-C)}{5}Z_{5/0}+\frac{C}{5}Z_{5/5}\right].$$

From these relations trichromatic coefficients may be derived, as follows:

$$x_{V/C}=\frac{(V/C-1)x_{5/0}+(y_{5/0}/y_{5/5})x_{5/5}}{(V/C-1)+y_{5/0}/y_{5/5}},$$
$$y_{V/C}=\frac{(V/C)y_{5/0}}{(V/C-1)+y_{5/0}/y_{5/5}}. \qquad [7]$$

Note that in Eqs. [7], V/C is the only parameter; it follows that all samples of a given hue and for which V/C is a constant will have the same trichromatic coefficients (x, y). For example, R 2/2, R 3/3, R 4/4, and R 7/7 will have the same (x, y) values as R 5/5; and G 8/4 will have the same (x, y) values as G 4/2. The convention of writing Munsell value as the numerator of a fractional form whose denominator is Munsell chroma thus takes on an added meaning from the disk-mixture rule given in the Atlas apparently not foreseen at the time the convention was originated.

For a given dominant wave-length, excitation purity is proportional to distance on the Maxwell triangle, which, in turn may be measured by its projection either onto the x axis or the y axis of the (x, y) diagram, or both. The relation between excitation purity and Munsell chroma on the basis of the psychophysical relation given by Munsell may be written out from Eqs. [7] as follows:

$$\frac{P_{e(V/C)}}{P_{e(5/5)}}=\frac{y_{V/C}-y_{5/0}}{y_{5/5}-y_{5/0}}=\frac{y_{5/0}}{(y_{5/5})(V/C-1)+y_{5/0}}. \qquad [8]$$

This derivation holds only for $y_{5/5}$ different from $y_{5/0}$, but if these two are equal, the same result may be obtained from the x differences.

As might be anticipated from the psychophysical definition of chroma by disk mixture, the relation with colorimetric purity is even simpler. From the known relation between excitation purity and colorimetric purity (7, p. 59), which in present terms is:

$$P_c=\frac{y_\lambda P_e}{y_{5/0}+P_e(y_\lambda-y_{5/0})}$$
$$P_{c(5/5)}=\left(\frac{y_\lambda}{y_{5/5}}\right)P_{e(5/5)}, \qquad [9]$$

combined with Eq. [8], we obtain

$$P_{c(V/C)}=CP_{c(5/5)}/V \qquad [10]$$

or

$$C=VP_{c(V/C)}/P_{c(5/5)}. \qquad [11]$$

Equation [8] enables us to test the psychophysical nature of the Munsell system as exemplified by the samples measured in 1919 and 1926; that is, to see if the actual samples conform to this relation derived on the basis of disk mixture according to the Atlas instructions.

** Although the notation for a complementary color is taken as $V/-C$, the actual values of C for both the 5/5 and the complementary color are positive in accord with Eq. [1].

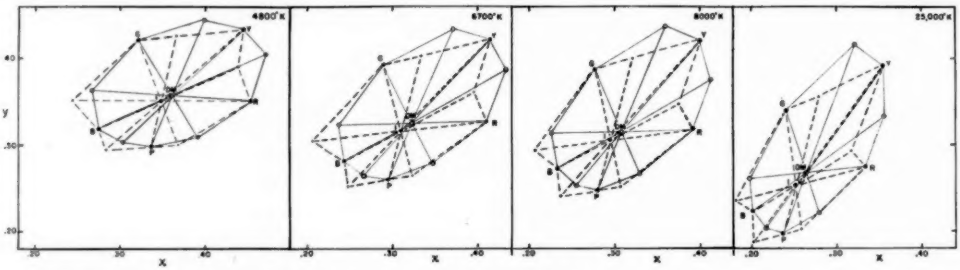

FIG. 6. The second of the above diagrams (labeled 6700°K) is identical with the respective part of Fig. 4. The other diagrams above show that change of illuminant from 6700°K (I.C.I. Illuminant *C*) to 8000°K, 25000°K or 4800°K (I.C.I. Illuminant *B*) effects no appreciable improvement in the shape of the figure defined by complementaries derived by Eq. [5] using the illuminant as the reference point. In all four cases, the use of the equal-area disk-mixture point (DM) for computing the complementaries yields a much more regular figure.

Before carrying out this test, however, choice must be made of the trichromatic coefficients, $x_{5/0}$ and $y_{5/0}$. According to Fig. 4 there is considerable doubt whether I.C.I. Illuminant should be taken to represent Munsell neutral gray; should we perhaps instead use the point given by disk mixture of the five principal hues in equal proportions?

It is believed that a definite answer to this question is given by computing the complements of R 5/5, Y 5/5, G 5/5, B 5/5, and P 5/5 by expressions analogous to Eqs. [7] derived from Eqs. [5], first with I.C.I. Illuminant *C** and second with values obtained by equal-area disk mixture of the 5/5 samples.† As already noted, this disk-mixture point is designated by the symbol, DM. In the first case an erratic outline is obtained, in the second case a regular elliptical outline is suggested, as shown in Fig. 4 and in that part of Fig. 6 marked 6700°K. In this second case the complementaries fall between the adjacent primaries at regular distances from the neutral (DM) point. From whatever cause, it is apparent that the ten principal and complementary hues space symmetrically about the DM point far better than they do about the point *C*.

In Table VI are given the tristimulus specifications, the trichromatic coefficients, the dominant wave-lengths, and the colorimetric and excitation purities, for the five principal 5/5 samples (1919 data) on which this psychophysical system is based. Corresponding data are also given for the neutral (DM) 5/0 sample resulting from equal-area disk mixture of these five principal samples and for the five 5/5 complementary samples computed relative to the DM point by Eqs. [5]. From these data in Table VI may be computed for each of the ten hues, the tristimulus specifications, the trichromatic coefficients, and the colorimetric and excitation purities for any other sample of desired *V* and *C*. Values of dominant wave-length remain unchanged for each hue. The values of *X*, *Y*, *Z*, *x*, and *y* given in Table III of the Tyler-Hardy paper (11) were computed in this way by using Eqs. [5], [6] and [7].

Before proceeding to compare the 1919 and 1926 data with the data resulting from the psychophysical system thus developed, the meaning of the shift of the neutral point from I.C.I. Illuminant *C* to the DM point may be considered. Three possibilities may be noted.

First, perhaps I.C.I. Illuminant *C* is not as blue as that used in building up the Munsell system; perhaps clear north sky was used in selecting the Atlas papers. This possibility has been explored by computing the trichromatic coefficients for the five principal hues and their complementaries, both for the spectral distribution for Planckian 8000°K and for a blue-sky distribution (one of those used by the authors (13)) having a color temperature of approximately 25,000°K. The result is shown in Fig. 6 which also shows a similar plot for I.C.I. Illuminant *B* (4800°K). None of these illuminants renders less irregular the shape of the area delimited by the five principal 5/5 colors and

* $x_{5/0}=0.3101$, $y_{5/0}=0.3163$.

† $x_{5/0}=0.3234$, $y_{5/0}=0.3255$; this point is slightly off the Planckian locus at approximately 6000°K.

their 5/5 complementaries computed by Eqs. [5] when the tristimulus specifications of the illuminant are used for $X_{5/0}$, $Y_{5/0}$, and $Z_{5/0}$. It is concluded that the irregularity of the 5/5 locus computed about the illuminant point cannot be ascribed to a disparity between the illuminant used in the computations and that used in the selection of the colors of the Munsell Atlas.

Second, perhaps the Munsell gray samples are sufficiently nonselective in the yellowish sense to account for the difference. Some of those illustrated in Bureau of Standards Technologic Paper No. 167 (2) are slightly yellowish, but only N 7/, N 8/, and N 9/ show any important selectivity. Even the yellowest of these, N 9/ ($x=0.3167$, and $y=0.3256$ for I.C.I. Illuminant C), is not sufficiently selective to bridge the gap between the color of the illuminant and that of equal-area disk mixture of the five principal colors. Hence the average color of the Munsell neutral samples, at least in 1919, is not sufficiently different from that of the illuminant to account for the difference.*

Third, it is possible that one or more of the five principal colors, by the time they were measured in 1919, may have changed sufficiently to shift the mixture point from the illuminant point to the DM point. If the five colors of the original system did spin to match a nonselective neutral at the time of their selection, then a regular system, of the sort represented here, would have resulted. The DM point would at that time have been identical with the illuminant point. There seems to be no way to test this possibility, but it is pointed out elsewhere that no certain changes in the samples have occurred between 1919 and 1926.

We may now proceed by Eq. [8] with a test of the psychophysical nature of the Munsell system exemplified by the papers measured in 1919 and 1926. The curves in Fig. 7 show C/V plotted against the ratio of excitation purities given by Eq. [8] for the five principal Munsell hues and their complements.* If the measurements of the papers had resulted in dominant wave-length constant for each hue, the desired comparison would be given by plotting, on the same graphs, C/V for each color also against the ratio of excitation purities. Since, as shown in Fig. 5, considerable departure from dominant-wave-length constancy has been found, C/V for each color is plotted instead against the ratio of distances from the neutral (DM) point on the (x, y)-diagram. This distance ratio is given by the expression:

$$\left[\frac{(x_{V/C}-x_{5/0})^2+(y_{V/C}-y_{5/0})^2}{(x_{5/5}-x_{5/0})^2+(y_{5/5}-y_{5/0})^2}\right]^{\frac{1}{2}},$$

all of whose terms are known (Tables II, III,

* It may be noted that equal-area disk mixture of the five principal colors without adjustment to $Y=0.2500$ yields $x_{5/0}=0.3213$ and $y_{5/0}=0.3262$, not importantly different from the trichromatic coefficients obtained with this adjustment. It is curious, however, that the neutral point obtained by disk mixture of the five principal colors without adjustment, and the neutral point given by N 9/, both give better representative reference points for the dominant wave-length lines than do either I. C. I. Illuminant C or the disk-mixture (DM) point with the adjustment. The most symmetrical shape for the area defined by the five principal colors and their complementaries is, however, given by the DM point.

TABLE VI. *Specifications of the five principal Munsell colors, for the Munsell N 5/ given by equal-area disk mixture of these five colors, and for the complements of these five colors at 5/5. The tristimulus specifications of each color have been multiplied by a factor to make $Y=0.2500$.*

Munsell Notation	Tristimulus Specifications			Trichromatic Coefficients		Dominant Wave-Length and Purities (Reference Point:* $x=0.3234$, $y=0.3255$)		
	X	Y	Z	x	y	λ†	P_c‡	P_e§
R 5/5	0.31298	0.25000	0.20018	0.41011	0.32759	610.5	25.7	25.3
Y 5/5	.24459	.25000	.09613	.41405	.42321	576.8	64.2	53.4
G 5/5	.18454	.25000	.20198	.28992	.39276	510.5	28.1	13.3
B 5/5	.21634	.25000	.42235	.24344	.28131	484.	20.7	31.5
P 5/5	.28326	.25000	.42761	.29480	.26018	568.c	0.8	19.4
N_{DM} 5/	.24834	.25000	.26965	.32336	.32553	—	0.0	0.0
BG 5/5	.18370	.25000	.33912	.23770	.32349	491.	22.8	23.3
PB 5/5	.25208	.25000	.44318	.26668	.26448	476.	9.1	25.4
RP 5/5	.31214	.25000	.33732	.34703	.27794	519.c	10.2	23.3
YR 5/5	.28034	.25000	.11694	.43311	.38623	585.8	56.9	48.9
GY 5/5	.21342	.25000	.11170	.37109	.43469	568.	58.6	44.8

* The reference point for this system is the neutral point N 5/ resulting from equal-area disk mixture of the five principal 5/5 samples; it differs slightly from the point representing I.C.I. Illuminant C.

† Dominant wave-lengths were read from a large-scale (x,y)-plot of the spectrum locus by extending straight lines from the point representing the N_{DM} mixture through the point representing the 5/5 sample in question to the spectrum locus.

‡ Values of P_e were calculated from the Judd (18) formula, except that for nonspectral colors the line connecting the extremes of the spectrum was taken to represent unit purity. With these values of $P_{c(5/5)}$, P_c for all other samples in this psychophysical system can be calculated from Eq. [10].

§ Values of P_e were calculated from a variation of the Hardy formula (7, p. 59) which results in: $P_e=P_c(y/y_\lambda)$. P_e for all other samples in this psychophysical system can be calculated from Eq. [8].

* In preparing Fig. 7 the data and curves for the complements were based on equations analogous to Eqs. [7] and [8] (derived from Eqs. [5]) which express $x_{V/-C}$, $y_{V/-C}$ and $P_{e(V/-C)}$ in terms of $x_{5/5}$, $y_{5/5}$ and $P_{e(5/5)}$. This explains why the dashed curves of Fig. 7 do not pass through the 1, 1 point, and further illustrates that the whole psychophysical system can be expressed in terms of the five principal colors.

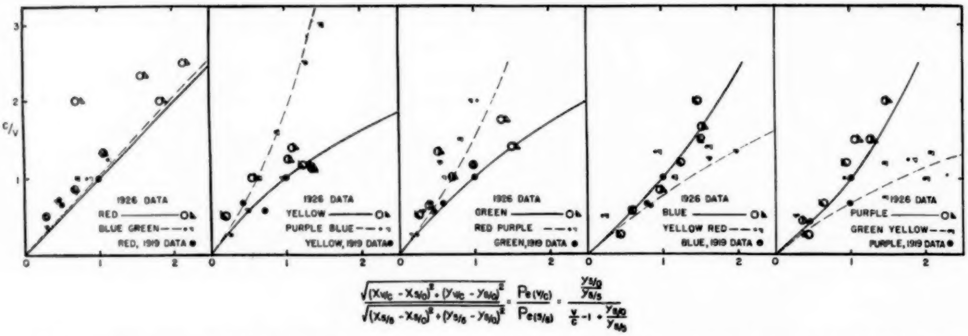

FIG. 7. Comparison of the 1919 and 1926 experimental data with values computed from the psychophysical relations. For the five principal colors the relations are as expressed in Eqs. [7] and [8] and as given in the abscissa legend. For the five complementary colors, analogous relations for $x_{V/-C}$, $y_{V/-C}$ and $P_{e(V/-C)}$ were used, based also on $x_{5/5}$, $y_{5/5}$ and $P_{e(5/5)}$; this explains why the dashed curves do not pass through the point, 1, 1 as do the continuous curves. While there is rough agreement between data and curves, large individual deviations may be noted.

IV and VI). For dominant wave-length constant, this ratio is the same as the ratio of excitation purities given in Eq. [8], and for minor deviations in dominant wave-length it is closely equivalent.

In Fig. 8 are plotted the "ideal" trichromatic coefficients of the colors, computed from Eqs. [7] and analogous equations derived from Eqs. [5]; data for Munsell values 2/, 4/, 6/, and 8/ are shown. In Fig. 8 are also plotted the 1926 data for the actual samples, these data being indicated by small triangles and circles (as in Fig. 4). The difference between the sample data and the psychophysical data for the same Munsell notation are shown by the dotted lines which connect these respective pairs of points.

It may be seen from Fig. 7 that there is rough agreement between the curves and the plotted points, although the large erratic deviations in some cases make a mental averaging of the data difficult. For certain of the colors it is apparent that the 5/5 sample on which the curves are based is not too well representative of the other colors. It may be seen that there is no certain average difference between the 1919 and 1926 data. Reference to Fig. 8 shows certain trends not apparent from Fig. 7. Figure 8 shows the increasing departures of the experimental data from the psychophysical system as one departs from value 5/, either higher in value through 6/ and 8/, or lower in value through 4/ and 2/; a distinct tendency is shown for the chromas of the lowest Munsell value to be too weak to fit the psychophysical relation, and for the chromas of the highest Munsell value to be too strong to fit this relation.

It may therefore be concluded that the Atlas papers fail to follow the disk-mixture rule resulting in Eq. [11]. The deviations are not merely erratic, as would be expected from the technical difficulties of reproducing the colors by pigments; but also, for both high and low Munsell values, the deviations show consistent tendencies and indicate that selection of these colors was not made solely on the basis of disk mixture.

TESTS FOR CONFORMITY TO A PSYCHOLOGICAL SYSTEM

Most people who have used the Munsell system have taken A. H. Munsell at his word, and have found the system to be a workable approximation of one "built up by equal and decimal steps of sensation." That it could be improved upon is indicated by the fact that the Munsell Research Laboratory was established to develop data upon which such an improvement could be based. Much work was done in the 1920's toward this end (1), with the result that in 1929 the *Munsell Book of Color* was published (14). Although individual papers of the *Book of Color* differ somewhat from those of the Atlas, the only important regular change is that the relation, $V^2=k(100\ Y)$, is replaced by a somewhat less simple relation.

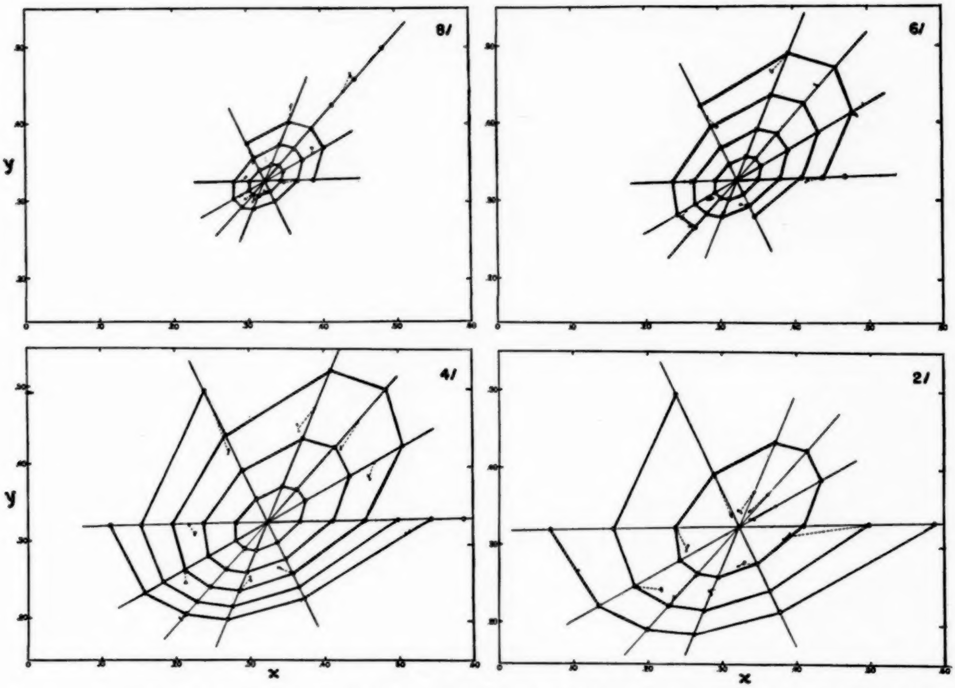

FIG. 8. Illustration of the psychophysical system developed in this paper as expressed in Eq. [7], using the 5/5 R, Y, G, B, and P 1919 data as basic starting points and the equal-area disk-mixture data (DM) as the neutral point. The open circles are plotted at chromas 0, 2, 4, 6, 8, etc. Deviations of the 1926 Atlas data from this system are also shown. Corresponding charts for the 3/, 5/, and 7/ value levels are omitted.

Probably the most satisfactory way by which the data reported in this paper can be tested psychologically is to compare them with the data obtained by the Newhall subcommittee. These data, some of which are reported in the final paper of this series by Newhall (15), have been based upon observations made on samples of the *Book of Color* to see what changes, both in magnitude and direction, would be necessary to bring about a still better representation of the ideal psychological color system, in which the steps are truly representative of equally perceptible changes in any single color attribute.

Regarding value, we already know that a definite relationship between value and reflectance was intended by Munsell, and that the Munsell value scale was intended to represent equal sensation steps. In regard to hue, we know, from Fig. 5, that the dominant wave-lengths of certain hues tend to change in accord with the requirements of a psychological system when the illuminant point is taken for a reference point. In regard to chroma, we can compare the excitation purities for samples of the 70 Atlas colors measured in 1926, both with excitation purities obtained from the data of the psychophysical relation developed in an earlier portion of this paper, and with excitation purities obtained on a basis of the Glenn-Killian (16) data, modified by the Newhall (15) data. Table VII enables this comparison to be made.

As the comparison is made, we begin to realize that a psychophysical system such as developed in this paper and a psychological system may not be as far apart as might have been supposed. However, the 1926 data at the low Munsell values in most cases agree with the data indicated by the Newhall report better than with those indicated by the psychophysical system. At the other values the data of Table VII are not so conclusive, although, except for value 8/, the agreement of the 1926 data with the psychological

TABLE VII. *Excitation purities for 70 Munsell notations: derived from the disk-mixture rule (psychophysical); computed from 1926 spectrophotometric data both for diffuse and 45° illumination (1926 data); and from the Glenn-Killian data on the papers of the Munsell Book of Color, with conformity to the Newhall psychological check indicated by direction of difference (psychological).*

Munsell Notation	Excitation Purity						Notation Munsell	Excitation Purity					
			1926 Data							1926 Data			
	Psycho-physical[1]	*	Dif-fuse[2]	45°[3]	*	Psycho-logical[4]		Psycho-physical[1]	*	Dif-fuse[2]	45°[3]	*	Psycho-logical[4]
R 2/4	50.7		18.0	22.0	*n*	19.8++	R 6/8	33.8		30.1	31.5	*n*	30.0+
YR 2/1	24.5		12.5	13.8	*n*	15.4+	YR 6/8	65.3	*n*	71.5	71.8		59.6−
Y 2/1	26.7		16.1	14.7	*n*	10.0+	Y 6/7	62.3		68.2	67.5	*n*	69.0−
GY 2/1	22.4		11.2	11.5	*n*	7.8	GY 6/8	59.8		57.0	57.0		55.5−
G 2/1	6.6	*n*	7.5	6.8		4.5−	G 6/7	15.5		18.4	17.7	*n*	19.4−−−
BG 2/2	23.2	*n*	22.0	23.9		15.5	BG 6/5	19.4		17.8	17.8	*n*	17.7
B 2/4	62.9		41.6	41.3	*n*	40.2	B 6/5	26.2		26.0	26.9		28.9−−
PB 2/2	25.2		39.5	37.0		26.5	PB 6/6	25.2	*n*	23.7	24.5		27.2
P 2/3	29.1		24.7	24.7	*n*	29.8−−	P 6/4	12.9	*n*	12.2	12.1		16.0−
RP 2/2	23.3		19.0	18.3	*n*	20.0	RP 6/4	15.5		12.5	12.5	*n*	12.1+
R 3/7	59.1		40.5	43.2	*n*	39.2	R 7/6	21.7	*n*	21.0	22.0		17.4+
YR 3/4	65.3		35.8	38.0	*n*	47.9−	YR 7/7	49.0		44.0	45.2	*n*	46.1−
Y 3/3	53.4		34.0	35.9	*n*	23.7++	Y 7/8	61.1		73.5	73.4	*n*	75.2−−
GY 3/3	44.9		28.3	29.2	*n*	20.6+	GY 7/7	44.9		55.0	56.5	*n*	50.7−
G 3/4	17.7		6.8	7.2	*n*	15.2−−	G 7/7	13.3		12.3	12.2		13.9−−
BG 3/4	31.0		29.3	29.2		27.2−	BG 7/5	16.6		8.4	7.8	*n*	13.9
B 3/5	52.4		43.0	43.4	*n*	45.6−	B 7/4	18.0		14.7	14.7		17.4
PB 3/9	75.6		58.3	59.0	*n*	54.7	PB 7/4	14.4		17.9	17.6	*n*	18.2
P 3/6	38.8		29.0	30.9	*n*	36.1−	P 7/3	8.3	*n*	6.0	6.7		10.9−
RP 3/6	46.6		31.3	30.2	*n*	33.0	RP 7/4	13.3		9.8	9.5	*n*	8.0+
R 4/10	63.3		52.2	54.1	*n*	51.2−	R 8/4	12.7	*n*	12.1	12.1		9.1
YR 4/5	61.2	*n*	58.2	58.8		50.8−	YR 8/5	30.6	*n*	34.5	34.1		25.9
Y 4/5	66.8		58.1	59.2	*n*	58.5−	Y 8/9	60.1		73.8	74.4	*n*	70.6−
GY 4/5	56.1	*n*	49.5	51.0		35.8	GY 8/6	33.6		41.7	42.6	*n*	40.6−
G 4/7	23.2		18.8	20.3		25.0−−	G 8/5	8.3	*n*	8.3	9.0		7.2−
BG 4/5	29.1	*n*	31.5	32.2		27.0−	BG 8/3	8.7		4.5	4.1		7.8
B 4/6	47.2		43.6	42.9	*n*	45.3−	B 8/2	7.9		9.0	7.9		9.6
PB 4/10	63.0		51.5	52.1	*n*	51.9−	PB 8/2	6.3	*n*	7.0	6.8		12.0−
P 4/6	29.1		23.0	25.0		28.7+	P 8/2	4.8		6.0	5.0		5.9
RP 4/6	35.0		24.6	26.0	*n*	27.8	RP 8/2	5.8		4.7	3.5		3.7−
R 5/10	50.7		47.1	48.2	*n*	47.0−							
YR 5/7	68.6		57.5	59.8	*n*	59.6−							
Y 5/7	74.8		60.8	61.2		75.6−							
GY 5/6	53.8		40.1	41.8	*n*	46.0							
G 5/7	18.6		20.5	21.2		19.2−−							
BG 5/5	23.3		16.4	16.4		24.0							
B 5/6	37.8	*n*	35.5	36.0		41.4−−							
PB 5/8	40.3		34.5	34.7		40.1−							
P 5/6	23.3		18.3	18.2		26.8−−							
RP 5/6	28.0		17.0	17.2	*n*	22.1+							

[1] From Eq. [8].
[2] From Table III.
[3] From Table IV.
[4] Read or interpolated from Table I of the next paper in this series (16) which gives the Glenn-Killian measurements of the papers in the 1929 *Munsell Book of Color.* The plus and minus signs indicate the directions of the changes necessary to improve agreement with the psychological requirements evaluated in the Newhall subcommittee report (15) forming the final paper of this series. For example, for R 6/8 the excitation purity given by Glenn and Killian is 30.0; but the Newhall data indicate that R 6/8, if it is to fit into the ideal psychological system, should be slightly higher in excitation purity; so a plus sign is added. Two plus signs indicate that the difference is more than slight.
* The notations in these columns indicate whether the excitation purities for the 1926 data agree better with the psychophysical system or the psychological. An "*n*" between the first and second columns of excitation purities indicates "nearer to the psychophysical system," while "nearer to the psychological system" is indicated by an "*n*" between the third and fourth columns. If the excitation purity found from the 1926 data does not agree significantly better with one than the other, no notation is given.

data appears somewhat better than with the psychophysical system.

Before we can answer definitely, therefore, we shall need to study in further detail the preliminary report of the Newhall subcommittee (15), and may need also to wait for the final report which is expected to explore thoroughly the possibility of constructing a psychophysical color system based upon photometry and disk mixture which will be in satisfactory agreement with the requirements of an ideal psychological system. It would seem to be worth while to study the psychophysical color system resulting from five new principal colors chosen so that their equal-area disk mixture will have the same trichromatic coefficients (x, y) as the illuminant. When this is done, we should be able to decide with certainty not only whether the 1919, 1926, or 1929 series of Munsell colors more closely approach a psychological system or the psychophysical system dealt with here, but also the more important question whether or not a simply defined psychophysical color system similar to it can be made to meet the requirements of the ideal psychological system envisaged by A. H. Munsell.

Summary

An examination has been made of the Munsell color system as it existed in 1919 and 1926. This examination has been based on colorimetric data derived from published and unpublished spectrophotometric measurements made in those years on samples representative of the Munsell Atlas.

The relation between Munsell value and luminous apparent reflectance, $V^2 = 100k(Y - 0.007)$, closely similar to that found by others, has been confirmed in a general way. While there are large individual variations, it is found that the above relation, with k close to unity, adequately represents the data as a whole. The white point on this scale corresponds to magnesium oxide, the black point to a sample reflecting diffusely about 0.7 percent.

The relation between Munsell Atlas hue and dominant wave-length depends upon the neutral (reference) point adopted. At best there are significant deviations from one-to-one correspondence. Therefore the terms for dominant wave-length and for Munsell hue as illustrated by the original papers of the Munsell system cannot be used interchangeably.

A psychophysical system has been developed, based on the inverse CV weighting indicated in the Atlas instructions for a disk mixture to yield neutral gray.

In this psychophysical system the trichromatic coefficients (x, y) of a Munsell color of a given hue depend only upon the ratio of value to chroma (V/C). The following relations between excitation purity and colorimetric purity on the one hand and Munsell chroma and value on the other are obtained from this derivation:

$$P_{e(V/C)} = \frac{P_{e(5/5)} y_{5/0}}{y_{5/5}(V/C - 1) + y_{5/0}}.$$

$$P_{c(V/C)} = (C/V) P_{c(5/5)}.$$

The 1919 and 1926 data indicate rough agreement with these relations, particularly for middle Munsell values; but there are consistent deviations from them, greater at low Munsell values than at high. Comparison of the data of this paper with the psychological data obtained by the Newhall subcommittee indicates that the above departures from the psychophysical system are in the direction to give chroma scales which are perceptually more uniform, and therefore that there has been an intentional departure from the psychophysical system.

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Trichromatic Analysis of the *Munsell Book of Color*

JAMES J. GLENN, *Sidney Blumenthal & Company, Shelton, Connecticut*
AND
JAMES T. KILLIAN, *Pope & Gray, Inc., New York, New York*

THE *Atlas of the Munsell Color System* was superseded in 1929 by the *Munsell Book of Color.* The advantages and disadvantages of the new color system are discussed elsewhere in this series of papers. The purpose of this paper is to establish the connection between the color system represented by the *Munsell Book of Color* and the system adopted in 1931 by the International Commission on Illumination. The data contained herein were obtained during 1934,[1] and were originally intended for publication in the forthcoming report of the Optical Society of America Committee on Colorimetry. When the present series of papers was recently proposed, it seemed appropriate that publication should not be further delayed.

[1] Bachelor's Thesis, Department of Physics, Massachusetts Institute of Technology, 1935.

TABLE I.

Munsell Notation	X	Y	Z	x	y	Dominant Wave-Length	Excitation Purity
10 PB 7/6	0.4543	0.4307	0.7338	0.2806	0.2661	460.4	17.6
7/4	.4650	.4495	.6976	.2884	.2788	460.0	13.0
6/8	.3627	.3214	.6815	.2656	.2354	456.0	27.6
6/6	.3372	.3098	.5889	.2728	.2507	458.0	22.8
6/4	.3495	.3295	.5591	.2823	.2661	456.0	17.2
5/10	.2359	.1968	.5232	.2468	.2059	459.0	38.4
5/8	.2413	.2070	.5027	.2537	.2177	459.0	34.2
5/6	.2352	.2109	.4470	.2634	.2361	460.0	28.0
5/4	.2352	.2179	.4014	.2752	.2550	458.0	21.2
4/10	.1570	.1234	.3697	.2415	.1898	454.0	43.1
4/8	.1578	.1288	.3557	.2457	.2005	456.0	39.8
4/6	.1566	.1334	.3092	.2613	.2226	451.0	31.4
4/4	.1436	.1279	.2504	.2751	.2451	444.0	23.5
3/10	.1041	.0703	.2847	.2267	.1531	449.0	54.6
3/8	.0974	.0755	.2247	.2450	.1899	450.0	42.4
3/6	.0904	.0740	.1913	.2541	.2080	451.0	36.3
3/4	.0842	.0729	.1635	.2626	.2274	453.5	30.2
2/6	.0498	.0408	.1021	.2584	.2117	445.0	34.6
2/4	.0490	.0408	.1007	.2573	.2141	450.5	34.3
PB 8/2	.6253	.6411	.9302	.2847	.2919	478.0	12.0
7/6	.4447	.4550	.8020	.2613	.2674	477.5	23.2
7/4	.4627	.4745	.7653	.2718	.2787	477.8	18.2
7/2	.4723	.4877	.6965	.2851	.2944	477.3	11.5
6/8	.3277	.3314	.6960	.2418	.2446	476.6	33.0
6/6	.3358	.3398	.6466	.2540	.2570	476.6	27.2
6/4	.3495	.3562	.5998	.2677	.2728	477.1	20.4
6/2	.3378	.3430	.5171	.2820	.2863	476.2	13.7
5/10	.2212	.2282	.5684	.2173	.2242	477.6	44.2
5/8	.2197	.2249	.5260	.2264	.2317	477.4	40.1
5/6	.2168	.2206	.4552	.2429	.2471	477.0	32.3
5/4	.2066	.2104	.3784	.2597	.2645	477.0	24.3
5/2	.2055	.2091	.3292	.2763	.2811	476.9	16.3
4/10	.1460	.1455	.4254	.2037	.2030	476.4	51.9
4/8	.1407	.1409	.3676	.2167	.2170	476.5	45.4
4/6	.1370	.1379	.3109	.2339	.2354	476.5	37.0
4/4	.1348	.1357	.2612	.2535	.2552	476.2	27.6
4/2	.1332	.1349	.2110	.2780	.2816	476.0	15.7
3/12	.0827	.0799	.2949	.1808	.1746	475.8	63.6
3/10	.0853	.0825	.2749	.1927	.1864	475.7	57.9
3/8	.0806	.0788	.2329	.2055	.2009	475.7	51.5
3/6	.0770	.0756	.1933	.2226	.2186	475.5	43.2
3/4	.0739	.0734	.1587	.2415	.2399	475.4	33.8
3/2	.0718	.0724	.1231	.2686	.2709	476.0	20.4
2/6	.0423	.0418	.1230	.2042	.2018	476.1	51.9
2/4	.0405	.0402	.1012	.2226	.2210	476.0	42.9
2/2	.0368	.0364	.0698	.2573	.2545	474.7	26.5

TABLE I.—*Continued.*

Munsell Notation		X	Y	Z	x	y	Dominant Wave-Length	Excitation Purity
10	B 7/6	0.4203	0.4614	0.7937	0.2509	0.2754	482.2	26.0
	7/4	.4217	.4552	.6987	.2676	.2889	482.8	18.5
	6/6	.2936	.3283	.6033	.2396	.2680	482.3	30.9
	6/4	.3140	.3382	.5605	.2589	.2789	481.7	22.7
	5/6	.1963	.2193	.4454	.2280	.2547	481.3	36.6
	5/4	.1986	.2154	.3805	.2500	.2711	481.1	26.7
	4/8	.1171	.1338	.3337	.2003	.2289	480.7	49.4
	4/6	.1232	.1350	.3100	.2168	.2376	480.0	42.7
	4/4	.1250	.1355	.2481	.2458	.2664	480.9	28.9
	3/8	.0730	.0849	.2423	.1824	.2121	480.4	58.0
	3/6	.0699	.0792	.1955	.2028	.2298	480.5	48.6
	3/4	.0693	.0763	.1580	.2283	.2513	480.7	36.9
	B 8/4	.5415	.5984	.8100	.2777	.3069	487.2	12.9
	8/2	.5737	.6193	.8130	.2860	.3087	486.9	9.6
	7/6	.3906	.4467	.6979	.2544	.2910	485.2	22.9
	7/4	.4054	.4546	.6576	.2671	.2996	486.2	17.4
	7/2	.4295	.4657	.6139	.2846	.3086	487.1	10.1
	6/6	.2575	.3103	.5576	.2288	.2757	484.8	34.0
	6/4	.2869	.3249	.5199	.2535	.2871	484.6	23.8
	6/2	.2962	.3206	.4662	.2735	.2960	484.0	15.4
	5/6	.1633	.2025	.4046	.2120	.2629	484.2	41.4
	5/4	.1660	.1958	.3466	.2343	.2764	484.4	31.8
	5/2	.1823	.1994	.2913	.2709	.2963	484.6	16.4
	4/8	.0935	.1163	.2701	.1948	.2423	482.9	50.0
	4/6	.1033	.1283	.2749	.2039	.2533	483.5	45.3
	4/4	.1225	.1438	.2598	.2328	.2733	484.0	32.8
	4/2	.1246	.1386	.2085	.2642	.2938	484.8	19.2
	3/6	.0624	.0832	.1854	.1885	.2514	484.3	51.2
	3/4	.0600	.0744	.1450	.2147	.2663	484.5	40.0
	3/2	.0662	.0739	.1171	.2574	.2873	484.1	22.3
	2/2	.0371	.0417	.0632	.2613	.2937	485.2	20.1
10	BG 7/4	.4008	.4619	.6258	.2693	.3103	489.2	15.6
	6/6	.2675	.3412	.5083	.2395	.3055	489.1	27.2
	6/4	.2743	.3266	.4606	.2584	.3077	488.9	20.0
	5/6	.1649	.2191	.3697	.2188	.2907	487.5	36.1
	5/4	.1713	.2094	.3142	.2465	.3013	488.1	25.0
	4/6	.0991	.1345	.2266	.2153	.2923	487.9	37.2
	4/4	.1056	.1322	.1977	.2425	.3036	488.6	26.2
	3/6	.0500	.0724	.1351	.1942	.2812	487.3	46.0
	3/4	.0605	.0791	.1298	.2246	.2936	487.7	33.7
	BG 8/2	.5473	.6106	.7010	.2944	.3285	500.5	5.2
	7/4	.3917	.4616	.5549	.2782	.3278	495.6	11.1
	7/2	.4233	.4754	.5598	.2902	.3260	496.9	6.7
	6/6	.2760	.3518	.4525	.2555	.3257	493.0	19.8
	6/4	.2815	.3438	.4322	.2662	.3251	493.4	15.6
	6/2	.2903	.3314	.4045	.2829	.3229	493.8	9.8
	5/6	.1566	.2174	.2962	.2337	.3244	492.3	27.9
	5/4	.1660	.2103	.2762	.2544	.3223	492.3	20.2
	5/2	.1818	.2119	.2612	.2776	.3236	493.7	11.5

Some 400 color samples were obtained from the Munsell Color Company in November, 1934. These samples, backed by a standard white material, were compared spectrophotometrically against a freshly smoked surface of magnesium oxide deposited on magnesium carbonate. The spectrophotometer employed was of a type[2] that records the diffuse reflection factors of the sample relative to those of the magnesium-oxide standard. These spectral reflection factors were converted by integration into tristimulus values, using a selected-ordinate method with thirty ordinates.

In Table I, column 1 indicates the Munsell designation of the color. Columns 2, 3, and 4 give the tristimulus values for the 1931 I.C.I. standard observer and Illuminant *C*. Columns 5 and 6 list the

[2] J. Opt. Soc. Am. **25**, 305 (1935).

TABLE I.—*Continued.*

Munsell Notation	X	Y	Z	x	y	Dominant Wave-Length	Excitation Purity
BG 4/6	0.0911	0.1317	0.1867	0.2225	0.3216	491.6	32.1
4/4	.1071	.1379	.1841	.2496	.3214	491.9	22.0
4/2	.1185	.1389	.1789	.2716	.3184	491.6	14.0
3/6	.0551	.0805	.1198	.2157	.3152	490.8	35.2
3/4	.0531	.0724	.0996	.2359	.3216	491.8	27.2
3/2	.0603	.0740	.0982	.2594	.3183	491.5	18.9
2/4	.0351	.0455	.0630	.2445	.3168	491.3	24.2
2/2	.0377	.0448	.0581	.2679	.3187	491.6	15.5
10 G 7/4	.3875	.4680	.5261	.2805	.3387	500.2	9.8
6/6	.2641	.3580	.3992	.2586	.3505	499.1	17.3
6/4	.2700	.3409	.3933	.2689	.3395	497.8	14.0
5/6	.1366	.2067	.2313	.2377	.3597	498.3	24.3
5/4	.1612	.2105	.2368	.2649	.3459	498.9	15.0
4/4	.0931	.1274	.1438	.2556	.3497	498.4	18.3
3/4	.0517	.0753	.0838	.2453	.3572	498.7	21.7
G 8/6	.4551	.5661	.5755	.2850	.3545	511.6	8.6
8/4	.5017	.5892	.6180	.2936	.3448	513.5	5.9
8/2	.5098	.5739	.6132	.3004	.3382	521.0	4.3
7/6	.3303	.4371	.4380	.2740	.3626	507.5	11.9
7/4	.3499	.4324	.4500	.2839	.3509	506.5	8.6
7/2	.3722	.4199	.4631	.2965	.3345	508.3	4.4
6/6	.2073	.3058	.2830	.2604	.3841	508.6	16.6
6/4	.2385	.3099	.3058	.2792	.3628	510.1	10.4
6/2	.2628	.3052	.3266	.2938	.3412	511.5	5.6
5/8	.1074	.1813	.1471	.2464	.4160	511.3	21.8
5/6	.1235	.1850	.1621	.2624	.3931	512.0	16.6
5/4	.1443	.1920	.1857	.2764	.3678	511.0	11.6
5/2	.1603	.1871	.2018	.2919	.3407	508.5	6.0
4/4	.0908	.1293	.1180	.2686	.3824	511.8	14.3
4/2	.1076	.1289	.1352	.2895	.3468	510.5	7.0
3/4	.0527	.0767	.0678	.2672	.3889	513.1	15.2
3/2	.0574	.0719	.0721	.2850	.3570	512.5	8.8
2/2	.0346	.0420	.0457	.2827	.3435	503.3	9.0
10 GY 8/6	.4734	.5851	.4375	.3164	.3911	555.0	21.8
8/4	.5216	.6177	.5275	.3129	.3706	553.7	15.5
7/8	.3202	.4513	.2434	.3155	.4447	553.2	36.2
7/6	.3416	.4514	.3003	.3124	.4129	552.3	26.8
7/4	.3783	.4549	.3776	.3124	.3757	553.0	16.8
6/10	.2099	.3116	.1344	.3200	.4751	554.2	45.6
6/8	.2334	.3288	.1660	.3205	.4515	554.8	39.3
6/6	.2303	.3162	.1899	.3127	.4294	552.3	31.3
6/4	.2478	.3120	.2475	.3069	.3865	548.8	18.3
5/8	.1311	.1955	.0889	.3155	.4705	552.8	43.2
5/6	.1532	.2177	.1145	.3156	.4485	553.2	37.3
5/4	.1661	.2086	.1569	.3125	.3924	552.6	21.2
4/6	.1007	.1406	.0876	.3062	.4275	549.2	29.3
4/4	.1053	.1367	.1053	.3032	.3936	546.1	19.3
3/4	.0598	.0813	.0555	.3039	.4138	547.6	24.8

trichromatic coefficients. The last two columns list the dominant wave-length in millimicrons and the excitation purity in percent.[3] The dominant wave-length in the case of purples is indicated by listing the wave-length of the complementary color.

We wish here to acknowledge our indebtedness to Professor Arthur C. Hardy, who suggested this undertaking and offered much helpful advice during the progress of the work. We are indebted also to Dr. David L. MacAdam for operating the spectrophotometer during the determination of the spectrophotometric data.

[3] *The Handbook of Colorimetry* (Technology Press, Cambridge. Massachusetts, 1936).

TABLE I.—*Continued.*

Munsell Notation	X	Y	Z	x	y	Dominant Wave-Length	Excitation Purity
GY 8/8	0.4912	0.6116	0.2059	0.3753	0.4673	566.9	58.1
8/6	.5050	.6018	.3166	.3548	.4228	566.5	40.6
8/4	.5256	.5939	.4463	.3357	.3793	566.3	23.8
8/2	.5410	.5810	.5567	.3223	.3461	566.4	11.2
7/10	.3404	.4325	.1021	.3890	.4943	567.2	69.1
7/8	.3636	.4499	.1637	.3721	.4628	566.7	56.0
7/6	.3710	.4490	.2108	.3599	.4356	566.5	45.4
7/4	.3918	.4468	.3175	.3389	.3865	566.4	26.6
7/2	.3959	.4269	.4003	.3237	.3490	566.4	12.5
6/8	.2578	.3257	.1170	.3680	.4650	565.8	55.5
6/6	.2657	.3221	.1287	.3708	.4495	567.4	52.0
6/4	.2749	.3184	.2047	.3445	.3990	566.4	31.4
6/2	.2912	.3157	.2897	.3248	.3521	566.3	13.6
5/8	.1665	.2129	.0680	.3722	.4759	565.8	59.6
5/6	.1680	.2075	.0952	.3569	.4408	565.4	46.0
5/4	.1792	.2102	.1247	.3486	.4089	566.4	35.2
5/2	.1954	.2144	.1866	.3276	.3595	566.2	16.3
4/6	.1068	.1283	.0675	.3529	.4240	566.0	40.5
4/4	.1146	.1336	.0861	.3428	.3996	565.8	31.1
4/2	.1225	.1344	.1200	.3250	.3566	565.1	14.8
3/4	.0701	.0800	.0584	.3362	.3837	565.7	25.0
3/2	.0727	.0798	.0695	.3275	.3595	566.1	16.2
2/2	.0463	.0519	.0453	.3226	.3617	562.4	15.5
10 Y 8/8	.5333	.6108	.1683	.4064	.4654	571.7	65.7
8/6	.5329	.5922	.2983	.3744	.4160	571.7	44.0
8/4	.5525	.5996	.4328	.3486	.3783	571.2	26.9
7/8	.3890	.4443	.0924	.4202	.4800	572.3	73.5
7/6	.3812	.4320	.1571	.3929	.4452	571.7	56.9
7/4	.4026	.4398	.2892	.3558	.3887	571.4	31.6
6/6	.2913	.3290	.0891	.4106	.4638	572.4	66.5
6/4	.3017	.3296	.1871	.3686	.4027	572.3	38.8
5/6	.2017	.2275	.0788	.3970	.4478	572.1	58.7
5/4	.1951	.2177	.1072	.3752	.4187	571.5	44.8
4/4	.1258	.1393	.0687	.3769	.4173	572.0	44.8
Y 8/12	.5426	.5726	.0717	.4572	.4824	575.9	84.0
8/10	.5512	.5798	.0995	.4479	.4712	576.0	78.6
8/8	.5449	.5780	.1827	.4174	.4427	575.3	62.7
8/6	.5456	.5702	.2887	.3885	.4060	575.7	45.0
8/4	.5423	.5604	.3982	.3613	.3734	576.1	29.1
8/2	.5413	.5570	.5169	.3351	.3448	575.8	14.4
7/10	.4063	.4226	.0797	.4472	.4651	576.5	76.8
7/8	.3927	.4175	.0834	.4395	.4672	575.5	75.2
7/6	.4040	.4199	.1598	.4107	.4269	576.3	56.7
7/4	.4108	.4244	.2790	.3687	.3809	576.2	33.0
7/2	.4281	.4403	.4031	.3367	.3463	575.7	15.2
6/8	.3107	.3241	.0721	.4395	.4585	576.3	72.8
6/6	.2964	.3064	.0900	.4278	.4423	576.7	65.2
6/4	.3034	.3122	.1816	.3806	.3916	576.7	39.0
Y 6/2	.3068	.3148	.2764	.3416	.3506	576.4	17.6
5/6	.1935	.2022	.0603	.4243	.4434	576.2	64.8
5/4	.1983	.2054	.1070	.3883	.4022	576.3	44.0
5/2	.2008	.2060	.1774	.3437	.3526	576.4	18.8
4/4	.1264	.1308	.0639	.3936	.4073	576.4	46.8
4/2	.1406	.1451	.1183	.3480	.3592	575.8	21.7
3/2	.0749	.0771	.0697	.3378	.3478	575.7	15.8
2/2	.0529	.0544	.0457	.3458	.3556	576.1	20.0

TABLE I.—*Continued.*

Munsell Notation	X	Y	Z	x	y	Dominant Wave-Length	Excitation Purity
10 YR 8/6	0.6308	0.6121	0.3619	0.3931	0.3814	580.9	39.8
8/4	.6082	.5995	.4700	.3625	.3573	581.0	25.0
7/10	.4556	.4298	.0845	.4697	.4431	580.8	76.8
7/8	.4673	.4441	.1417	.4437	.4217	580.8	64.0
7/6	.4548	.4388	.2061	.4136	.3990	580.7	50.0
7/4	.4711	.4573	.3316	.3739	.3629	582.0	29.6
6/10	.3855	.3584	.0754	.4705	.4374	581.6	75.5
6/8	.3728	.3495	.1064	.4499	.4217	581.5	65.7
6/6	.3573	.3390	.1383	.4281	.4062	581.4	55.8
6/4	.3253	.3188	.1998	.3855	.3778	580.5	36.7
5/8	.2277	.2120	.0576	.4579	.4263	581.7	69.1
5/6	.2259	.2122	.0872	.4300	.4040	582.0	55.7
5/4	.2171	.2083	.1118	.4041	.3878	581.4	44.3
4/4	.1459	.1370	.0608	.4245	.3986	582.2	52.8
YR 8/4	.6304	.5994	.5185	.3606	.3428	586.6	20.7
8/2	.6147	.6060	.6182	.3343	.3295	586.0	10.0
7/10	.5037	.4266	.1353	.4727	.4003	586.8	66.0
7/8	.5089	.4392	.2027	.4422	.3816	587.4	53.0
7/6	.4844	.4313	.2688	.4089	.3641	587.7	39.2
7/4	.4763	.4414	.3487	.3761	.3485	587.6	26.3
7/2	.4505	.4363	.4310	.3419	.3311	588.1	12.4
6/12	.4025	.3393	.0651	.4988	.4205	585.8	78.5
6/10	.3925	.3225	.0906	.4872	.4003	587.9	70.0
6/8	.3815	.3252	.1259	.4582	.3906	587.2	59.6
6/6	.3619	.3215	.1817	.4183	.3716	587.0	43.8
6/4	.3354	.3093	.2323	.3824	.3527	587.1	29.1
6/2	.3172	.3074	.2876	.3477	.3370	585.9	15.6
5/10	.2578	.2105	.0512	.4962	.4052	587.8	73.6
5/8	.2503	.2091	.0696	.4732	.3953	587.7	64.9
5/6	.2369	.2044	.0912	.4449	.3838	587.2	54.3
5/4	.2185	.1947	.1214	.4087	.3642	587.7	39.2
5/2	.1978	.1890	.1726	.3536	.3379	587.2	17.3
4/8	.1603	.1363	.0500	.4625	.3932	587.1	61.5
4/6	.1717	.1458	.0629	.4514	.3833	588.0	55.7
4/4	.1603	.1410	.0761	.4247	.3736	587.2	46.0
4/2	.1365	.1273	.1052	.3699	.3450	587.8	23.6
3/4	.0932	.0815	.0422	.4297	.3757	587.4	47.9
3/2	.0770	.0713	.0576	.3740	.3463	588.1	25.1
2/2	.0544	.0504	.0365	.3850	.3567	586.2	30.8
RYR 8/4	.6653	.6218	.5709	.3581	.3347	591.0	17.8
7/8	.5279	.4392	.2814	.4228	.3518	593.3	39.7
7/6	.5191	.4511	.3575	.3910	.3398	594.3	28.0
7/4	.4998	.4462	.3908	.3739	.3338	595.0	21.8
6/10	.4355	.3330	.1385	.4802	.3671	594.0	59.2
6/8	.4172	.3356	.1817	.4464	.3591	593.3	48.0
6/6	.3968	.3351	.2225	.4158	.3511	592.7	37.5
6/4	.3643	.3250	.2727	.3787	.3378	593.3	24.0
5/10	.2786	.2025	.0697	.5058	.3676	595.6	66.2
5/8	.2862	.2193	.0996	.4730	.3624	594.6	56.0
5/6	.2634	.2077	.1149	.4495	.3544	595.0	47.5
5/4	.2420	.2055	.1537	.4025	.3418	595.0	31.5
4/10	.2169	.1532	.0602	.5041	.3560	597.4	62.7
4/8	.1983	.1446	.0608	.4912	.3582	597.0	59.9
4/6	.1878	.1430	.0717	.4666	.3553	596.0	52.5
4/4	.1639	.1360	.0920	.4182	.3470	594.5	37.2
3/6	.1105	.0845	.0474	.4559	.3486	597.5	47.5
3/4	.0958	.0766	.0535	.4241	.3391	598.7	36.7

TABLE I.—*Continued.*

Munsell Notation	X	Y	Z	x	y	Dominant Wave-Length	Excitation Purity
R 8/4	0.6359	0.5922	0.6312	0.3420	0.3185	609.0	9.1
8/2	.6049	.5846	.6586	.3273	.3163	619.0	4.5
7/8	.5142	.4247	.3906	.3868	.3194	611.0	21.3
7/6	.5222	.4483	.4321	.3723	.3196	610.0	17.4
7/4	.4992	.4394	.4388	.3624	.3190	610.0	14.7
7/2	.4615	.4380	.4800	.3345	.3175	610.5	6.8
6/10	.4455	.3278	.2473	.4365	.3212	610.4	35.5
6/8	.4100	.3190	.2606	.4143	.3224	608.5	30.0
6/6	.3983	.3281	.2963	.3895	.3208	610.0	22.6
6/4	.3744	.3288	.3198	.3660	.3214	606.0	16.4
6/2	.3360	.3183	.3459	.3359	.3182	608.2	7.5
5/12	.3175	.1971	.0972	.5190	.3222	612.5	57.3
5/10	.3260	.2169	.1335	.4820	.3207	613.8	47.0
5/8	.2905	.2013	.1292	.4678	.3242	610.0	44.3
5/6	.2625	.1960	.1565	.4268	.3187	613.5	31.8
5/4	.2377	.1934	.1753	.3920	.3189	612.0	22.8
5/2	.2100	.1904	.1983	.3508	.3180	610.0	11.3
4/14	.2432	.1410	.0595	.5481	.3178	615.5	64.0
4/12	.2339	.1385	.0666	.5328	.3155	617.0	59.4
4/10	.2162	.1358	.0784	.5023	.3155	617.0	51.2
4/8	.1995	.1341	.0878	.4734	.3182	614.5	44.1
4/6	.1751	.1279	.0979	.4368	.3190	613.5	34.5
4/4	.1573	.1265	.1149	.3945	.3173	616.0	23.0
4/2	.1464	.1291	.1330	.3584	.3160	618.0	12.9
3/10	.1212	.0759	.0433	.5042	.3157	617.0	51.8
3/8	.1127	.0753	.0505	.4725	.3157	617.5	43.3
3/6	.1200	.0852	.0655	.4433	.3147	618.0	35.2
3/4	.0987	.0752	.0647	.4137	.3152	618.0	27.3
3/2	.0854	.0744	.0773	.3602	.3138	628.0	12.6
2/6	.0632	.0461	.0405	.4219	.3078	636.0	27.5
2/4	.0555	.0436	.0424	.3922	.3081	650.0	19.8
2/2	.0526	.0453	.0487	.3586	.3094	492.7 *c*	12.0
10 RP 8/6	.6890	.6366	.7165	.3374	.3117	493.0 *c*	7.0
8/4	.6419	.6092	.6866	.3313	.3144	492.5 *c*	5.3
7/8	.5359	.4595	.4987	.3587	.3075	493.0 *c*	12.8
7/6	.5251	.4650	.5130	.3493	.3094	493.2 *c*	10.2
7/4	.4977	.4449	.5028	.3443	.3078	493.9 *c*	10.0
6/10	.4367	.3298	.3367	.3958	.2990	493.5 *c*	23.0
6/8	.4131	.3303	.3499	.3778	.3021	493.3 *c*	18.3
6/6	.3824	.3225	.3543	.3610	.3045	493.8 *c*	14.3
6/4	.3606	.3213	.3593	.3463	.3086	493.5 *c*	10.0
5/10	.3340	.2263	.2201	.4280	.2900	493.7 *c*	32.8
5/8	.3095	.2229	.2189	.4120	.2967	493.3 *c*	27.0
5/6	.2887	.2256	.2323	.3867	.3022	493.2 *c*	20.0
5/4	.2554	.2193	.2331	.3608	.3098	492.7 *c*	12.2
4/10	.2178	.1408	.1435	.4338	.2804	494.4 *c*	37.5
4/8	.1964	.1345	.1429	.4145	.2839	494.7 *c*	32.6
4/6	.1806	.1329	.1407	.3976	.2926	494.2 *c*	26.0
4/4	.1587	.1317	.1453	.3642	.3023	494.0 *c*	15.8
3/10	.1293	.0777	.0891	.4367	.2624	496.1 *c*	45.3
3/8	.1111	.0717	.0796	.4234	.2732	495.5 *c*	38.5
3/6	.1030	.0730	.0804	.4017	.2847	495.1 *c*	30.0
3/4	.0860	.0685	.0779	.3701	.2948	495.3 *c*	20.0
2/6	.0648	.0446	.0551	.3939	.2711	497.5 *c*	33.8
2/4	.0612	.0458	.0569	.3734	.2794	498.1 *c*	26.8

TABLE I.—*Continued.*

Munsell Notation	X	Y	Z	x	y	Dominant Wave-Length	Excitation Purity
RP 8/6	0.6784	0.6304	0.7605	0.3278	0.3046	499.0 *c*	8.1
8/4	.6628	.6272	.7670	.3222	.3049	502.7 *c*	7.0
8/2	.6767	.6583	.7726	.3211	.3123	495.0 *c*	3.7
7/8	.5529	.4878	.5982	.3374	.2976	499.4 *c*	12.7
7/6	.5492	.4923	.5913	.3364	.3015	497.8 *c*	11.0
7/4	.5311	.4922	.5872	.3298	.3056	497.8 *c*	8.0
7/2	.4993	.4795	.5681	.3228	.3100	497.1 *c*	5.0
6/10	.4450	.3415	.4391	.3631	.2786	499.7 *c*	25.2
6/8	.4198	.3361	.4234	.3560	.2850	499.4 *c*	21.2
6/6	.3923	.3322	.4129	.3449	.2921	499.5 *c*	16.2
6/4	.3670	.3268	.4034	.3345	.2978	500.3 *c*	12.1
6/2	.3409	.3238	.3927	.3224	.3062	501.0 *c*	6.4
5/10	.3296	.2315	.3017	.3820	.2683	499.1 *c*	32.7
5/8	.3034	.2271	.2984	.3660	.2740	500.3 *c*	27.5
5/6	.2718	.2161	.2781	.3548	.2821	500.4 *c*	22.1
5/4	.2491	.2131	.2644	.3428	.2933	499.5 *c*	15.3
5/2	.2327	.2169	.2640	.3261	.3040	500.5 *c*	8.0
4/12	.2255	.1422	.2112	.3895	.2456	502.1 *c*	43.4
4/10	.2234	.1462	.2144	.3825	.2503	502.3 *c*	40.0
4/8	.2021	.1418	.1983	.3727	.2615	501.9 *c*	33.7
4/6	.1872	.1404	.1941	.3585	.2698	503.1 *c*	27.8
4/4	.1693	.1395	.1835	.3439	.2834	503.2 *c*	19.6
4/2	.1573	.1444	.1810	.3259	.2992	504.8 *c*	9.9
3/10	.1317	.0811	.1219	.3935	.2423	502.0 *c*	45.3
3/8	.1123	.0744	.1070	.3824	.2533	501.8 *c*	38.8
3/6	.0996	.0706	.0998	.3689	.2615	502.6 *c*	33.0
RP 3/4	.0902	.0710	.0956	.3512	.2765	503.0 *c*	23.8
3/2	.0802	.0707	.0905	.3322	.2929	504.6 *c*	13.7
2/6	.0663	.0447	.0730	.3603	.2429	510.0 *c*	39.0
2/4	.0594	.0430	.0638	.3574	.2587	506.8 *c*	32.1
2/2	.0473	.0388	.0512	.3445	.2826	503.5 *c*	20.0
10 P 8/4	.6610	.6266	.8387	.3109	.2947	549.7 *c*	8.9
7/8	.5460	.4755	.6842	.3201	.2788	534.4 *c*	17.0
7/6	.5215	.4698	.6441	.3189	.2873	530.3 *c*	13.3
7/4	.5107	.4690	.6248	.3183	.2923	528.7 *c*	11.2
6/8	.4120	.3288	.5393	.3218	.2569	539.2 *c*	26.0
6/6	.3949	.3348	.5094	.3187	.2702	539.8 *c*	20.1
6/4	.3747	.3313	.4670	.3194	.2824	533.0 *c*	15.3
5/10	.3215	.2255	.4138	.3346	.2347	531.3 *c*	37.4
5/8	.2919	.2145	.3674	.3341	.2455	528.4 *c*	33.0
5/6	.2724	.2152	.3388	.3296	.2604	533.5 *c*	25.2
5/4	.2534	.2164	.3118	.3242	.2769	527.3 *c*	18.5
4/10	.2048	.1336	.2772	.3327	.2170	537.0 *c*	44.1
4/8	.2015	.1434	.2691	.3282	.2336	537.5 *c*	36.7
4/6	.1831	.1407	.2364	.3268	.2512	534.6 *c*	29.2
4/4	.1723	.1438	.2193	.3218	.2686	535.7 *c*	21.3
3/10	.1157	.0722	.1727	.3209	.2022	546.0 *c*	48.7
3/8	.1126	.0754	.1606	.3230	.2163	543.9 *c*	42.7
3/6	.1039	.0764	.1481	.3164	.2326	547.0 *c*	34.8
3/4	.0953	.0739	.1282	.3204	.2485	542.3 *c*	29.2
2/6	.0610	.0416	.0904	.3161	.2155	547.9 *c*	41.6
2/4	.0561	.0411	.0828	.3117	.2283	550.1 *c*	35.6

Table I.—*Continued.*

Munsell Notation	X	Y	Z	x	y	Dominant Wave-Length	Excitation Purity
P 8/4	0.6342	0.5943	0.9016	0.2977	0.2790	564.4 *c*	12.6
8/2	.6071	.5956	.7875	.3050	.2993	563.0 *c*	5.9
7/6	.4934	.4325	.7520	.2941	.2578	562.4 *c*	20.5
7/4	.4756	.4390	.6802	.2982	.2753	563.0 *c*	14.3
7/2	.4603	.4468	.6123	.3029	.2941	564.2 *c*	7.5
6/8	.3818	.3119	.6382	.2867	.2342	562.8 *c*	28.6
6/6	.3681	.3170	.5833	.2902	.2499	563.1 *c*	23.1
6/4	.3572	.3261	.5291	.2946	.2690	564.0 *c*	16.0
6/2	.3367	.3211	.4607	.3010	.2871	564.0 *c*	10.0
5/10	.2722	.2005	.4957	.2811	.2070	562.0 *c*	38.5
5/8	.2571	.2002	.4463	.2845	.2216	562.3 *c*	33.4
5/6	.2345	.1944	.3800	.2899	.2403	562.1 *c*	26.8
5/4	.2225	.1967	.3386	.2936	.2596	563.0 *c*	19.8
5/2	.2145	.2034	.2934	.3016	.2860	562.7 *c*	10.5
4/12	.1944	.1247	.3753	.2800	.1796	560.5 *c*	49.4
4/10	.1766	.1261	.3250	.2813	.2009	561.5 *c*	41.0
4/8	.1649	.1241	.2874	.2861	.2153	561.2 *c*	36.1
4/6	.1573	.1280	.2581	.2895	.2356	561.9 *c*	28.7
4/4	.1503	.1301	.2262	.2967	.2568	560.9 *c*	21.3
4/2	.1401	.1311	.1929	.3019	.2825	561.5 *c*	12.0
3/10	.1297	.0783	.2646	.2744	.1657	561.1 *c*	54.1
P 3/8	.1131	.0779	.2130	.2800	.1928	561.4 *c*	44.0
3/6	.1023	.0773	.1804	.2842	.2147	561.8 *c*	36.1
3/4	.0918	.0745	.1507	.2896	.2350	561.7 *c*	29.0
3/2	.0856	.0778	.1226	.2993	.2720	561.5 *c*	15.8
2/6	.0530	.0378	.0979	.2809	.2003	561.7 *c*	41.2
2/4	.0505	.0382	.0850	.2907	.2199	559.9 *c*	35.0
2/2	.0451	.0378	.0687	.2975	.2493	559.4 *c*	24.6
Neutral							
1	.0196	.0200	.0236	.3101	.3165	—	—
2	.0355	.0360	.0425	.3114	.3158	497.2 *c*	0.3
3	.0697	.0710	.0840	.3102	.3160	—	—
4	.1259	.1280	.1525	.3098	.3150	400.0	0.6
5	.1896	.1933	.2306	.3090	.3151	479.0	0.6
6	.2976	.3039	.3644	.3081	.3146	484.5	1.0
7	.4384	.4486	.5275	.3099	.3171	492.0	3.3
8	.5521	.5658	.6543	.3115	.3193	569.0	1.3
9	.7196	.7379	.8388	.3134	.3213	572.2	2.2
9.4	.8247	.8447	.9489	.3150	.3226	573.0	3.0
9.6	.8906	.9121	1.0466	.3126	.3201	571.0	1.5

Preliminary Report of the O.S.A. Subcommittee on the Spacing of the Munsell Colors

SIDNEY M. NEWHALL*
Johns Hopkins University, Baltimore, Maryland

The spacing problem consists in the detection and correction of errors of allocation in surface-color space of the regular 1929 Munsell samples. This amounts to the adjustment of imperfections in a real chromatic skeleton of 400 units so that it will more properly fit into an ideal chromatic body. For the last five years various observers have been making visual estimates of the color spacings and the accumulated data have been summarized and are presented herewith in tabular form. These data will provide a psychological basis for defining smooth contours of Munsell hue, value, and chroma in terms of the 1931 I.C.I. colorimetric coordinate system. The plan is to present those contours in the final report. The present report includes charts of a preliminary smoothing of chroma based on the earlier visual estimates.

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INTRODUCTION

THE familiar principle of specifying color by spatial location underlies the design of various color solids (10–14, 34, 39, 43–45, 53, 63, 64). The ideal of this investigation is a psychological color-solid in which cylindrical coordinates of Euclidean space represent the principal attributes of colors perceived as belonging to surfaces and equal linear extents represent equal sense-distances. Along the color scales there is variation in but one attribute at a time, and the scalar graduations are perceptually uniform. Furthermore, any horizontal section through the solid would define a plane of constant lightness (Munsell value) while any vertical plane originating at the achromatic axis would be a plane of constant hue. Finally, a cylindrical section concentric with the axis would constitute a surface of constant saturation (Munsell chroma). Just how closely this psychological ideal can be realized in either theory or practice still remains somewhat conjectural.

One question arises at once. A marked influence of surrounding-field reflectance on surface-color perception has long been evident (1, 4, 25–28, 37, 58, 65, 71, p. 546; 82). Since the color perceived as belonging to a surface may vary with the background, there is the question of what ground to employ. Present views suggest grounds similar to samples for ideal viewing but continual changes in observational conditions seemed neither feasible nor desirable in the present study. Therefore, the subcommittee decided to have all observations made against three approximately neutral grounds of high, low, and intermediate reflectance (white, black and gray), and to decide later, by reference to the comparative data thus secured, what to do regarding this important problem of specifying an ideal or standard viewing ground.

The principal practical advantage of defining

* Chairman of the Subcommittee. This subcommittee is a part of the O.S.A. committee on colorimetry, L. A. Jones, Chairman.

a close approximation to the psychological solid is that the resulting scales facilitate adequate interpolation among the adjacent members of a finite system of samples. For if the chromatic continua are equi-stepped variations in but one attribute at a time, an unknown color can be evaluated quite definitely and quickly by assigning to it the notational equivalent of its appropriate position in the color system (39, p. 362). In the absence of such psychological scales, on the contrary, a relatively haphazard and laborious succession of comparisons must be made. That is because close interpolation is then scarcely possible, and the system must include a far larger assortment of samples to permit the employment of the alternative method of evaluating the unknown by matching or approximately matching it.

A further practical advantage of uniform color-scales lies in the convenient assignment of color tolerances. Of course, "noticeability of color variations" is not the only important determinant of color tolerances (46, p. 416). On the other hand, the general population considers that visual appearance or "how it looks" is very often crucial, and so perceptual tolerances are correspondingly important for many scientific and industrial colorists (5, 9, 27, 35, 36, 39, 57, 59).

Spacing Problem and Procedure

Historical note

Long recognized as the outstanding practical device for color specification by pigmented-surface standards (38), the Munsell system of color (49, 52–54) has become the subject of several other recent studies (15, 16, 23, 61). As early as 1919, however, Priest, Gibson, and others were already making constructive proposals for its improvement with special emphasis on scientific specification and the value scale (68) of the Atlas colors (54). Subsequently, A. E. O. Munsell, Godlove, and Sloan markedly improved the neutral-scale value spacings (18, 50). When the original report of the Glenn-Killian data (16) was circulated in 1935, numerous irregularities became apparent. There were general irregularities which could be referred to the I.C.I. coordinate system in which the data were expressed, and there were local irregularities due to clerical or to measurement errors, as one might expect. A third class of irregularities could be ascribed to various field factors including spatial arrangement and background reflectance, but a fourth class seemed to be due to real errors in the Munsell samples themselves (49). Some of these irregularities are shown in Figs. 7 to 14, to be discussed later.

The idea of improving the Munsell system by visually smoothing it appears to have occurred independently to three people in 1935, *viz.*, H. P. Gage, Dorothy Nickerson, and W. B. VanArsdel. In 1936 there appeared a mimeographed statement by D. B. Judd and Dorothy Nickerson entitled the "Review of the spacing of the Munsell colors" (40), which not only pointed out the desirability of smoothing irregularities but also outlined procedure for reviewing the constant-value charts and recording the observers' estimates of the true notation for each sample. The procedural details employed in securing most of the present data will be described later. Suffice it to say here that the principal features were included in that original statement of 1936 and that the essential ratio method involved had been known as early as 1929 (73).

The smoothing process is designed, of course, to eliminate only those irregularities which represent real departures from psychological regularity in the samples themselves. Thus sweeping irregularities in the coordinate system of reference can be allowed to remain as a part of the normal baseline. Most of the clerical errors can be corrected by checking. Irregularities due to field factors can be controlled, in part at least, by the systematic employment of masks and backgrounds of varied form and reflectance (Fig. 4). The residual should lie largely in the Munsell notations assigned to the individual samples, and it is the smoothing out of these individual-sample errors which constitutes the principal task of the subcommittee.

The subcommittee did not undertake to evolve a single scaling unit for the entire solid, or for any attributive dimension of it. As is well known, the Munsell scaling units for hue, value, and chroma are far from equivalent perceptually. The relation between these units is, and remains, roughly as follows: 1 value unit = 2 chroma units = 3 hue units (at /5 chroma) (59). Even were the three units equated at the /5 chroma level, the resultant probably would remain an unsuitable scaling unit for the solid as a whole. This is because the size of each unit seems to exhibit some tendency to vary from one part of the color solid to another (8, 12, 48, 66, 70). The best single scaling unit would seem to be some kind of equal-contrast unit like the National Bureau of Standards unit (36), but that is a consideration for the future. At present, it seems unwise to attempt any changes which would do away with the well-known and useful Munsell notation (52, 53).*

Incidentally, the spacing of the samples of nearly neutral colors on the constant-value charts of the *Book of Color* (49) is intentionally wider than that suggested by the psychological color solid; this distortion is a practical expedient to provide sufficient space for the inclusion of low-chroma samples.

As early as 1935, some chromatic smoothing was accomplished by Gage** and by VanArsdel.‡ The latter's analysis was confined to yellowish hues but showed also a connection between the Munsell samples and samples of maximum chromatic efficiency (23, 44, 45).

In the same year, the 1929 Munsell constant-value samples were plotted in three different colorimetric-coordinate systems, and five years later in a fourth system. Illustrative charts of given (5/ value) data plotted in these several systems of coordinates are presented as Fig. 1. The location corresponding to Munsell neutral five (N 5/) is indicated by the open circle near the center of each chart, and that corresponding to I.C.I. Illuminant *C* (22, 33) by the small triangle. Of course, the constant-hue loci are oriented differently in each chart. These trials were made with original samples, unadjusted by any visual smoothing, the object being to discover a coordinate system which would effect minimum distortion of the concentric circular spacing proper to constant chroma loci at the various Munsell value levels. Such a system would facilitate the smoothing operation, partly because a circle is easy to draw and partly because departures from a circle are easy to estimate.

The Glenn-Killian determinations (16) for value 5/ are shown in Fig. 1 plotted on the I.C.I. (x, y) diagram. Decentering and elliptoid forms of distortion are obviously present and they persist in varied amounts at the other value levels. The U.C.S. (35) chart shows the spacing, if anything, to be less uniform than in the I.C.I. chart. A great improvement is evidently effected by the use of Judd's modification of his U.C.S. system.* However, the fit was nearly optimum around value 5/ shown in Fig. 1 and there is considerable and increasing distortion toward the extreme value levels. The remaining diagram illustrates Adams' (2) adaptation of the I.C.I. system in which $X-Y$ is plotted against $Z-Y$.† This diagram yields the closest approximation to

* This notation is briefly described here for the convenience of any reader who does not happen to be familiar with it. In general the notation correlates with the coordinates of the surface-color solid described in the first paragraph of this paper. Thus, hue is indicated by angle about the neutral axis, value corresponds to distance above the base plane containing the point representing black, and chroma corresponds to distance from the neutral axis. A number and one or two letters indicate location of the given color in the hue circuit which is divided into 100 hue steps. Each of the 10 principal Munsell hues (R, YR, Y, GY, G, BG, B, PB, P, RP) may be accompanied by any number from 1 to 10 to indicate the lesser variations or steps in the circuit. The principal hues are understood to fall at positions indicated by the number 5, and it is conventional to omit this number in the hue notation. Any hue with a designation greater than 5 lies farther along in the above hue series (clockwise direction) while designations less than 5 indicate counter-clockwise departures from the principal hue. Thus, 9R is a yellowish red, for it departs from R (or 5R) by four hue steps in the direction of yellow-red (YR). On the other hand, 2R is a somewhat purplish red because it lies three steps in the counter-clockwise direction toward RP. Numbers ranging from 0 to 10 indicate location on the value scale. Thus, value 1/ indicates a near black, 5/ indicates middle gray, and 9/ a near white. The extreme values or ideal limits, 0 and 10, are not realized in practice. Numbers ranging upward toward theoretical limits (23) represent degrees of chroma. Upper limits in practice depend upon the availability of suitable pigments. Zero chroma means an achromatic or gray color in which hue is absent. In the complete notation of a color, the hue designation is given first, followed by a fractional form of which the numerator is the value designation and the denominator is the chroma designation. Thus, for instance, 7R 3/8 specifies a color which is predominantly red in hue with a minor yellow component, somewhat low in value, and only moderately high in chroma.

** Reported in a memorandum to D. Nickerson (1935).

‡ Reported to the Research Department of the Brown Company (1935).

* The transformation from Judd's U.C.S. system (R, G, B) to the modified system (R′, G′, B′):

$$R' = R - 0.2G + 1.6B$$
$$G' = 0.3R + 0.7G + 0.5B$$
$$B' = 1.5B$$

† After E. Q. Adams, from data received by D. Nickerson. The near-coincidence of points 10GY 5/6 and 10GY 5/8 appears to constitute a real peculiarity of this plot; at least, it is not due to error in plotting the Glenn-Killian data.

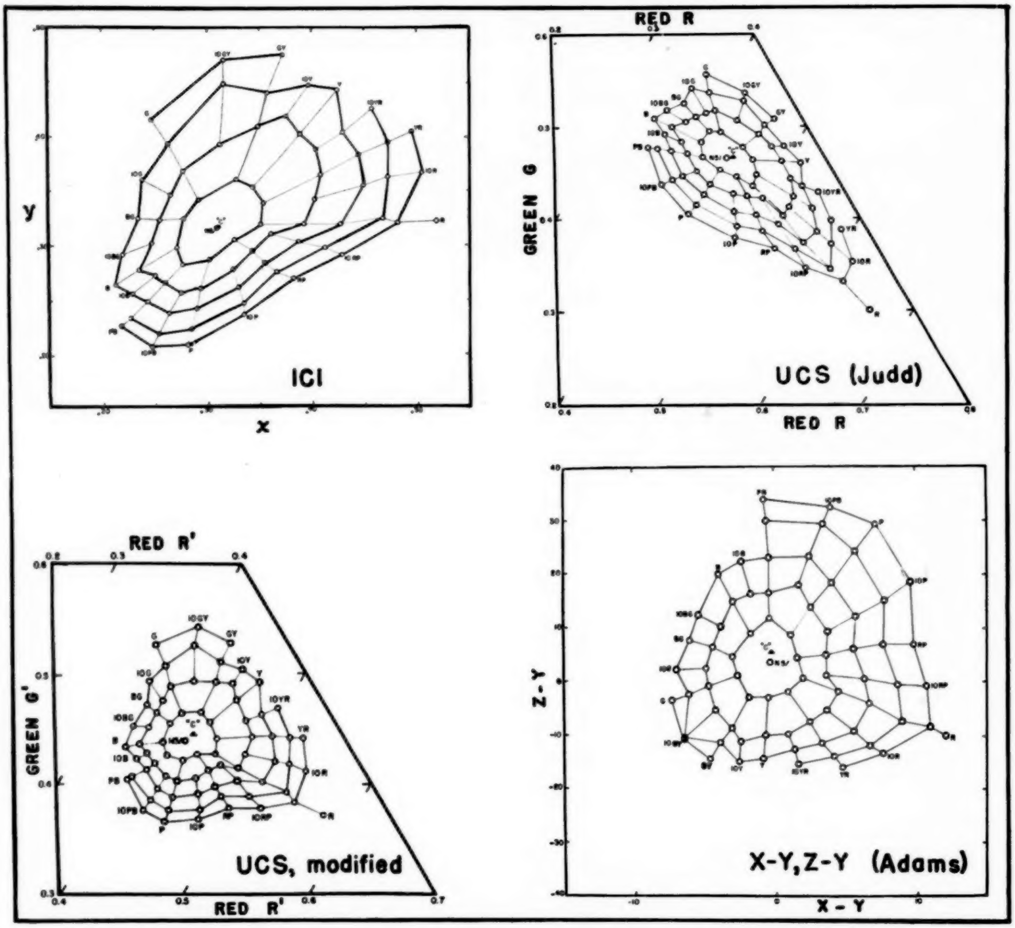

FIG. 1. The unsmoothed Glenn-Killian measurements of the 5/ value samples as plotted in four different colorimetric-coordinate systems.

the centered circularity of chroma loci expected of a uniform chromaticity-scale system, and it was given due consideration in choosing the system for the final smoothing of the data. It was rejected, however, because the neutral point changes rapidly with the value level and there would be practical difficulties in combining the determinations made at the different levels. The adapted U.C.S. system was rejected because it did not eliminate distortion, especially near black and white. The points in favor of the I.C.I. system are its standard character and wide acceptance. There is also the essential fact that like the other three systems, it does not present sharp irregularities which would be confused with those to be smoothed out of the Munsell data.

The present committee on the spacing of the Munsell colors was appointed by L. A. Jones in 1937 as a Subcommittee of the Colorimetry Committee of the Optical Society of America. The present personnel includes B. R. Bellamy, H. P. Gage, D. B. Judd, Dorothy Nickerson, W. B. VanArsdel, and S. M. Newhall.

Ratio method

The ratio method, which has been relied upon from the beginning in this survey, consists in the estimation by direct impression of the ratio of

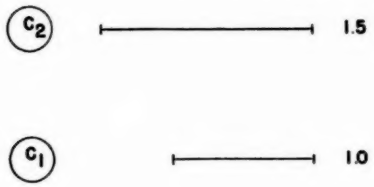

FIG. 2. Recording of estimates made by the simple ratio method.

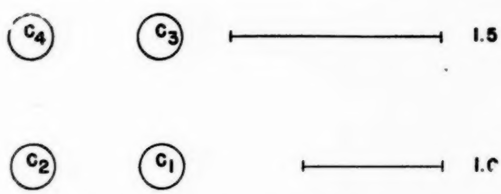

FIG. 3. Recording of estimates made by the difference ratio method.

supraliminal sense magnitudes or intervals (17, 19, 21, 47, 57, 72–78).* The one magnitude or interval is taken as standard and the ratio of the other to it is then estimated directly.

The two forms of this method are applicable to color problems and both were applied in the present review. The first form may be referred to as the simple ratio or R form and represented by the simple operational equation

$$(C_2/C_1)_A = R_A$$

in which C_1 represents the color perceived as belonging to the chosen standard; C_2, the color to be evaluated; R, the estimate of the ratio; and the subscript $_A$, the attribute with respect to which the estimate is made. Thus, the given color C_2 is judged equal to RC_1 with respect to $_A$. Suppose that C_1 and C_2 represent two surface-color perceptions and the observer's task were to estimate relative lightness. He would compare the two colors directly with each other and report a quantitative judgment concerning the fraction or multiple which the lightness of C_2 is of C_1. In case of surface-color perception, as when one views the Munsell samples, $_A$ may become either $_H$, $_S$ or $_L$, according to whether hue, saturation, or lightness is the attribute being estimated. According to the existing O.S.A. definitions (31, p. 213) hue, saturation, and lightness correspond closely to Munsell hue, chroma, and value.

The second, or difference ratio, method is designated by R' and represented by the analogous equation

$$(|C_4 - C_3| / |C_2 - C_1|) = R'_A$$

in which $|C_2 - C_1|$ is the perceived standard difference or interval, $|C_4 - C_3|$ is the difference to be evaluated, and R' is the estimate of the ratio of intervals with respect to $_A$, the particular aspect under estimate.

The observer records his estimate either by numbers or by linear extents which seem to him to be in the ratio of the sense magnitudes in question. Perhaps the easiest method is to adjust the relative positions of the samples themselves until the space ratio represents the sense ratio. A more generally practicable recording method, however, is graphically to indicate rather than actually to make, the representative space adjustment. Figure 2 suggests the application of graphic recording to the R form. The observer represents the attributive magnitude of C_1 by a line of convenient length. He then draws a second line, representing C_2, of such length relative to the first line that the ratio formed by the two lines is the same as the estimated ratio. Figure 3 shows the same kind of recording in case of the R' form of the ratio method. Here the one line is drawn to represent the sense difference or sense distance between C_2 and C_1, while the other line is so drawn that its length relative to the first will be the same as $C_4 - C_3$ relative to $C_2 - C_1$.

The difference-form (R') of estimate is more reliable because the perceptual unit is defined by its beginning point (C_1) and its end point (C_2), both presented to the observer during the estimate. The analytically simpler form (R) implies a beginning point corresponding to zero (zero lightness, or zero saturation), but no sample exemplifying this beginning point is present. Therefore greatest reliance was placed on estimates by the difference-form (R').

The use of the ratio method seems peculiarly

* Reference 57 contains a detailed discussion of the ratio method and its application to the spacing problem; and much of that material has been adapted and included in the present report. Figs. 2 and 3 of the earlier paper have been reproduced as Figs. 2 and 3 herein.

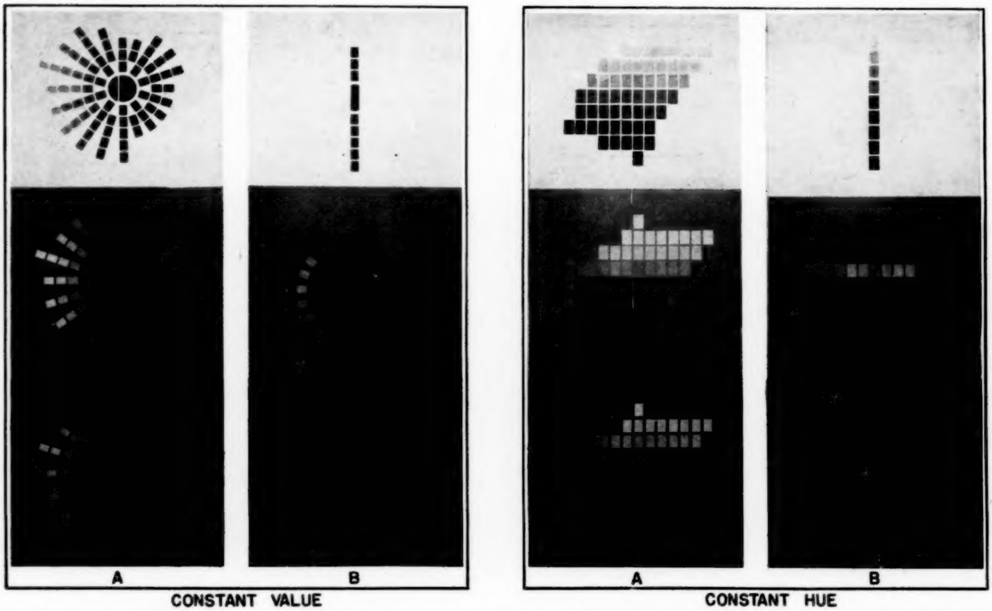

Fig. 4. Examples of Munsell constant-value charts and constant-hue charts mounted on white, gray, and black grounds; shown (A) without and (B) with several types of masks used to facilitate visual estimates by exposing simultaneously only samples designed to differ in a single attribute.

significant because, as pointed out by Judd,‡ it amounts to the direct application of the definitions of the attributes of color-perception. Until other methods are proved comparable, only the ratio method is strictly applicable. Then, too, precision psychophysical threshold methods of the traditional sort (20, p. 23) were not considered feasible, partly because of the great length of time required and partly because the inescapable preliminary problem of the equality of supraliminal magnitudes representing equal numbers of just noticeable differences still remains to be solved (5, p. 286; 20, p. 143).

Procedural details

The observers were instructed to use daylight or its equivalent, to illuminate the samples at 45°, and to view them along the perpendicular as recommended in 1931 by the International Commission on Illumination (33). They were also requested not to fixate a given sample for long but to keep the fixation relatively mobile; for preadaptation is an important factor (29, 37, 42, 55, 71, p. 544). They made visual estimates of hue, lightness, and saturation on the Munsell constant-value and constant-hue charts. All of these charts were mounted and viewed on three different, approximately neutral grounds of relatively high, medium, and low reflectance, respectively; see Fig. 4. The I.C.I. tristimulus specifications (33, 38) of these white, gray, and black (matt cardboard) surfaces were determined under artificial daylight illumination approximating 6500°K.** The daylight apparent reflectance relative to magnesium oxide (Y) and the trilinear coordinates (x, y) were, respectively, as follows: white, $Y=0.852$, $x=0.3204$, $y=0.3292$; gray, $Y=0.253$, $x=0.3140$, $y=0.3244$; black, $Y=0.040$, $x=0.307$, $y=0.312$. Masks of the same materials, Fig. 4, were made and used to expose separately the various rows, columns, and arcs of samples designed to yield colors constant in two attributes and regularly varying in the third. These grounds and masks were of some service in controlling the psychological phenom-

‡ From an unpublished manuscript entitled "Color measurement and the just noticeable difference," (March 30, 1935).

** Nat. Bur. Stand. test No. 81810 (1937).

ena of contrast and end-effect (24–28, 37, 71, p. 546; 79, 82, 85, p. 567) due to field factors aforementioned. The manner of using the masks is indicated later.

The *R* form of the ratio method here involved the direct comparison of several samples with respect to a given attribute while the *R′* or difference-ratio form called for the comparison of the attributive differences between samples. Thus, in the one case the observer asked himself, "How much does each of these colors differ in this attribute from my chosen standard?" And in the other case, "How much do the attributive intervals between these various pairs of adjacent colors differ from my standard interval?" In both cases, the estimates of the departures from the standards were recorded in vectorial notation. The record forms used by the observers are shown in Fig. 5 and are similar in shape and pattern to the color charts themselves.

The observers were instructed to represent their estimates of the kinds and degrees of departure by drawing vectors of appropriate directions and proportionate lengths. Outlines of the prescribed procedure for estimating hue, saturation and lightness differences are as follows.

Hue differences were estimated from the constant-value charts. The series of samples in a given radius of constant Munsell hue was isolated by masking the remainder of the chart, and the series was then examined for variations in hue. If such were observed, the effort was made to estimate a representative or average hue and indicate departures therefrom by tangential vector notation (*R′* form). The same procedure was followed in turn for each radius of constant Munsell hue on the chart. Next, the hue spacings of the hue radii considered as wholes were examined, and if the hue differences seemed unequal, a tangential vector of length proportional to the estimated adjustment required was affixed to the end of the radius (*R′* form).

Saturation differences, like hue differences, were estimated from the constant-value charts. The samples in a given constant-chroma ring were masked off, and the subject looked them over in an effort to select a sample of representative chroma to serve as standard. Any sample

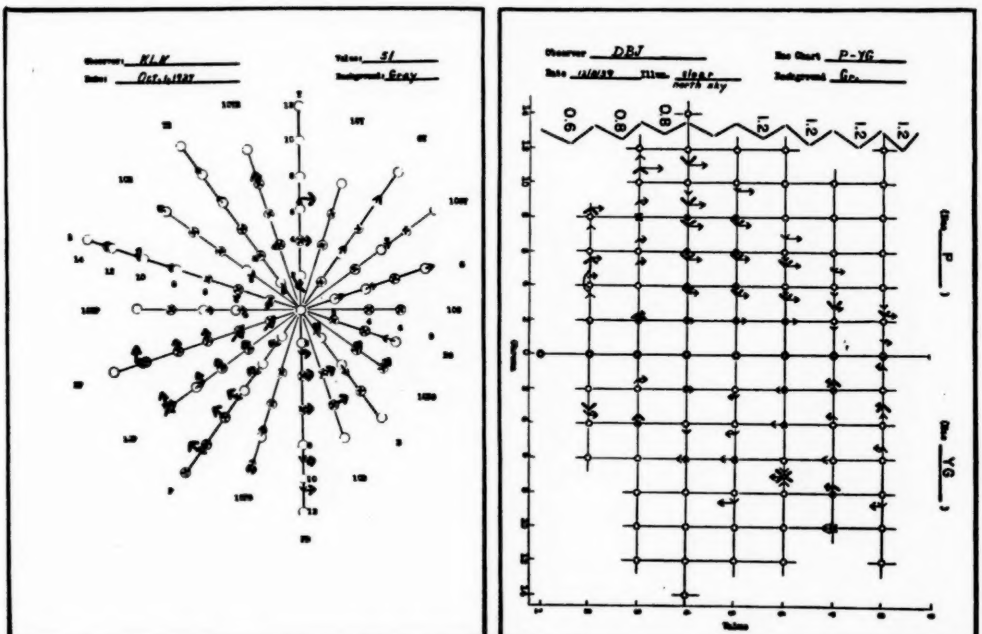

FIG. 5. Examples of original forms for recording in vectorial notation visual estimates from a constant-value chart (left), and from a constant-hue chart (right).

which seemed to differ in chroma from the standard was then evaluated in terms of it, and a suitable radial vector was drawn to indicate the displacement (*R* form). Subsequently, the masks were removed, and the radii of constant Munsell hue were examined for irregularities in the size of the saturation steps between adjacent colors. After selection of a representative saturation step, each of the other steps could be evaluated in terms of it (*R′* form).

Saturation differences were estimated again, this time from the constant-hue charts. A constant-chroma column was masked off, and the *R* form applied. After each column had been so studied, the masks were removed, and the equality of the chroma steps checked by the *R′* form. Incidentally, most subjects found the applications of the *R′* form to saturation the most difficult part of the entire procedure.

Lightness differences were also estimated from the constant-hue charts. Rows of constant Munsell value were masked off and deviations in lightness of each sample from the average lightness of the row were evaluated by the *R* form, after which the masks were removed, and the size of the lightness difference between successive constant-value rows was estimated by the *R′* procedure. These estimates were recorded numerically as the ratio of the actual size to the average size of value step.

It will be noted that two color attributes were estimated from both types of chart, and it frequently happened that two vectors, each for a different attribute, had to be recorded for a single sample. If, for a sample on a constant-value chart, a radial vector had been drawn already to indicate a chroma deviation, the tangential vector to indicate a hue deviation would be started from the end or arrow-head of the radial vector. Thus the resultant of the two vectors would be indicated by the position of the final arrow-head, and would represent the difference between the 1929 Munsell notation of the sample and that estimated by the observer to indicate the color. In case of constant-hue charts an analogous combination of horizontal and vertical vectors would be required to record combined saturation and lightness deviations.

Complications

The unusual difficulties of the judgmental situation justify some account of the special problems reported by the observers.

(A) There was the problem of complex chromatic comparisons forcing, as it does, the abstraction of the attribute to be estimated. Attributive abstraction is peculiarly difficult in cases of strong association; for instance, when saturation is the judged attribute, hue being constant and lightness variable, there is a strong tendency to estimate darker colors as of higher saturation. This relation is often found in everyday life. A familiar related problem is that of comparing the lightness of colors differing in hue. A similar difficulty, especially for unsophisticated subjects, is that of comparing chromatic and achromatic colors in respect to lightness. The untrained observer usually perceives chromatic samples as lighter relative to achromatic samples than does the trained observer. Inspection of data from the constant-hue charts revealed the interesting fact that the vectorial lightness indications for the chromatic samples were rarely downward. The indication was usually that the chromatic sample seemed too light relative to the achromatic sample of the same Munsell value.

(B) Observers making estimates of saturation difference by the *R′* method reported greater facility when all colors departed definitely from neutral gray than when one of the colors was perceived as gray. The trouble seemed to be that a first step extending from zero saturation appeared as a qualitative step and so tended to give the impression of an infinite quantitative step. The second step was, on the other hand, a definitely limited quantitative step. Seven of the observers made a written memorandum to the effect that the first step was or seemed definitely too great.

Possibly related to this was a certain change of attitude correlated with presence or absence of gray. When observing saturation differences from gray some observers reported that they "just look for any difference" whereas between two chromatic colors of the same hue they think more definitely in terms of saturation. Such a change of attitude might be expected to occur on the basis of least effort. Looking for a mere difference would be easier when the detection of saturation was difficult, whereas looking for a saturation difference would be easier when both colors are saturated to an obvious degree.

(C) The long recognized difficulties of spatial and temporal separation of compared samples were evidently present in this study where widely separated parts of a chart so often must be compared. Contrast and end-effects due to proximity of samples and terminal positions have already been mentioned.

(D) Finally, the visual estimates of the colors were all made with the samples in the regular positions and patterns of the Munsell system. This condition in itself would serve as a resistance to change. The untrained subject, or even the trained subject in a doubtful case, would tend to be affected or guided by the system (56); therefore, slight adjustments were probably not made and larger adjustments may not have been great enough. Still, this resistance to change might be considered advantageous in the sense of producing conservative estimates of the revisions required.

In the face of all of these difficulties what did the observers actually do? Only the more typical tendencies can be mentioned here. (a) The series of colors, or color differences, to be judged was first surveyed as a whole and the observer essayed a decision with respect to rank order for the attribute in question. Often no progressive graduation was found; and instead of arriving at an order, the observer was able to identify a few extreme colors and a number which seemed about equal with respect to the attribute in question. (b) After some such preliminary survey, the observer might proceed to the assignment of vectors. A common practice was to draw in vectors representing the more extreme displacements first, and then, partly on the basis of those, to fill in the shorter vectors indicating the lesser irregularities. (c) There was the tendency to "carry" a standard subjectively even though some particular perceptual standard had been chosen. Occasionally, the subject might refer to the standard sample for verification, but would often make many comparisons without doing so.

This "absolute" procedure (20, p. 205; 84) and the ranking procedure (20, p. 244; 81) mentioned above were both hit upon by many subjects without instruction, probably because they facilitated the subject's difficult task. Certainly it is easier to decide which of two sensory magnitudes is greater than to estimate how much greater; and it is sometimes easier when making numerous comparisons to carry a subjective standard than to refer back each time to a perceptual one.

Evidently, it would be a mistake to conclude that the ratio method has been applied to the spacing problem in anything like pure form. The actual procedure was so complex that if the ratio method were not pointed out it might pass unrecognized. An advantage of the complicated instructions is that they call for so thorough an examination of the charts that marked irregularities in spacing can scarcely be overlooked.

Observers

Since there were 7 constant-value charts and 20 constant-hue charts used in the survey, and since each of these 27 charts was prepared with the three backgrounds, a total of 81 charts were to be examined, each chart requiring about 100 judgments. The task was exacting, and those observers who returned complete sets of data from observation of the constant-value charts, the constant-hue charts, or both, usually took a year or more to do so. Without substantial contributions of this character, the successful completion of the investigation would have been impossible.

Data were received from forty-one subjects. Complete or nearly complete returns were secured from the following: W. H. Beck, Marion Belknap, B. R. Bellamy, Elizabeth Burris-Meyer, Claire Dimmick, F. L. Dimmick, Dean Farnsworth, Loraine Fawcett, F. A. Geldard, W. C. Granville, Paul Henry, M. M. Jackson, D. B. Judd, K. L. Kelly, D. L. MacAdam, S. M. Newhall, Dorothy Nickerson, R. W. Russell, Walter Scott, L. L. Sloan, W. T. Spry, Samuel Talbot, Irving Taylor, J. Weitz. Partial or supplementary observations which were summarized with the others were furnished by the following: Genevieve Becker, H. P. Gage, S. R. Gilmore, I. H. Godlove, G. W. Haupt, R. S. Hunter, H. E. Hussong, L. A. Jones, E. M. Lowry, Alexander Murray, P. Nutting, M. R. Paul, F. H. Rahr, R. H. Sawyer, Albert Smith, W. B. VanArsdel, K. S. Weaver.

All subjects were similar in that they had some interest in color and passed the Ishihara test for color blindness (30),* but they differed widely in respect to the nature of their color interest and the character of their special training. In general they may be classified as follows: professional colorists in science or industry, 10; amateur or apprentice colorists, 8; professional physicists specialized or interested in color, 5; professional psychologists specially interested in color, 5; psychology students, 5; business executives with a broad or commercial interest in color, 3; specialists in dyes and pigments, 2; specialists in physiological optics, 2; graphic arts research, 1. There is much overlapping and this classification, like any other, is rather arbitrary.

The task of making visual estimates of colors and color differences is obviously a psychological one and the fact that one of our psychological observers, F. L. Dimmick, was opposed to the procedure as too demanding is duly noted. It should be noted, further, that the psychologists as a group were inevitably aware of numerous sources of error, technical imperfections, and general observational difficulty in the procedure. The various specific difficulties which seemed of any essential importance to the writer have been revealed in the preceding section on "complications." Most of them appeared to bother the nonpsychological observers relatively little or not at all. But one of these, D. L. MacAdam, also objected on psychological grounds. The subcommittee is grateful to both of these subjects for carrying through their series of observations in spite of their objections.

The advantages of having such a diverse group of subjects are; first, that participation by a wide representation of the color-interested population yields correspondingly representative results and, second, tends toward wide application of results.

A disadvantage of the fact that the data represent a heterogeneous sample of color-interested individuals is that they may not prove wholly satisfactory to any particular individual in the group. Lack of psychological training in scientific observation will tend to make the group results incorrect for the specialized sense-psychologist whose judgments in general might be assigned a higher validity than those of anyone else. Other observers would be more susceptible to the various recognized sources of error indicated in the section on "complications." Some of the sources of error are not even recognized by most of the untrained observers. These errors undoubtedly affect the results in ways not intended by the observers, but, on the other hand, they show various systematic tendencies which should correspond to the way the Munsell samples look to them. An example of the latter is the tendency to see chromatic colors as lighter than does the more experienced observer. As already indicated, there is something to be said for the view that what is really wanted here is a system of color which will seem right to the bulk of the population which will use it. Probably this population would never contain more than a minority who were specially trained in technical color observation.

A desirable later step, perhaps, would be to produce a surface-color solid which would be as correct as the most rigorous technical training could make it. In the meantime, however, we shall hope to make some comparisons between results secured from sense-psychologists and conscientious colorists; possibly the differences in their results will not prove to be intolerably large after all.

Visual Data and Computation

Averaging the estimates

Representative visual determinations were computed for the hue, value, and chroma of each of the standard Munsell colors as perceived against each of the three experimental grounds. Each of these determinations is an average of the individual estimates of the participating observers. The averaging procedure included two principal steps: (a) summarization of all of the available data, and (b) computation from the summary of the arithmetical means of hue, value, and chroma. A detailed description of these two principal steps is given below.

(a) The original vectorial records entered by the observers in the data sheets, of the form already illustrated in Fig. 5, were summarized on sheets of the form illustrated in Fig. 6. In this particular form, which was used in conjunction with the constant-value charts, the hori-

* A limited number of observations were made by an individual known to be deuteranopic, and these are available for reference.

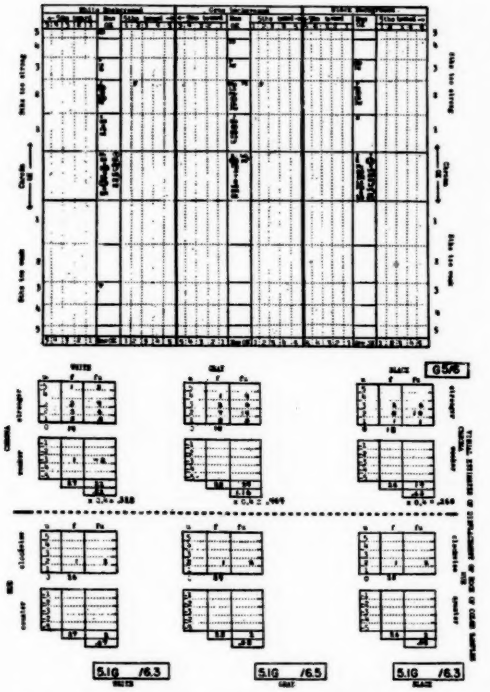

FIG. 6. *Upper.* Summarized visual estimates of hue and chroma of a particular Munsell sample (G 5/6) as presented on the three grounds. *Lower.* The corresponding numerical frequencies and averages.

zontal dimension represents hue while the perpendicular dimension represents chroma. The dimensions of a similar form used with the constant-hue charts represent value and chroma. On these forms each observer's estimate of the deviations of the particular color in respect to two of the attributes in question have been recorded by inserting his initials in the appropriate place. A total of 800 record sheets were required to summarize the color judgments, roughly three million in number.

The summarization forms are so similar that only the form for use with the data from the constant-value charts need be described in detail. Each vertical third contains data secured from the observations against a different background. In any third, entries falling in the central vertical column represent judgments that the Munsell hue notation is correct, while entries in parallel columns to the left or right represent, respectively, estimates of hue deviations in the counter-clockwise or clockwise direction around the hue circle. The recording unit of estimate is one Munsell hue-step. Similarly, the middle horizontal column represents the judgment that the Munsell chroma notation is correct, while the parallel columns above and below include respective estimates of "too strong" and "too weak." The recorder's unit of estimate is here 0.4 chroma-step. Of course, entries falling in the central rectangle, formed by the intersection of the central columns, represent judgments of correctness for both attributes. Preliminary estimates (encircled initials) by the *R* method, and final or check estimates (unencircled initials) by the *R'* method, were made on each of the three grounds. Consequently the initials of a given observer usually appear several times on the summary sheet for a given color. Inspection of Fig. 6 shows at once that the particular color sample, G 5/6, was judged on the average to have a chroma higher than /6 and hue corresponding closely to the Munsell notation, regardless of background.*

The summarization process varied somewhat with the attribute. In case of hue, it will be recalled, the final instructions called for an unmasked inspection of the general spacing of the several hue radii in the constant-value charts, and the assignment of tangential vectors when adjacent hue radii, considered as wholes, seemed too close together or too far apart. The hue-shifts represented by such general radial adjustments were individually added to the results of the preliminary hue adjustments of the colors concerned. Incidentally, it may be noted, that only a minority of the subjects made any general adjustments.

In case of value, an analogous type of treatment was required. The instructions had called for an unmasked inspection of the spacings of the successive value rows in the constant-hue charts, and the indication of departures from perceptual uniformity by direct numerical estimates in terms of the standard value-step unit. The given observer estimated the eight spacings between values 1/ and 9/, and the results were added to his preliminary value estimates. If the

* These data were not complete and checked when Fig. 6 was made; and they differ (insignificantly) from the correct figures which are presented in Table II.

TABLE I. *Average value determinations derived from the estimates of general value spacing, exclusive of the preliminary estimates. The observations were made for samples of each value on white, gray, and black grounds.*

Munsell Hue	Munsell Value 2/			3/			4/			5/			6/			7/			8/		
	Wh	Gr	Bl	Wh	Gr	Bl	Wh	Gr	Bl	Wh	Gr	Bl	Wh	Gr	Bl	Wh	Gr	Bl	Wh	Gr	Bl
R	1.8	1.8	2.3	2.8	2.8	3.7	3.8	3.8	4.8	4.8	4.7	5.6	5.9	6.2	6.6	6.9	7.2	7.4	8.0	8.1	8.2
10R	1.7	1.7	2.1	2.6	2.7	3.4	3.6	3.7	4.6	4.5	4.7	5.5	5.6	6.1	6.5	6.7	7.3	7.4	7.8	8.1	8.2
YR	1.7	1.7	2.2	2.6	2.7	3.6	3.6	3.6	4.7	4.5	4.6	5.6	5.6	6.0	6.6	6.7	7.2	7.5	7.8	8.1	8.3
10YR	1.8	1.8	2.2	2.8	2.8	3.6	3.8	3.6	4.7	4.7	4.7	5.6	5.7	6.2	6.5	6.7	7.3	7.4	7.9	8.1	8.2
Y	1.7	1.8	2.3	2.6	2.6	3.6	3.7	3.6	4.8	4.6	4.7	5.7	5.7	6.1	6.6	6.8	7.2	7.4	7.9	8.1	8.2
10Y	1.7	1.7	2.2	2.7	2.7	3.5	3.6	3.6	4.8	4.6	4.6	5.7	5.6	6.1	6.6	6.7	7.2	7.4	7.9	8.1	8.2
GY	1.7	1.7	2.2	2.7	2.7	3.7	3.7	3.5	4.8	4.6	4.5	5.7	5.7	6.0	6.7	6.8	7.2	7.5	7.9	8.1	8.2
10GY	1.7	1.8	2.2	2.6	2.7	3.7	3.6	3.7	4.8	4.6	4.7	5.7	5.6	6.1	6.6	6.7	7.3	7.4	7.8	8.2	8.2
G	1.8	1.8	2.2	2.7	2.7	3.7	3.6	3.7	4.9	4.6	4.6	5.7	5.6	6.1	6.7	6.7	7.3	7.6	7.8	8.1	8.3
10G	1.7	1.7	2.2	2.7	2.6	3.5	3.7	3.6	4.7	4.6	4.6	5.6	5.7	6.1	6.6	6.7	7.2	7.5	7.8	8.1	8.2
BG	1.8	1.8	2.3	2.8	2.8	3.8	3.8	3.7	4.8	4.8	4.8	5.6	5.8	6.2	6.6	6.9	7.3	7.4	8.0	8.1	8.2
10BG	1.7	1.7	2.2	2.6	2.7	3.4	3.6	3.7	4.5	4.6	4.7	5.5	5.6	6.1	6.5	6.7	7.2	7.3	7.8	8.1	8.2
B	1.7	1.7	2.2	2.6	2.7	3.6	3.6	3.7	4.7	4.6	4.6	5.7	5.6	6.0	6.6	6.7	7.2	7.5	7.8	8.1	8.2
10B	1.8	1.8	2.2	2.8	2.8	3.6	3.8	3.6	4.7	4.7	4.6	5.6	5.7	6.1	6.5	6.8	7.2	7.4	7.9	8.1	8.2
PB	1.8	1.8	2.3	2.6	2.7	3.6	3.6	3.7	4.7	4.6	4.7	5.6	5.7	6.1	6.6	6.8	7.3	7.4	7.9	8.1	8.2
10PB	1.7	1.7	2.2	2.7	2.7	3.7	3.7	3.6	4.9	4.7	4.6	5.8	5.7	6.0	6.7	6.8	7.2	7.5	7.9	8.1	8.2
P	1.7	1.7	2.2	2.7	2.7	3.7	3.6	3.5	4.8	4.6	4.5	5.7	5.7	6.0	6.7	6.8	7.2	7.5	7.9	8.1	8.2
10P	1.7	1.8	2.2	2.6	2.7	3.8	3.6	3.7	4.8	4.6	4.7	5.7	5.6	6.2	6.6	6.6	7.4	7.5	7.8	8.2	8.2
RP	1.8	1.8	2.2	2.7	2.7	3.7	3.6	3.7	4.9	4.6	4.6	5.8	5.6	6.1	6.7	6.7	7.3	7.6	7.8	8.1	8.3
10RP	1.7	1.8	2.2	2.7	2.6	3.5	3.7	3.6	4.8	4.6	4.6	5.7	5.7	6.1	6.6	6.7	7.2	7.5	7.8	8.1	8.2
Average	1.7	1.7	2.2	2.7	2.7	3.6	3.7	3.6	4.8	4.6	4.6	5.7	5.7	6.1	6.6	6.7	7.2	7.5	7.9	8.1	8.2

spacing-estimates did not total eight, they were proportionally adjusted before application to the preliminary data.

All of the observers of the constant-hue charts made the general spacing-estimates just referred to, and these modified the preliminary value estimates so substantially that it seemed well to provide some means of recovering the preliminary adjustments in case they should ever be wanted separately. This can be accomplished easily by subtracting out the grosser effects of the final step. The necessary constants for this purpose are supplied in Table I. Munsell value is indicated in the top row across the table while in the several columns below are presented mean spacing estimates corresponding to sample-hue and background. To determine the magnitude of a preliminary adjustment, given the total estimate, all that is necessary is to find the difference between the total estimate recorded in Table II and the corresponding partial estimate in Table I. Thus, for instance, in the case of G 5/6 on the white ground, the total estimate is found in Table II to be 4.7; the corresponding figure for the final step in Table I is 4.6; and the difference, 0.1, represents the amount of the preliminary adjustment required. The averages for all hues given in the bottom row of Table I may be taken as approximate lightness estimates of the Munsell neutral samples.

Unlike hue and value, there was in the case of chroma no special problem in arriving at the summarized estimates, but only a simple averaging operation which will be mentioned presently.

(b) The other principal step in the averaging procedure was to enter the summarized final estimates (unencircled initials) as numerical frequencies in averaging sheets of the form shown at the bottom of Fig. 6. The arithmetical means† of the estimates of the given color on

† Often the distributions proved to be violently skewed, so the question arose as to the most appropriate central representation to employ. Were the median chosen there would be less weighting of the extreme cases. On the other hand, there is some reason to believe that the extreme cases should be weighted. The reason is that there is a tendency to make "O.K." judgments (estimates of zero displacement) unless there is somewhat clear evidence that displacement should be indicated. As a result one may reasonably suppose that the mode and median fall in the "O.K." division more frequently than they should. Displacement

each of the three grounds were computed in the usual manner. These means were multiplied by the appropriate constants to transform them from the investigator's recording scales to the Munsell attributive scales. These constants were 1.0, 0.1, and 0.4, respectively. In this way, averaged estimates of the hue of each color were secured from the constant-value chart data, and averaged estimates of the value of each color were secured from the constant-hue chart data. Since the estimates from both sets of charts included chroma, the two sets of chroma data were weighted in proportion to the numbers of observations and averaged together to yield a single representative chroma determination.

Thus in the end, there became available one representative estimate for each attribute of each chromatic color on each ground. These 3500 determinations are presented in the body of Table II.

The averaged estimates

The first column of Table II shows the 1929 notation of hue, value, and chroma; the next three (double) columns to the right show the average hue estimates and uncertainties, corresponding to the observations with the three different viewing grounds; the next three columns present the corresponding value data; and the final three columns, the chroma data. All determinations are presented to the first decimal place of the respective Munsell attributive unit.

The measure of uncertainty or variability consists of the range within which the middle 80 percent of the individual estimates fall. This range could be found only approximately from our summary sheets; but it provides a considerably more reliable and representative measure than would the full range. Where no measure is given, as is often true of the hue estimates, the fact is that the 80 percent fell within a single recording unit of estimate. Though expressed in tenths, the limits of the 80 percent attributive ranges are given only to the nearest unit of estimate. Thus, one may note, the hue ranges are expressed in full hue steps, chroma in 0.4 steps and value in 0.1 steps.

In certain rare instances the mean may be found to fall without the 80 percent range. This anomaly is possible because of the skewness of distributions and the fact that means are computed in smaller units than ranges.

Asterisks in the hue columns accent a few instances in which the hue means are absent because hue data could not be taken. These instances concern the /2 chroma intermediate colors which do not appear on the constant-value charts. Corresponding value and chroma data could be given in Table II, however, because they were secured from the constant-hue charts upon which the samples in question do appear.

Before pointing out some general results, one more technical detail concerning Table II must be mentioned. This is the marked variation in the number, n, of cases upon which any given mean and range depend. In general, the chroma data are based on the largest numbers of observations (around 35) because results from both types of charts could be combined. Only in the case of the /2 chroma intermediate colors, mentioned above, are the chroma data scanty, for here only the few observers of the constant-hue charts could contribute. The hue data are next most plentiful ($n \doteq 25$), being based on the relatively numerous observations with the constant-value charts. The lightness data, on the other hand, could be secured only from the 10 subjects who observed the constant-hue charts, and the results from one of these could not be used because of a failure to follow instructions. More lightness data had been expected and, unquestionably, more are desirable. Fortunately, however, lightness has been the most investigated attribute, and there are visual data on Munsell value in the laboratory files of the Munsell company as well as in the literature (18, 50, 68). These sources will be consulted in conjunction with the final smoothing operation.

General indications

A detailed analysis of Table II will constitute a part of the smoothing operation to be performed in preparation for the final report, but

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estimates are especially significant, and so should, if anything, be weighted more heavily rather than taken simply at their face value. If the extreme judgments, which are usually displacement judgments, are more heavily weighted, a closer approximation to "true" averages may be expected. Thus in a measure, the use of the mean in dealing with these skewed distributions may be justified.

TABLE II. *Average visual estimates of the 1929 Munsell samples as viewed on white, gray, and black grounds, together with the corresponding ranges of the central 80 percent of the estimates.*

1929 Munsell Notation	Visual Estimates, Average and 80% Range																	
	Hue						Value						Chroma					
	White		Gray		Black		White		Gray		Black		White		Gray		Black	
H V/C	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range
R 8/4	4.8 R		4.5 R		4.8 R		8.1	*8.0–8.3*	8.1	*8.0–8.2*	8.2	*8.1–8.5*	4.2	*4.0–4.4*	3.8	*3.6–4.4*	3.9	*3.6–4.0*
2	3.0 R	*1* R–*5* R	4.1 R	*4* R–*5* R	4.3 R	*2* R–*5* R	8.1	*8.1–8.3*	8.1	*8.0–8.2*	8.2	*7.9–8.3*	2.0	*1.6–2.0*	2.0	*1.6–2.0*	1.9	
7/8	4.9 R		5.0 R		4.7 R		7.0	*7.0–7.3*	7.2	*7.2–7.4*	7.1	*6.9–7.4*	8.1	*7.2–8.4*	7.9	*7.6–8.4*	8.0	*7.6–8.4*
6	4.8 R		4.9 R		4.7 R		7.0	*7.0–7.3*	7.3	*7.0–7.5*	7.4	*7.2–7.7*	6.0	*6.0–6.4*	5.8	*5.2–6.4*	5.8	*5.6–6.4*
4	4.6 R		4.6 R		4.8 R		7.0	*7.0–7.3*	7.2	*6.9–7.4*	7.4	*7.2–7.8*	4.5	*4.0–4.8*	4.5	*3.6–5.2*	4.4	*3.6–4.8*
2	3.8 R	*2* R–*5* R	4.7 R		4.2 R	*3* R–*5* R	7.0	*6.9–7.3*	7.3	*7.0–7.4*	7.4	*7.2–7.8*	1.9	*1.6–2.0*	2.0	*1.6–2.0*	2.3	*1.6–2.8*
6/10	4.7 R		4.9 R		4.9 R		6.0	*5.9–6.2*	6.2	*5.9–6.5*	6.6	*6.2–6.7*	10.1	*9.2–10.4*	10.0	*9.6–10.0*	10.1	*9.6–10.4*
8	4.7 R		4.8 R		4.9 R		6.0	*5.7–6.2*	6.2	*5.9–6.4*	6.6	*6.2–7.0*	7.8	*7.6–8.0*	7.9	*7.6–8.0*	7.9	*7.6–8.4*
6	4.7 R	*4* R–*5* R	4.9 R		4.9 R		6.0	*5.7–6.3*	6.2	*5.9–6.4*	6.6	*6.2–6.6*	5.9	*5.6–6.0*	6.0	*5.6–6.0*	6.0	*6.0–6.4*
4	4.5 R	*4* R–*5* R	4.8 R		4.8 R		5.9	*5.7–6.3*	6.2	*5.9–6.4*	6.6	*6.3–7.1*	4.0		3.9	*3.6–4.0*	4.0	*3.6–4.0*
2	4.0 R	*3* R–*5* R	4.2 R	*4* R–*5* R	4.7 R		6.0	*5.7–6.2*	6.2	*5.9–6.4*	6.6	*6.2–6.6*	1.9	*1.6–2.0*	1.9		1.9	
5/12	5.0 R		5.1 R		5.1 R		4.9	*4.7–5.3*	4.8	*4.2–5.1*	5.7	*5.1–5.9*	12.3	*12.0–12.8*	12.3	*12.0–12.8*	12.3	*12.0–12.8*
10	5.0 R		5.0 R		5.1 R		4.9	*4.9–5.2*	4.8	*4.7–5.1*	5.7	*5.1–5.9*	10.1	*9.6–10.4*	10.1	*9.2–10.4*	10.1	*9.6–10.4*
8	5.0 R		5.0 R		5.0 R		4.9	*4.7–5.2*	4.8	*4.5–5.0*	5.7	*5.1–5.9*	8.3	*7.6–8.8*	8.5	*8.0–8.8*	8.3	*8.0–8.8*
6	4.7 R		4.6 R	*4* R–*5* R	4.8 R	*4* R–*5* R	4.9	*4.7–5.2*	4.8	*4.7–5.1*	5.7	*5.1–5.9*	6.2	*6.0–6.8*	6.3	*6.0–6.8*	6.3	*6.0–6.8*
4	4.4 R	*4* R–*5* R	4.4 R	*3* R–*5* R	4.7 R	*4* R–*5* R	4.9	*4.7–5.2*	4.8	*4.7–5.1*	5.7	*5.1–6.3*	4.3	*4.0–4.8*	4.2	*4.0–4.4*	4.2	*4.0–4.8*
2	4.1 R	*3* R–*5* R	4.1 R	*2* R–*6* R	4.0 R	*2* R–*5* R	4.9	*4.7–5.2*	4.8	*4.6–5.1*	5.7	*5.2–6.3*	2.1	*2.0–2.4*	2.1	*2.0–2.4*	2.1	*2.0–2.4*
4/14	5.0 R		5.0 R		5.0 R		3.9	*3.7–4.3*	3.8	*3.7–4.2*	4.8	*4.2–5.4*	13.9	*13.2–14.4*	13.9	*13.6–14.4*	13.9	*13.6–14.4*
12	5.0 R		5.0 R		5.0 R		3.9	*3.7–4.3*	3.8	*3.8–4.2*	4.8	*4.2–5.4*	12.1	*11.6–12.4*	12.2	*12.0–12.8*	12.2	*11.6–12.8*
10	4.9 R		4.9 R	*4* R–*5* R	4.8 R		3.9	*3.8–4.3*	3.8	*3.4–4.1*	4.8	*4.2–5.4*	10.1	*10.0–10.4*	10.1	*9.6–10.4*	10.2	*9.6–10.4*
8	4.9 R		4.8 R		4.9 R		3.9	*3.7–4.3*	3.8	*3.8–4.2*	4.8	*4.2–5.4*	8.0	*8.0–8.4*	8.2	*7.6–8.4*	8.1	*8.0–8.4*
6	4.7 R		5.0 R		4.7 R		3.9	*3.7–4.3*	3.8	*3.6–4.1*	4.8	*4.2–5.4*	6.0		6.1	*6.0–6.4*	6.0	*6.0–6.4*
4	4.3 R	*2* R–*5* R	4.6 R	*4* R–*5* R	4.2 R	*3* R–*5* R	3.9	*3.5–4.3*	3.8	*3.7–4.1*	4.8	*4.1–5.4*	4.0	*3.6–4.0*	4.1	*4.0–4.4*	4.0	*4.0–4.4*
2	4.4 R	*3* R–*5* R	4.6 R		4.5 R	*4* R–*5* R	3.9	*3.5–4.3*	3.8	*3.8–4.2*	4.8	*4.2–5.4*	2.0	*1.6–2.0*	2.0	*1.6–2.4*	2.0	
3/10	4.9 R		4.9 R		5.0 R		2.9	*2.5–3.3*	2.9	*2.4–3.1*	3.7	*3.1–4.2*	10.0	*10.0–10.4*	10.1	*10.0–10.8*	10.2	*10.0–10.4*
8	5.0 R		4.7 R		4.9 R		2.9	*2.5–3.3*	2.9	*2.8–3.1*	3.7	*3.3–4.2*	7.9	*7.6–8.4*	8.0	*7.6–8.4*	8.2	*8.0–8.4*
6	4.7 R	*4* R–*5* R	4.8 R	*4* R–*5* R	4.8 R		2.9	*2.5–3.3*	2.9	*2.7–3.1*	3.8	*3.2–4.3*	6.0	*5.6–6.0*	6.1	*6.0–6.4*	6.1	*6.0–6.4*
4	4.7 R		4.8 R		4.9 R		2.9	*2.3–3.3*	2.8	*2.6–3.1*	3.7	*3.3–4.2*	4.0		4.2	*4.0–4.8*	4.2	*4.0–4.4*
2	4.7 R	*3* R–*5* R	4.7 R		4.3 R	*3* R–*5* R	2.9	*2.3–3.3*	2.8	*2.8–3.1*	3.8	*3.3–4.3*	1.9	*1.6–2.0*	2.0	*1.6–2.0*	2.1	*2.0–2.4*
2/6	4.8 R		5.1 R	*4* R–*5* R	5.0 R		1.9	*1.4–2.3*	2.0	*1.6–2.2*	2.6	*2.1–3.0*	5.8	*5.2–6.0*	5.8	*5.2–6.4*	6.0	*5.6–6.4*
4	5.5 R	*5* R–*7* R	5.0 R		5.0 R	*3* R–*6* R	2.0	*1.6–2.3*	2.0	*1.7–2.2*	2.4	*2.0–2.9*	3.7	*3.6–4.0*	3.7	*3.6–4.0*	4.0	*3.6–4.8*
2	5.1 R	*5* R–*7* R	4.8 R	*2* R–*6* R	4.9 R	*2* R–*5* R	1.9	*1.5–2.2*	2.0	*1.6–2.1*	2.5	*2.0–2.7*	1.9		1.9	*1.6–2.0*	2.2	*2.0–2.8*
10 R 8/4	0.1 YR		0.2 YR		9.8 R		8.0	*7.4–8.2*	8.2	*8.0–8.3*	8.3	*8.1–8.6*	4.0	*4.0–4.4*	4.2	*4.0–4.4*	4.0	*4.0–4.4*
7/8	9.8 R	*9* R–*10* R	0.3 YR		9.9 R		6.7	*5.8–7.2*	7.2	*7.0–7.3*	7.4	*7.1–7.5*	8.2	*7.6–8.4*	8.1	*7.6–8.4*	8.0	*7.2–8.4*
6	9.6 R	*9* R–*10* R	9.9 R		9.8 R		6.8	*6.0–7.2*	7.2	*7.1–7.4*	7.4	*7.1–7.7*	5.9	*5.6–6.0*	5.9	*5.6–6.4*	5.8	*5.6–6.4*
4	9.5 R	*8* R–*10* R	9.8 R		9.6 R		6.8	*6.0–7.2*	7.2	*7.1–7.3*	7.4	*7.1–7.5*	4.1	*4.0–4.8*	4.1	*4.0–4.4*	4.1	*4.0–4.4*
6/10	10.0 R		10.0 R		0.2 YR	*10* R–*1* YR	5.8	*4.9–6.1*	5.9	*5.5–6.4*	6.5	*6.2–6.6*	10.4	*10.0–10.8*	10.6	*10.0–10.8*	10.2	*10.0–10.8*
8	0.1 YR		0.1 YR		10.0 R		5.7	*4.9–6.2*	6.1	*5.7–6.4*	6.5	*6.2–6.6*	8.0	*8.0–8.4*	8.0	*8.0–8.4*	8.0	*8.0–8.4*
6	9.9 R		10.0 R		10.0 R		5.7	*4.9–6.2*	6.2	*5.8–6.4*	6.5	*6.2–6.7*	6.0		6.0	*6.0–6.4*	6.0	*6.0–6.4*
4	9.3 R	*9* R–*10* R	9.6 R	*9* R–*10* R	9.7 R	*9* R–*10* R	5.6	*4.9–6.2*	6.2	*5.9–6.4*	6.5	*6.2–6.7*	3.9		4.0		4.0	
5/10	9.9 R		0.1 YR		10.0 R		4.6	*3.8–5.2*	4.6	*4.2–5.0*	5.5	*5.1–5.9*	10.2	*10.0–10.4*	10.2	*10.0–10.4*	10.2	*10.0–10.4*
8	10.0 R		10.0 R		10.0 R		4.6	*3.8–5.0*	4.7	*4.2–5.1*	5.6	*5.1–5.9*	8.1		8.1	*8.0–8.4*	8.0	*8.0–8.4*
6	10.0 R		9.9 R		9.9 R		4.6	*3.8–5.0*	4.7	*4.2–5.0*	5.5	*5.1–5.9*	6.1		6.2	*6.0–6.4*	6.0	
4	9.5 R	*9* R–*10* R	9.4 R	*9* R–*10* R	9.5 R	*9* R–*10* R	4.5	*3.8–5.2*	4.7	*4.2–5.0*	5.5	*5.0–5.7*	4.0	*3.6–4.0*	4.0		4.0	
4/10	9.9 R		0.1 YR		9.8 R		3.7	*2.8–4.1*	3.7	*3.5–4.1*	4.6	*4.2–4.9*	10.0	*9.2–10.0*	10.2	*9.6–10.4*	10.2	*10.0–10.4*
8	10.0 R		10.0 R		9.8 R		3.6	*2.8–4.0*	3.7	*3.5–4.1*	4.6	*4.2–4.9*	8.2	*7.6–8.4*	8.3	*8.0–8.8*	8.2	*7.6–8.4*
6	10.0 R		10.0 R		9.9 R		3.7	*2.8–4.0*	3.8	*3.5–4.2*	4.6	*4.2–4.9*	6.1	*6.0–6.8*	6.2	*6.0–6.4*	6.3	*6.0–6.8*
4	9.8 R		9.8 R	*9* R–*10* R	9.5 R	*9* R–*10* R	3.6	*2.8–4.0*	3.7	*3.5–4.0*	4.6	*4.1–4.9*	4.0	*4.0–4.4*	4.1		4.1	*3.6–4.4*
3/6	9.9 R		0.2 YR		0.1 YR		2.8	*2.0–3.2*	2.8	*2.4–3.1*	3.4	*2.9–4.0*	6.0	*5.6–6.0*	6.1	*6.0–6.4*	6.1	*6.0–6.4*
4	10.0 R		0.2 YR		9.9 R		2.7	*2.0–3.2*	2.8	*2.4–3.2*	3.4	*2.9–3.9*	4.0		4.1	*4.0–4.4*	4.1	*4.0–4.4*

TABLE II.—*Continued.*

1929 Munsell Notation	Visual Estimates, Average and 80% Range																	
	Hue						Value						Chroma					
	White		Gray		Black		White		Gray		Black		White		Gray		Black	
H V/C	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range
YR 8/4	4.4 YR	*4* YR–*5* YR	5.0 YR		4.8 YR		7.9	*7.5–8.4*	8.1	*8.0–8.2*	8.3	*8.0–8.5*	4.0	*3.6– 4.0*	4.0	*4.0– 4.4*	4.0	*3.6– 4.0*
2	3.6 YR	*2* YR–*5* YR	3.9 YR	*2* YR–*5* YR	4.3 YR	*3* YR–*5* YR	7.9	*7.5–8.1*	8.1	*8.0–8.2*	8.3	*8.1–8.5*	1.9	*1.6– 2.4*	1.9	*1.6– 2.0*	1.9	
7/10	5.2 YR		5.2 YR		5.2 YR		6.7	*6.2–7.2*	7.2	*7.0–7.4*	7.5	*7.2–7.8*	10.3	*10.0–10.8*	10.4	*10.0–10.8*	10.3	*10.0–10.8*
8	5.0 YR		4.9 YR		4.9 YR	*4* YR–*5* YR	6.8	*6.2–7.2*	7.2	*7.0–7.2*	7.5	*7.2–7.9*	8.2	*8.0– 8.4*	8.1	*8.0– 8.4*	8.0	*8.0– 8.4*
6	4.5 YR	*4* YR–*5* YR	4.7 YR	*4* YR–*5* YR	4.7 YR	*4* YR–*5* YR	6.7	*6.2–7.1*	7.2	*7.0–7.2*	7.5	*7.2–8.0*	6.1	*6.0– 6.4*	6.0		6.0	*5.6– 6.4*
4	4.2 YR	*3* YR–*5* YR	4.4 YR	*4* YR–*5* YR	4.2 YR	*3* YR–*5* YR	6.8	*6.2–7.1*	7.2	*7.0–7.3*	7.5	*7.2–8.0*	4.0	*4.0– 4.4*	3.9		4.0	
2	3.9 YR	*2* YR–*5* YR	4.6 YR		3.7 YR	*2* YR–*5* YR	6.7	*6.2–7.1*	7.2	*7.0–7.3*	7.5	*7.2–8.0*	2.0	*1.6– 2.0*	2.0		1.9	*1.6– 2.0*
6/12	5.1 YR	*5* YR–*6* YR	5.0 YR		5.0 YR		5.7	*5.1–6.4*	6.0	*5.7–6.3*	6.6	*6.2–7.0*	12.0	*12.0–12.4*	11.9	*10.8–12.4*	11.9	*11.2–12.4*
10	5.0 YR		5.2 YR		5.0 YR		5.7	*5.1–6.3*	6.0	*5.7–6.2*	6.6	*6.2–7.1*	10.1	*10.0–10.4*	10.2	*10.0–10.4*	10.1	*10.0–10.4*
8	5.0 YR		5.2 YR		4.9 YR		5.7	*5.1–6.2*	6.0	*5.7–6.2*	6.6	*6.1–7.1*	8.1	*8.0– 8.4*	8.2	*8.0– 8.4*	8.0	*8.0– 8.4*
6	4.7 YR		5.0 YR		4.7 YR	*4* YR–*5* YR	5.7	*5.1–6.2*	6.0	*6.0–6.2*	6.7	*6.2–7.0*	5.9	*5.6– 6.0*	5.9		5.9	*5.6– 6.0*
4	4.3 YR	*4* YR–*5* YR	4.6 YR	*4* YR–*5* YR	4.2 YR	*3* YR–*5* YR	5.6	*5.1–6.2*	6.0	*5.7–6.2*	6.6	*6.2–7.0*	3.9	*3.6– 4.0*	3.9		3.9	*3.6– 4.0*
2	4.5 YR		4.3 YR	*3* YR–*5* YR	4.2 YR	*4* YR–*5* YR	5.6	*5.4–6.2*	6.0	*5.7–6.2*	6.6	*6.2–7.0*	1.9	*1.6– 2.0*	2.0		1.8	*1.6– 2.0*
5/10	5.0 YR		5.0 YR		5.0 YR		4.7	*4.2–5.1*	4.6	*4.5–5.0*	5.8	*5.2–6.2*	10.1		10.1	*10.0–10.4*	10.1	*10.0–10.4*
8	5.0 YR		5.0 YR		5.2 YR		4.6	*4.0–5.1*	4.6	*4.2–5.0*	5.7	*5.2–6.2*	8.1	*8.0– 8.4*	8.1	*8.0– 8.4*	8.0	*8.0– 8.4*
6	5.1 YR		5.0 YR		5.1 YR		4.6	*4.0–5.1*	4.6	*4.2–5.0*	5.7	*5.2–6.2*	6.1		6.0	*6.0– 6.4*	5.9	*5.6– 6.0*
4	4.6 YR	*4* YR–*5* YR	4.5 YR	*4* YR–*5* YR	4.3 YR	*3* YR–*5* YR	4.6	*4.0–5.0*	4.6	*4.2–4.8*	5.7	*5.1–6.0*	4.0		4.1	*4.0– 4.4*	4.0	*4.0– 4.4*
2	4.3 YR		3.9 YR	*2* YR–*5* YR	4.0 YR	*2* YR–*5* YR	4.5	*3.9–5.0*	4.6	*4.2–4.8*	5.7	*5.1–6.2*	1.9	*1.6– 2.0*	1.9	*1.6– 2.4*	1.9	*1.6– 2.0*
4/8	5.2 YR		5.1 YR		4.9 YR		3.7	*3.0–4.1*	3.7	*3.2–4.0*	4.8	*4.4–5.2*	7.7	*7.2– 8.0*	8.0	*7.6– 8.8*	7.8	*7.2– 8.4*
6	5.1 YR		5.0 YR		5.1 YR		3.7	*3.0–4.1*	3.7	*3.2–4.0*	4.8	*4.3–5.2*	6.0	*5.6– 6.4*	6.2	*6.0– 6.8*	6.1	*5.6– 6.4*
4	5.0 YR		4.8 YR		5.0 YR		3.7	*3.0–4.1*	3.7	*3.2–4.0*	4.8	*4.2–5.2*	4.1	*4.0– 4.4*	4.2	*4.0– 4.8*	4.1	*4.0– 4.4*
2	4.4 YR		4.7 YR	*4* YR–*5* YR	3.7 YR	*2* YR–*7* YR	3.6	*3.0–4.1*	3.6	*3.2–3.9*	4.8	*4.2–5.2*	2.0	*1.6– 2.0*	2.0	*2.0– 2.4*	2.1	*2.0– 2.4*
3/4	5.2 YR		4.8 YR		5.0 YR		2.8	*2.3–3.1*	2.8	*2.4–3.0*	3.8	*3.3–4.0*	4.0	*3.6– 4.0*	4.3	*4.0– 4.8*	4.3	*4.0– 4.4*
2	4.8 YR		4.6 YR		4.8 YR		2.6	*2.1–3.0*	2.7	*2.2–3.0*	3.7	*3.2–4.0*	1.9	*1.6– 2.0*	2.1	*2.0– 2.4*	2.2	*2.0– 2.4*
2/2	5.3 YR		5.1 YR		5.0 YR		1.8	*1.5–2.1*	1.9	*1.6–2.1*	2.5	*2.1–2.7*	1.9		1.9	*1.6– 2.0*	2.1	*2.0– 2.4*
10 YR 8/6	9.8 YR	*9* YR–*10* YR	10.0 YR		10.0 YR		8.0	*8.0–8.3*	8.1	*7.9–8.2*	8.2	*8.0–8.5*	6.3	*6.0– 6.4*	6.3	*6.0– 6.8*	6.1	*5.2– 6.4*
4	9.8 YR	*9* YR–*10* YR	9.8 YR		9.8 YR		8.0	*8.0–8.2*	8.1	*8.0–8.1*	8.2	*8.0–8.4*	4.0	*3.6– 4.0*	3.8	*3.6– 4.0*	3.9	*3.6– 4.0*
7/10	10.0 YR		0.1 Y		9.9 YR		6.8	*6.6–7.0*	7.3	*7.1–7.4*	7.4	*7.2–7.5*	10.2	*10.0–10.4*	10.2	*10.0–10.8*	10.2	*10.0–10.4*
8	10.0 YR		10.0 YR		9.9 YR		6.8	*6.6–7.0*	7.3	*7.2–7.4*	7.4	*7.2–7.7*	8.0	*8.0– 8.4*	8.0	*7.6– 8.0*	8.0	*7.6– 8.0*
6	10.0 YR		10.0 YR		9.8 YR		6.8	*6.4–7.0*	7.3	*7.2–7.3*	7.4	*7.2–7.7*	6.0	*6.0– 6.4*	5.9	*5.6– 6.0*	5.9	*5.6– 6.0*
4	9.5 YR	*9* YR–*10* YR	9.3 YR	*8* YR–*10* YR	9.4 YR	*9* YR–*10* YR	6.8	*6.6–7.2*	7.3	*7.2–7.4*	7.4	*7.2–7.4*	3.9	*3.6– 4.0*	3.8	*3.6– 4.0*	4.0	*3.6– 4.0*
6/10	0.1 Y		0.1 Y		0.1 Y		5.8	*5.8–6.0*	6.3	*6.1–6.5*	6.6	*6.3–6.7*	10.0		9.8	*9.2–10.0*	10.2	*10.0–10.4*
8	10.0 YR		0.2 Y		0.1 Y		5.8	*5.8–6.0*	6.3	*6.1–6.4*	6.6	*6.3–6.6*	8.0	*7.6– 8.0*	8.0	*8.0– 8.4*	8.0	*7.6– 8.4*
6	9.9 YR		0.2 Y		10.0 YR		5.8	*5.8–6.0*	6.3	*6.1–6.5*	6.6	*6.3–6.6*	6.1	*6.0– 6.4*	6.2	*6.0– 6.4*	6.1	*6.0– 6.4*
4	·9.7 YR		10.0 YR		9.9 YR		5.7	*5.6–6.0*	6.2	*6.0–6.4*	6.5	*6.3–6.8*	3.9	*3.6– 4.0*	3.8	*3.6– 4.4*	3.9	*3.2– 4.0*
5/8	10.0 YR		10.0 YR		10.0 YR		4.8	*4.7–5.1*	4.8	*4.2–5.0*	5.6	*5.4–5.9*	8.0	*8.0– 8.4*	8.1	*8.0– 8.4*	8.1	*8.0– 8.4*
6	10.0 YR		10.0 YR		10.0 YR		4.8	*4.6–5.1*	4.8	*4.2–5.0*	5.6	*5.4–5.9*	5.9	*5.6– 6.4*	5.9	*5.6– 6.4*	5.8	*5.6– 6.0*
4	10.0 YR		9.8 YR		9.8 YR		4.8	*4.6–5.1*	4.8	*4.2–5.0*	5.6	*5.4–5.9*	3.9	*3.6– 4.0*	4.0	*4.0– 4.4*	4.0	*4.0– 4.4*
4/4	9.9 YR		9.8 YR		9.9 YR		3.9	*3.7–4.2*	3.7	*3.2–4.0*	4.8	*4.3–5.2*	4.0	*3.6– 4.8*	4.3	*4.0– 4.8*	4.3	*4.0– 4.8*
Y 8/12	5.3 Y		5.3 Y		5.2 Y		7.8	*7.5–8.1*	8.0	*8.0–8.1*	8.2	*8.0–8.2*	11.8	*11.2–12.4*	11.9	*11.2–12.4*	12.0	*11.2–12.4*
10	5.2 Y	*5* Y–*6* Y	5.4 Y	*5* Y–*6* Y	5.2 Y		7.9	*7.9–8.3*	8.0	*8.0–8.1*	8.2	*8.1–8.4*	10.2	*10.0–10.8*	10.3	*9.6–10.8*	10.4	*10.0–10.8*
8	5.5 Y	*5* Y–*6* Y	5.6 Y	*5* Y–*6* Y	5.3 Y	*5* Y–*6* Y	7.9	*7.8–8.2*	8.1	*8.0–8.1*	8.2	*8.0–8.3*	8.0	*7.6– 8.0*	8.1	*8.0– 8.4*	8.0	*7.6– 8.4*
6	4.8 Y	*4* Y–*5* Y	4.9 Y	*4* Y–*6* Y	4.6 Y	*4* Y–*5* Y	7.9	*7.5–8.1*	8.1	*8.0–8.1*	8.2	*8.0–8.2*	5.8	*5.6– 6.0*	5.9	*5.6– 6.0*	5.8	*5.2– 6.0*
4	4.8 Y	*4* Y–*5* Y	4.6 Y	*3* Y–*5* Y	4.5 Y	*3* Y–*5* Y	7.9	*7.6–8.2*	8.1	*8.0–8.1*	8.2	*8.0–8.2*	3.8	*3.6– 4.0*	3.9	*3.2– 4.0*	3.8	*3.2– 4.0*
2	5.1 Y		4.8 Y	*5* Y–*7* Y	4.5 Y	*3* Y–*5* Y	7.9	*7.9–8.1*	8.1	*8.0–8.1*	8.2	*8.0–8.2*	1.6	*1.6– 2.0*	1.8	*1.6– 2.0*	1.9	*1.6– 2.0*
7/10	5.2 Y		5.2 Y		5.3 Y		6.7	*6.3–7.1*	7.2	*7.0–7.3*	7.4	*6.9–7.5*	9.8	*9.6–10.4*	9.8	*9.6–10.4*	9.9	*9.2–10.0*
8	5.5 Y	*5* Y–*6* Y	5.5 Y		5.8 Y	*5* Y–*7* Y	6.8	*6.4–7.3*	7.2	*7.1–7.4*	7.4	*7.2–7.8*	8.4	*8.0– 8.8*	8.4	*8.0– 8.8*	8.6	*8.0– 9.2*
6	5.2 Y		5.3 Y		5.3 Y	*5* Y–*6* Y	6.7	*6.2–7.1*	7.1	*7.0–7.3*	7.4	*7.2–7.8*	5.9	*5.6– 6.0*	6.1	*6.0– 6.4*	6.1	*6.0– 6.4*
4	5.1 Y		4.8 Y	*4* Y–*5* Y	4.8 Y		6.7	*6.5–7.1*	7.3	*7.1–7.3*	7.4	*7.1–8.0*	3.8	*3.6– 4.4*	4.0	*3.6– 4.4*	3.9	*3.6– 4.0*
2	5.0 Y		4.6 Y		5.2 Y		6.7	*6.4–7.1*	7.2	*7.0–7.4*	7.4	*7.0–7.5*	1.6	*1.2– 2.0*	1.8	*1.2– 2.0*	1.8	*1.2– 2.0*
6/8	5.4 Y		5.4 Y		5.3 Y		5.6	*5.4–6.2*	6.1	*5.7–6.3*	6.6	*6.2–7.3*	8.0	*7.6– 8.4*	8.0	*8.0– 8.4*	8.2	*8.0– 8.8*
6	5.4 Y		5.5 Y	*5* Y–*6* Y	5.2 Y		5.6	*5.4–6.2*	6.0	*5.7–6.3*	6.5	*6.2–7.2*	6.3	*6.0– 6.8*	6.4	*6.0– 7.2*	6.5	*6.0– 6.8*
4	5.2 Y		5.4 Y		5.0 Y	*5* Y–*6* Y	5.7	*5.6–6.2*	6.0	*5.6–6.3*	6.6	*6.2–7.3*	4.0	*3.6– 4.0*	4.0	*3.6– 4.4*	3.8	*3.2– 4.0*
2	5.0 Y		5.1 Y		4.8 Y		5.7	*5.2–6.1*	6.1	*5.7–6.2*	6.6	*6.2–7.4*	1.8	*1.2– 2.0*	1.9	*1.6– 2.0*	1.8	*1.6– 2.0*

TABLE II.—*Continued.*

1929 Munsell Notation	Visual Estimates, Average and 80% Range																	
	Hue						Value						Chroma					
	White		Gray		Black		White		Gray		Black		White		Gray		Black	
H V/C	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range
Y 5/6	5.5 Y	*5* Y–*7* Y	5.5 Y	*5* Y–*6* Y	5.4 Y	*5* Y–*6* Y	4.6	*4.2–5.2*	4.7	*4.2–5.1*	5.7	*5.2–6.3*	6.0	*5.6– 6.4*	6.2	*5.6– 6.4*	6.3	*6.0– 6.8*
4	5.3 Y		5.2 Y		5.3 Y		4.6	*4.2–5.2*	4.7	*4.2–5.0*	5.7	*5.1–6.2*	3.9	*3.6– 4.4*	3.9	*3.6– 4.4*	3.9	*3.6– 4.4*
2	5.2 Y		5.1 Y		4.9 Y		4.7	*4.6–5.2*	5.1	*4.7–5.3*	5.6	*5.1–6.3*	1.9	*1.6– 2.4*	1.7	*1.2– 2.0*	1.8	*1.2– 2.0*
4/4	5.6 Y	*5* Y–*6* Y	5.1 Y		5.2 Y		3.7	*3.2–4.3*	3.6	*3.2–4.1*	4.8	*4.0–5.3*	4.1	*3.6– 4.4*	4.3	*4.0– 4.8*	4.2	*4.0– 4.8*
2	5.2 Y		5.0 Y		5.0 Y		3.8	*3.4–4.3*	3.7	*3.2–4.2*	4.8	*4.1–5.5*	1.9	*1.2– 2.0*	2.0	*1.6– 2.4*	2.0	*1.6– 2.4*
3/2	5.5 Y		5.2 Y		5.2 Y		2.6	*2.2–2.9*	2.6	*2.4–3.0*	3.7	*3.0–4.3*	1.6	*1.2– 2.0*	1.6	*1.2– 2.0*	1.8	*1.6– 2.0*
2/2	5.2 Y		5.4 Y		5.1 Y		1.9	*1.5–2.2*	1.9	*1.7–2.0*	2.6	*2.2–3.1*	1.9		1.9	*1.6– 2.8*	1.9	*1.2– 2.0*
10 Y 8/8	10.0 Y		10.0 Y		10.0 Y		7.9	*7.3–8.2*	8.0	*7.8–8.1*	8.2	*8.0–8.5*	8.2	*7.6– 8.4*	8.1	*8.0– 8.4*	8.1	*8.0– 8.4*
6	10.0 Y		0.1 GY		0.1 GY		7.9	*7.3–8.3*	8.0	*8.0–8.1*	8.1	*8.0–8.6*	5.9		5.9	*5.6– 6.0*	5.8	*5.6– 6.0*
4	10.0 Y		0.1 GY		10.0 Y		7.9	*7.4–8.3*	8.0	*8.0–8.1*	8.2	*8.0–8.5*	3.9	*3.6– 4.0*	3.8	*3.2– 4.0*	3.8	*3.2– 4.0*
7/8	0.1 GY		0.1 GY		9.9 Y		6.9	*5.9–7.1*	7.1	*6.9–7.2*	7.3	*7.0–7.7*	8.1	*8.0– 8.4*	8.1	*8.0– 8.4*	8.3	*8.0– 8.8*
6	0.1 GY		0.4 GY		0.2 GY		6.7	*7.0–7.1*	7.1	*7.0–7.3*	7.3	*7.0–7.8*	6.1	*6.0– 6.4*	6.1	*5.6– 6.4*	6.1	*6.0– 6.4*
4	10.0 Y		0.1 GY		0.1 GY		6.7	*6.8–7.2*	7.1	*7.0–7.3*	7.3	*6.8–7.7*	3.8	*3.6– 4.0*	3.8	*3.6– 4.4*	3.8	*3.6– 4.0*
6/6	9.8 Y		10.0 Y		10.0 Y		5.7	*5.8–6.2*	6.1	*5.7–6.4*	6.5	*6.0–6.8*	6.4	*6.0– 6.8*	6.5	*6.0– 6.8*	6.6	*6.0– 6.8*
4	0.2 GY		10.0 Y		9.8 Y		5.7	*5.6–6.1*	6.0	*5.7–6.3*	6.3	*6.0–6.6*	3.9	*3.6– 4.0*	4.0	*3.6– 4.0*	3.9	*3.6– 4.0*
5/6	10.0 Y		9.9 Y		10.0 Y		4.6	*4.5–5.1*	4.6	*4.2–5.0*	5.6	*5.2–6.3*	6.0		6.1	*6.0– 6.4*	6.1	
4	0.1 GY		10.0 Y		0.1 GY		4.6	*3.7–5.0*	4.6	*4.2–5.0*	5.6	*5.0–6.1*	4.2	*4.0– 4.4*	4.2	*4.0– 4.8*	4.2	*4.0– 4.4*
4/4	0.2 GY		0.1 GY		10.0 Y		3.7	*3.5–4.2*	3.6	*3.2–4.0*	4.7	*3.8–5.4*	4.2	*4.0– 4.4*	4.2	*4.0– 4.8*	4.3	*4.0– 4.8*
GY 8/8	5.0 GY		4.8 GY		4.7 GY	*4* GY–*5* GY	8.0	*7.2–8.4*	8.1	*8.0–8.4*	8.1	*8.0–8.3*	8.4	*8.0– 8.8*	8.3	*8.0– 8.8*	8.3	*8.0– 8.8*
6	5.0 GY		5.0 GY		5.0 GY		7.9	*7.9–8.3*	8.0	*8.0–8.2*	8.2	*8.0–8.3*	6.2	*6.0– 6.4*	6.2	*6.0– 6.8*	6.1	*6.0– 6.8*
4	5.2 GY		5.1 GY		5.0 GY		7.9	*7.4–8.2*	8.0	*8.0–8.2*	8.2	*8.0–8.4*	4.0		4.0	*4.0– 4.4*	3.9	*3.2– 4.0*
2	5.6 GY		4.9 GY		5.3 GY		7.9	*7.6–8.2*	8.0	*8.0–8.2*	8.2	*8.0–8.4*	1.9	*1.6– 2.0*	1.7	*1.2– 2.0*	1.8	*1.2– 2.0*
7/10	5.0 GY		4.8 GY		4.9 GY		6.7	*5.7–7.2*	7.1	*6.7–7.4*	7.5	*7.2–7.8*	10.3	*10.0–10.8*	10.1	*10.0–10.4*	10.3	*10.0–10.4*
8	5.1 GY		5.1 GY		5.1 GY		6.7	*5.9–7.1*	7.1	*6.9–7.4*	7.4	*7.2–7.6*	8.1	*7.6– 8.4*	7.9	*7.2– 8.4*	8.0	*7.6– 8.8*
6	5.0 GY		5.0 GY		5.2 GY		6.7	*5.9–7.1*	7.1	*7.0–7.4*	7.4	*7.2–7.9*	6.1	*6.0– 6.4*	6.1	*6.0– 6.4*	6.1	*6.0– 6.4*
4	5.1 GY		5.2 GY		5.3 GY		6.7	*6.0–7.1*	7.1	*7.0–7.4*	7.5	*7.2–7.9*	4.0	*4.0– 4.4*	4.0	*4.0– 4.4*	4.0	*3.6– 4.0*
2	5.3 GY		5.2 GY		5.3 GY		6.6	*5.9–7.0*	7.1	*7.0–7.4*	7.4	*7.0–7.6*	2.1	*1.6– 2.4*	2.0	*1.6– 2.4*	1.9	*1.6– 2.0*
6/8	5.1 GY		4.9 GY		5.0 GY		5.6	*4.6–6.1*	5.9	*5.7–6.4*	6.6	*6.3–7.1*	8.1	*7.6– 8.4*	8.0	*7.6– 8.4*	8.0	*8.0– 8.4*
6	5.1 GY		5.2 GY		5.0 GY		5.6	*4.6–6.0*	5.9	*5.7–6.4*	6.7	*6.1–7.3*	6.3	*6.0– 6.8*	6.4	*6.0– 6.8*	6.4	*6.0– 6.8*
4	5.2 GY		5.3 GY		4.9 GY		5.6	*5.6–6.1*	6.0	*5.7–6.4*	6.7	*6.2–7.3*	4.1		4.1	*4.0– 4.4*	4.0	
2	5.2 GY		5.4 GY		5.0 GY		5.6	*4.8–6.0*	6.0	*5.7–6.4*	6.7	*6.2–7.3*	1.9	*1.6– 2.0*	1.9	*1.6– 2.0*	1.9	*1.6– 2.0*
5/8	5.1 GY		5.0 GY		5.0 GY		4.6	*4.7–5.1*	4.5	*3.8–5.0*	5.8	*5.0–6.0*	8.1	*8.0– 8.4*	8.2	*8.0– 8.8*	8.3	*8.0– 8.8*
6	5.2 GY		5.0 GY		5.2 GY		4.6	*4.6–5.1*	4.4	*3.9–5.0*	5.7	*5.3–6.5*	6.1	*6.0– 6.4*	5.8	*5.6– 6.0*	6.0	*5.6– 6.0*
4	5.1 GY		5.1 GY		5.0 GY		4.6	*4.5–5.1*	4.5	*4.0–5.0*	5.7	*5.0–6.0*	4.2	*4.0– 4.4*	4.2	*4.0– 4.4*	4.2	*4.0– 4.4*
2	5.3 GY		5.2 GY		5.0 GY		4.6	*3.6–5.0*	4.5	*4.0–5.0*	5.8	*5.1–6.0*	2.0	*2.0– 2.4*	2.1	*2.0– 2.4*	2.0	*1.6– 2.4*
4/6	5.1 GY		4.7 GY	*3* GY–*5* GY	5.3 GY		3.6	*3.6–4.0*	3.5	*3.0–3.9*	4.9	*4.2–5.2*	5.9	*5.6– 6.4*	6.0	*5.6– 6.0*	6.0	*5.6– 6.4*
4	4.9 GY		4.8 GY		5.0 GY		3.7	*2.7–4.0*	3.5	*3.2–4.0*	4.8	*4.0–5.7*	4.0	*3.6– 4.0*	4.1	*4.0– 4.8*	4.1	*4.0– 4.4*
2	4.9 GY		5.3 GY		5.3 GY		3.6	*3.6–4.0*	3.6	*3.2–4.0*	4.9	*4.2–5.2*	1.9	*1.6– 2.0*	2.0	*1.6– 2.4*	1.9	*1.6– 2.4*
3/4	5.0 GY		5.0 GY		4.7 GY		2.8	*2.3–3.2*	2.7	*2.4–3.1*	3.8	*3.3–4.2*	3.7	*3.2– 4.0*	3.9	*3.2– 4.4*	4.0	*3.6– 4.8*
2	5.1 GY		5.1 GY		5.0 GY		2.7	*2.0–3.0*	2.7	*2.4–3.0*	3.7	*3.3–4.0*	1.9	*1.6– 2.0*	2.0	*1.6– 2.0*	2.0	*1.6– 2.4*
2/2	5.0 GY		5.2 GY		5.0 GY		1.8	*1.6–2.2*	1.9	*1.6–2.0*	2.5	*2.2–3.0*	2.0	*2.0– 2.4*	2.1	*1.6– 2.4*	2.3	*2.0– 2.8*
10 GY 8/6	10.0 GY		10.0 GY		10.0 GY		7.8	*7.4–8.0*	8.2	*8.0–8.4*	8.2	*8.0–8.3*	6.1	*6.0– 6.8*	5.9	*5.6– 6.4*	5.9	*5.2– 6.0*
4	10.0 GY		10.0 GY		10.0 GY		7.8	*7.6–8.1*	8.2	*8.0–8.2*	8.3	*8.1–8.4*	4.4	*4.0– 4.8*	4.1	*4.0– 4.4*	4.2	*4.0– 4.8*
7/8	9.9 GY		9.8 GY		9.8 GY	*9* GY–*10* GY	6.7	*6.3–7.1*	7.3	*7.2–7.4*	7.4	*7.1–7.9*	8.4	*8.0– 8.8*	8.3	*8.0– 8.8*	8.2	*8.0– 8.8*
6	10.0 GY		10.0 GY		10.0 GY		6.7	*6.6–7.1*	7.3	*7.2–7.5*	7.4	*7.1–7.5*	6.3	*6.0– 6.8*	6.1	*6.0– 6.8*	6.1	*6.0– 6.8*
4	10.0 GY		9.9 GY		0.1 G		6.6	*6.3–7.1*	7.3	*7.2–7.7*	7.5	*7.1–7.6*	4.0	*4.0– 4.4*	4.0	*4.0– 4.4*	3.9	*3.6– 4.0*
6/10	10.0 GY		0.1 G		9.9 GY		5.6	*5.4–6.0*	6.2	*6.0–6.9*	6.6	*6.4–7.3*	10.3	*10.0–10.8*	10.2	*10.0–10.4*	10.3	*10.0–10.8*
8	9.8 GY		10.0 GY		9.9 GY		5.6	*5.4–6.1*	6.2	*5.8–6.4*	6.6	*6.0–6.6*	8.5	*8.0– 9.2*	8.4	*8.0– 8.8*	8.3	*7.6– 8.8*
6	0.1 G		10.0 GY		10.0 GY		5.6	*5.4–6.1*	6.2	*5.9–6.4*	6.6	*6.0–6.8*	6.5	*6.0– 6.8*	6.3	*6.0– 6.8*	6.2	*6.0– 6.4*
4	0.4 G		0.2 G		0.1 G		5.6	*5.4–6.1*	6.1	*5.8–6.4*	6.6	*6.2–7.3*	4.2	*4.0– 4.8*	4.2	*4.0– 4.4*	4.1	*3.6– 4.8*
5/8	0.1 G		0.1 G		9.8 GY		4.6	*4.2–5.1*	4.7	*4.2–5.1*	5.7	*5.2–6.3*	8.4	*8.0– 8.8*	8.4	*8.0– 8.8*	8.5	*8.0– 8.8*
6	9.9 GY		9.8 GY		9.7 GY		4.6	*4.2–5.2*	4.7	*4.2–5.1*	5.7	*5.0–5.9*	6.5	*6.0– 6.8*	6.5	*6.0– 6.8*	6.7	*6.0– 6.8*
4	0.3 G		0.1 G		0.1 G		4.6	*4.2–5.1*	4.7	*4.2–5.1*	5.8	*5.2–6.5*	4.0	*3.6– 4.4*	4.1		4.0	*3.6– 4.0*

TABLE II.—*Continued.*

1929 Munsell Notation	Visual Estimates, Average and 80% Range																	
	Hue						Value						Chroma					
	White		Gray		Black		White		Gray		Black		White		Gray		Black	
H V/C	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range
10 GY 4/6	0.3 G		0.1 G		0.4 G		3.7	*3.2–4.2*	3.8	*3.5–4.2*	4.9	*4.1–5.6*	6.3	*6.0–6.8*	6.4	*6.0–6.8*	6.3	*6.0–6.8*
4	0.2 G		0.2 G		0.3 G		3.6	*3.2–4.1*	3.8	*3.5–4.2*	4.8	*4.2–5.6*	4.2	*4.0–4.4*	4.2	*4.0–4.4*	4.2	*4.0–4.4*
3/4	10.0 GY		9.9 GY		9.7 GY		2.7	*2.3–4.2*	2.8	*2.4–3.3*	3.9	*3.0–4.0*	4.5	*4.0–4.8*	4.7	*4.0–4.8*	4.7	*4.0–5.2*
G 8/6	5.0 G		5.2 G		5.2 G		7.8	*7.5–8.2*	8.1	*8.0–8.2*	8.2	*8.0–8.4*	6.3	*6.0–6.8*	6.2	*6.0–6.8*	6.0	
4	5.2 G		5.3 G		5.2 G		7.9	*7.7–8.2*	8.2	*8.0–8.2*	8.3	*8.1–8.6*	4.2	*4.0–4.8*	4.0	*3.6–4.4*	3.9	*3.2–4.0*
2	5.3 G		5.3 G		5.4 G		7.9	*7.9–8.2*	8.1	*8.0–8.3*	8.3	*8.1–8.6*	2.3	*2.0–2.4*	2.1	*2.0–2.4*	2.1	*2.0–2.8*
7/6	5.0 G		4.9 G		5.1 G		6.8	*6.8–7.2*	7.3	*7.1–7.4*	7.6	*7.3–7.8*	6.3	*6.0–6.8*	6.3	*6.0–6.8*	6.1	*6.0–6.4*
4	5.4 G		5.0 G		5.2 G		6.8	*6.6–7.2*	7.2	*7.0–7.3*	7.5	*7.2–7.7*	4.2	*4.0–4.4*	4.2	*4.0–4.8*	4.1	*4.0–4.4*
2	5.3 G		5.0 G		5.2 G		6.7	*6.4–7.2*	7.2	*7.1–7.4*	7.6	*7.2–7.8*	2.2	*2.0–2.4*	2.2	*2.0–2.4*	2.1	*2.0–2.4*
6/6	5.0 G	*4* G–*5* G	5.2 G		5.1 G		5.7	*5.5–6.3*	6.1	*5.7–6.5*	6.7	*6.4–7.2*	6.6	*6.4–7.2*	6.8	*6.0–7.2*	6.6	*6.0–6.8*
4	5.2 G		5.1 G		5.1 G		5.7	*5.3–6.2*	6.1	*5.8–6.3*	6.7	*6.4–7.5*	4.3	*4.0–4.8*	4.3	*4.0–4.8*	4.1	*4.0–4.4*
2	5.3 G		5.6 G		5.2 G		5.6	*5.3–6.2*	6.1	*5.8–6.3*	6.7	*6.2–6.9*	2.3	*2.0–2.4*	2.3	*2.0–2.8*	2.1	
5/8	5.0 G		4.9 G		5.0 G		4.7	*4.1–5.2*	4.7	*4.5–5.2*	5.8	*5.5–6.5*	8.5	*8.0–8.8*	8.5	*8.0–8.8*	8.4	*8.0–8.8*
6	5.1 G		5.0 G		5.1 G		4.7	*4.1–5.2*	4.6	*4.2–5.0*	5.8	*5.5–6.5*	6.4	*6.0–6.8*	6.4	*6.0–6.8*	6.3	*6.0–6.8*
4	5.2 G		5.0 G		5.2 G		4.7	*4.1–5.2*	4.6	*4.2–5.0*	5.8	*5.5–6.5*	4.3	*4.0–4.4*	4.3	*4.0–4.8*	4.2	*4.0–4.4*
2	5.0 G		5.0 G		5.2 G		4.6	*4.2–5.2*	4.6	*4.2–5.0*	5.8	*5.4–6.7*	2.1		2.2	*2.0–2.4*	2.0	*2.0–2.4*
4/4	5.1 G		5.0 G		5.2 G		3.7	*3.1–4.2*	3.8	*3.7–4.2*	5.0	*4.5–5.8*	4.4	*4.0–4.8*	4.5	*4.0–4.8*	4.6	*4.0–5.2*
2	5.0 G		5.0 G		6.0 G	*5* G–*7* G	3.7	*3.1–4.1*	3.7	*3.2–4.0*	4.9	*4.4–5.8*	2.2	*2.0–2.4*	2.3	*2.0–2.4*	2.2	*2.0–2.8*
3/4	5.0 G		5.2 G		4.9 G		2.7	*2.3–3.2*	2.9	*2.6–3.1*	4.0	*3.6–4.7*	4.3	*4.0–4.8*	4.4	*4.0–4.8*	4.5	*4.0–4.8*
2	5.1 G		5.0 G		4.9 G		2.7	*2.2–3.1*	2.8	*2.4–2.9*	3.8	*3.4–4.6*	2.3	*2.0–2.8*	2.4	*2.0–2.8*	2.3	*2.0–2.8*
2/2	5.1 G		5.2 G		5.4 G		1.8	*1.6–2.1*	1.9	*1.8–2.1*	2.4	*2.0–2.8*	2.1	*2.0–2.4*	2.2	*2.0–2.8*	2.6	*2.0–2.8*
10 G 7/4	9.8 G		10.0 G		10.0 G		6.8	*6.6–7.1*	7.3	*7.2–7.4*	7.5	*7.2–8.1*	4.0		4.0		4.1	*3.6–4.4*
6/6	10.0 G		10.0 G		0.2 BG		5.8	*5.2–6.2*	6.2	*6.0–6.4*	6.7	*6.3–7.3*	6.0	*5.6–6.0*	6.0	*5.6–6.0*	6.0	*5.6–6.0*
4	0.1 BG		0.1 BG		0.3 BG		5.7	*5.3–6.2*	6.2	*5.7–6.3*	6.7	*6.3–7.3*	4.2	*4.0–4.4*	4.0	*4.0–4.4*	4.0	
5/6	10.0 G		0.2 BG		0.1 BG		4.7	*4.3–5.1*	4.7	*4.2–5.1*	5.7	*5.2–6.5*	6.4	*6.0–6.8*	6.3	*6.0–6.4*	6.4	*6.0–6.8*
4	9.9 G		0.3 BG		10.0 G		4.6	*4.0–5.0*	4.7	*4.2–5.0*	5.7	*5.2–6.5*	4.0		4.0		4.0	
4/4	9.9 G		10.0 G		0.1 BG		3.7	*3.5–4.2*	3.7	*3.5–4.1*	4.8	*4.1–5.7*	4.2	*4.0–4.4*	4.1	*4.0–4.4*	4.1	*4.0–4.4*
3/4	9.8 G		0.1 BG		9.9 G		2.8	*2.3–3.1*	2.7	*2.4–3.0*	3.7	*2.9–4.3*	4.2	*4.0–4.4*	4.2	*4.0–4.4*	4.2	*4.0–4.4*
BG 8/2	4.8 BG		4.9 BG		4.8 BG		8.0	*8.0–8.3*	8.2	*8.0–8.2*	8.2	*8.1–8.5*	2.1		2.0	*2.0–2.4*	1.9	*1.6–2.0*
7/4	4.7 BG		4.7 BG		4.9 BG		6.9	*6.7–7.2*	7.3	*7.2–7.4*	7.5	*7.3–7.9*	4.0	*4.0–4.4*	4.0	*4.0–4.4*	3.9	*3.6–4.0*
2	4.7 BG		4.6 BG		4.6 BG		7.0	*7.0–7.3*	7.3	*7.2–7.4*	7.5	*7.2–7.4*	2.1	*2.0–2.4*	2.0	*2.0–2.4*	2.0	
6/6	4.7 BG		5.0 BG		4.9 BG		5.9	*5.5–6.2*	6.3	*6.1–6.5*	6.7	*6.3–6.6*	6.0	*5.2–6.4*	5.9	*5.2–6.4*	5.8	*5.6–6.0*
4	4.7 BG		4.9 BG		4.8 BG		5.9	*5.5–6.2*	6.3	*5.7–6.4*	6.6	*6.3–6.6*	4.1	*4.0–4.1*	4.0		4.0	
2	4.8 BG		5.0 BG		5.1 BG		5.9	*5.9–6.2*	6.3	*6.2–6.5*	6.6	*6.3–7.2*	2.1	*2.0–2.4*	2.0		2.1	
5/6	5.0 BG		5.0 BG		5.0 BG		4.9	*4.7–5.2*	4.9	*4.7–5.2*	5.7	*5.2–6.3*	6.1	*6.0–6.4*	5.9	*5.6–6.4*	6.0	*5.6–6.0*
4	5.0 BG		5.0 BG		5.1 BG		4.9	*4.7–5.2*	4.8	*4.5–5.1*	5.7	*5.2–6.3*	4.0	*4.0–4.4*	4.0	*4.0–4.4*	3.9	*3.6–4.0*
2	5.0 BG		4.8 BG		5.1 BG		4.8	*4.8–5.2*	4.8	*4.5–5.1*	5.7	*5.4–6.3*	2.1	*2.0–2.4*	2.1	*2.0–2.4*	2.0	*2.0–2.4*
4/6	4.8 BG	*4* BG–*5* BG	5.0 BG		5.3 BG		3.9	*3.8–4.2*	3.9	*3.8–4.2*	4.9	*4.3–5.4*	6.2	*6.0–6.8*	6.2	*6.0–6.4*	6.2	*6.0–6.4*
4	5.1 BG		5.0 BG		5.3 BG		3.8	*3.6–4.2*	3.8	*3.6–4.1*	4.8	*4.4–6.0*	4.0	*4.0–4.4*	4.0	*3.6–4.0*	4.0	*3.6–4.0*
2	5.1 BG		4.9 BG		4.9 BG		3.8	*3.5–4.2*	3.8	*3.8–4.0*	4.8	*4.2–5.2*	2.1	*2.0–2.4*	2.2	*2.0–2.4*	2.1	*2.0–2.8*
3/6	5.0 BG		5.1 BG		5.0 BG		2.9	*2.6–3.3*	2.9	*2.8–3.1*	3.9	*3.6–4.5*	6.1	*6.0–6.8*	6.2	*6.0–6.8*	6.3	*6.0–6.8*
4	4.9 BG		4.8 BG		4.9 BG		2.9	*2.5–3.2*	2.8	*2.8–3.1*	3.8	*3.4–4.3*	4.0	*4.0–4.4*	4.1	*4.0–4.4*	4.2	*4.0–4.8*
2	4.7 BG		5.2 BG		4.9 BG		2.9	*2.4–3.2*	2.8	*2.8–3.1*	3.8	*3.6–4.4*	2.2	*2.0–2.4*	2.2	*2.2–2.8*	2.2	*1.6–2.8*
2/4	4.9 BG		5.0 BG		4.8 BG		2.0	*1.6–2.3*	2.0	*1.7–2.2*	2.5	*2.2–3.3*	4.0	*3.6–4.4*	4.2	*4.0–4.8*	4.4	*3.6–5.2*
2	4.9 BG		5.0 BG		4.7 BG		1.9	*1.4–2.2*	2.0	*1.9–2.3*	2.5	*2.2–3.2*	2.0	*2.0–2.4*	2.1	*2.0–2.8*	2.2	*1.6–2.4*
10 BG 7/4	10.0 BG		10.0 BG		9.9 BG		6.8	*6.0–7.2*	7.3	*7.2–7.6*	7.5	*7.3–7.9*	4.1		4.0		4.0	*3.6–4.4*
6/6	10.0 BG		9.8 BG		9.9 BG		5.8	*4.9–6.2*	6.2	*5.9–6.4*	6.6	*6.2–6.9*	6.1	*6.0–6.4*	6.0	*5.6–6.0*	6.1	*6.0–6.4*
4	10.0 BG		9.7 BG		9.9 BG		5.7	*4.9–6.1*	6.2	*6.0–6.4*	6.5	*6.1–6.8*	4.1		4.1		4.0	
5/6	0.1 B		10.0 BG		0.2 B		4.8	*4.0–5.3*	4.8	*4.3–5.1*	5.6	*5.1–5.9*	6.2	*6.0–6.4*	6.2	*6.0–6.8*	6.1	*6.0–6.4*
4	0.1 B		0.1 B		10.0 BG		4.7	*3.9–5.0*	4.7	*4.2–5.0*	5.5	*5.0–5.7*	4.0		4.0		4.0	
4/6	9.5 BG	*9* BG–*10* BG	9.8 BG		10.0 BG		3.7	*2.9–4.0*	3.8	*3.3–4.0*	4.6	*4.1–5.2*	6.0	*5.6–6.0*	6.0	*6.0–6.4*	6.0	
4	9.6 BG	*9* BG–*10* BG	10.0 BG	*9* BG–*10* BG	10.0 BG	*9* BG–*10* BG	3.7	*2.8–4.0*	3.7	*3.2–4.0*	4.5	*4.0–5.2*	4.0	*3.6–4.0*	4.1	*4.0–4.4*	4.0	

TABLE II.—*Continued.*

1929 Munsell Notation	Visual Estimates, Average and 80% Range																	
	Hue						Value						Chroma					
	White		Gray		Black		White		Gray		Black		White		Gray		Black	
H V/C	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range
10 BG 3/6	10.0 BG		10.0 BG	*9* BG–*10* BG	9.8 BG		2.8	*2.0–3.2*	2.8	*2.6–3.1*	3.5	*3.0–4.0*	6.1		6.1	*6.0–6.4*	6.3	*6.0–6.8*
4	10.0 BG		9.7 BG		9.7 BG		2.8	*2.0–3.2*	2.8	*2.5–3.2*	3.5	*3.0–4.0*	4.0		4.1		4.2	*4.0–4.8*
B 8/4	4.8 B		4.9 B		4.8 B		7.9	*7.5–8.3*	8.1	*8.0–8.1*	8.3	*8.1–8.5*	4.1	*4.0–4.4*	3.9	*3.2–4.0*	3.9	*3.6–4.0*
2	5.3 B		5.0 B		4.9 B		8.0	*7.5–8.3*	8.1	*8.0–8.2*	8.4	*8.1–8.7*	2.1	*2.0–2.4*	2.0	*2.0–2.4*	2.0	*2.0–2.4*
7/6	4.9 B		4.9 B		4.8 B		6.7	*6.2–7.2*	7.2	*7.2–7.4*	7.6	*7.3–8.0*	5.9	*5.2–6.0*	5.8	*5.2–6.0*	5.8	
4	5.0 B		4.9 B		4.6 B		6.8	*6.2–7.3*	7.2	*7.2–7.4*	7.7	*7.3–8.0*	4.0	*3.6–4.0*	4.0		4.0	*4.0–4.4*
2	5.0 B		5.1 B		4.7 B		6.9	*6.4–7.3*	7.2	*7.2–7.5*	7.7	*7.3–8.0*	2.0	*1.6–2.0*	2.0	*1.6–2.0*	2.0	*1.6–2.0*
6/6	5.0 B		4.8 B		4.9 B		5.8	*5.3–6.4*	6.1	*5.7–6.3*	6.8	*6.4–7.0*	6.5	*6.0–6.8*	6.4	*6.0–6.8*	6.3	*6.0–6.8*
4	5.0 B		5.0 B		5.0 B		5.7	*5.5–6.3*	6.1	*6.0–6.3*	6.7	*6.4–7.0*	4.1	*4.0–4.4*	4.1	*4.0–4.4*	4.1	*4.0–4.4*
2	5.0 B		5.1 B		5.3 B		5.7	*5.5–6.2*	6.1	*6.0–6.4*	6.7	*6.4–7.1*	2.1	*2.0–2.4*	2.0	*2.0–2.4*	2.2	*2.0–2.4*
5/6	4.9 B		4.9 B		5.0 B		4.7	*4.0–5.3*	4.8	*4.4–5.1*	5.8	*5.4–6.2*	6.3	*6.0–6.8*	6.4	*6.0–6.8*	6.4	*6.0–6.8*
4	5.2 B		4.8 B		5.0 B		4.6	*4.0–5.1*	4.7	*4.5–5.3*	5.7	*5.3–6.2*	4.1	*4.0–4.4*	4.4	*4.0–4.8*	4.4	*4.0–4.8*
2	5.2 B		5.2 B		5.3 B		4.6	*4.0–5.1*	4.7	*4.5–5.3*	5.7	*5.5–6.5*	2.0		2.0	*2.0–2.4*	2.0	*1.6–2.4*
4/8	4.8 B		5.1 B		4.9 B		3.7	*3.0–4.2*	3.8	*3.3–4.1*	4.9	*4.5–5.9*	8.1	*8.0–8.4*	8.2	*8.0–8.8*	8.3	*8.0–8.8*
6	4.6 B	*4* B–*5* B	5.2 B		5.0 B		3.7	*3.0–4.1*	3.7	*3.3–4.1*	4.9	*4.5–5.7*	6.0	*6.0–6.4*	6.2	*6.0–6.8*	6.4	*6.0–6.8*
4	4.7 B		5.0 B		5.0 B		3.7	*3.1–4.1*	3.8	*3.4–4.1*	4.9	*4.3–5.2*	4.1	*3.6–4.4*	4.2	*4.0–4.8*	4.3	*4.0–4.8*
2	4.9 B		5.0 B		5.3 B		3.7	*3.0–4.1*	3.7	*3.4–4.3*	4.9	*3.3–4.2*	2.0	*2.0–2.4*	2.0	*1.6–2.4*	2.2	*2.0–2.4*
3/6	4.7 B		4.6 B	*4* B–*5* B	4.8 B		2.8	*2.1–3.3*	2.8	*2.5–3.1*	3.8	*3.3–4.0*	6.0	*6.0–6.4*	6.3	*6.0–6.8*	6.3	*6.0–6.8*
4	5.0 B		4.7 B		4.9 B		2.7	*2.1–3.1*	2.7	*2.6–3.1*	3.7	*3.2–4.0*	4.0		4.1	*4.0–4.4*	4.3	*4.0–4.4*
2	4.7 B		4.8 B		5.2 B		2.7	*2.1–3.1*	2.7	*2.6–3.1*	3.7	*3.2–4.0*	2.0	*1.6–2.0*	2.0	*1.6–2.0*	2.0	*2.0–2.4*
2/2	4.5 B		4.4 B	*3* B–*5* B	4.5 B		1.8	*1.4–2.2*	1.9	*1.6–2.1*	2.4	*2.1–2.8*	1.9		2.0	*1.6–2.0*	2.0	*1.6–2.0*
10 B 7/6	9.7 B		9.9 B		9.9 B		6.9	*6.9–7.2*	7.3	*7.1–7.4*	7.4	*7.3–7.7*	6.3	*6.0–6.4*	6.1	*5.6–6.4*	6.1	*6.0–6.4*
4	9.7 B		9.8 B		9.8 B		6.8	*6.9–7.0*	7.2	*7.1–7.3*	7.4	*7.2–7.7*	4.1	*4.0–4.4*	4.0		4.0	*4.0–4.4*
6/6	9.7 B		9.6 B		9.7 B		5.9	*5.8–6.2*	6.2	*6.1–6.4*	6.6	*6.3–6.8*	6.2	*6.0–6.4*	6.1	*6.0–6.4*	6.0	*6.0–6.4*
/4	9.6 B		9.7 B		9.7 B		5.8	*5.8–6.1*	6.2	*6.1–6.3*	6.6	*6.3–6.8*	4.1	*4.0–4.4*	3.9		4.0	*4.0–4.4*
5/6	9.9 B		9.9 B		9.9 B		4.8	*4.8–5.1*	4.8	*4.7–5.1*	5.8	*5.4–5.9*	6.1	*6.0–6.4*	6.0	*6.0–6.4*	6.1	
4	9.9 B		9.9 B		9.9 B		4.8	*4.7–5.1*	4.7	*4.7–5.1*	5.7	*5.4–5.9*	4.0		4.0	*3.6–4.0*	4.0	*3.6–4.0*
4/8	9.8 B		9.7 B		9.6 B	*9* B–*10* B	4.0	*3.8–4.3*	3.7	*3.7–4.1*	4.9	*4.5–5.2*	8.0	*7.6–8.0*	8.0	*8.0–8.4*	8.1	*8.0–8.4*
6	9.8 B		9.9 B		9.9 B		3.9	*3.7–4.2*	3.7	*3.3–4.0*	4.9	*4.5–5.2*	6.0		6.0		6.2	*6.0–6.8*
4	9.9 B		9.9 B		10.0 B	*10* B–*2* PB	3.9	*3.7–4.2*	3.7	*3.6–4.1*	4.8	*4.4–5.2*	3.9	*3.6–4.0*	3.9	*3.6–4.0*	3.9	*3.6–4.0*
3/8	9.7 B	*9* B–*10* B	9.8 B		9.7 B	*9* B–*10* B	3.0	*2.8–4.3*	2.9	*2.6–3.0*	3.8	*3.5–4.1*	8.0	*7.6–8.4*	8.3	*8.0–8.8*	8.4	*8.0–8.8*
6	9.8 B	*9* B–*10* B	9.8 B		9.7 B		3.0	*2.7–3.2*	2.9	*2.5–3.0*	3.8	*3.5–5.1*	6.0		6.0	*6.0–6.4*	6.2	*6.0–6.8*
4	9.9 B	*9* B–*10* B	9.8 B		9.8 B	*9* B–*10* B	3.0	*2.6–3.2*	2.8	*2.8–3.1*	3.8	*3.5–4.1*	4.0	*3.6–4.0*	4.1	*3.6–4.0*	4.1	*4.0–4.4*
PB 8/2	4.7 PB		4.8 PB		4.6 PB		8.1	*8.0–8.4*	8.4	*8.0–8.5*	8.4	*8.0–8.4*	2.4	*2.0–2.8*	2.0	*2.0–2.4*	2.1	*2.0–2.4*
7/6	4.7 PB		5.0 PB		4.6 PB		6.8	*6.8–7.1*	7.4	*7.2–7.6*	7.5	*7.2–8.3*	6.0	*6.0–6.4*	5.8	*5.2–6.0*	5.9	*5.6–6.4*
4	4.7 PB		4.7 PB		4.8 PB		6.9	*6.8–7.2*	7.4	*7.2–7.6*	7.5	*7.2–8.5*	4.1	*4.0–4.4*	3.9	*3.6–4.4*	4.1	*4.0–4.4*
2	4.8 PB		5.0 PB		4.9 PB		6.9	*6.7–7.1*	7.4	*7.2–7.8*	7.5	*7.0–7.5*	2.2	*2.0–2.8*	2.0	*1.6–2.4*	2.0	
6/8	4.7 PB		4.8 PB		4.7 PB	*4* PB–*5* PB	5.7	*5.6–6.1*	6.2	*5.9–6.5*	6.7	*6.2–6.6*	8.1	*8.0–8.8*	8.1	*7.6–8.4*	7.8	*7.6–8.0*
6	4.6 PB		4.8 PB		4.9 PB		5.8	*5.6–6.1*	6.2	*6.0–6.4*	6.7	*6.2–6.6*	6.0	*5.6–6.0*	6.0	*5.6–6.4*	5.9	*5.6–6.0*
4	4.7 PB		4.8 PB		4.8 PB		5.8	*5.6–6.1*	6.3	*6.1–6.4*	6.7	*6.2–6.6*	4.0	*3.6–4.4*	3.8	*3.2–4.0*	3.8	*3.6–4.0*
2	5.2 PB		5.2 PB		5.1 PB		5.7	*5.6–6.2*	6.2	*5.9–6.4*	6.7	*6.2–7.7*	2.2	*2.0–2.4*	2.0	*1.6–2.0*	2.0	*2.0–2.4*
5/10	4.9 PB		4.9 PB		4.9 PB		4.8	*4.4–5.2*	4.8	*4.6–5.2*	5.9	*5.3–5.9*	10.0	*9.2–10.0*	10.0	*10.0–10.4*	10.1	*9.6–10.4*
8	4.7 PB		4.8 PB		4.8 PB		4.7	*4.2–5.2*	4.8	*4.5–5.1*	5.8	*5.3–7.0*	8.1	*8.0–8.4*	8.1	*8.0–8.4*	8.1	*8.0–8.8*
6	4.8 PB		5.0 PB		4.9 PB		4.7	*4.3–5.1*	4.8	*4.4–5.1*	5.8	*5.3–7.0*	5.9		5.9	*5.6–6.0*	6.0	*5.6–6.0*
4	4.9 PB		5.2 PB	*3* PB–*6* PB	5.0 PB		4.7	*4.3–5.0*	4.8	*4.4–5.0*	5.7	*5.3–6.9*	4.0		4.0		4.1	*4.0–4.4*
2	4.9 PB		5.7 PB	*3* PB–*8* PB	5.4 PB		4.6	*4.3–5.0*	4.8	*4.4–5.0*	5.7	*5.1–6.8*	2.1	*2.0–2.4*	2.2	*2.0–2.4*	2.2	*2.0–2.4*
4/10	4.6 PB		4.3 PB	*3* PB–*5* PB	4.4 PB	*4* PB–*5* PB	3.8	*3.4–4.3*	3.9	*3.4–4.3*	5.0	*4.3–6.0*	10.1	*9.6–10.4*	10.1	*10.0–10.4*	10.1	*10.0–10.4*
8	4.7 PB		4.5 PB	*4* PB–*5* PB	4.7 PB		3.7	*3.3–4.2*	3.8	*3.3–4.1*	4.9	*4.2–5.2*	8.0	*8.0–8.4*	8.0	*7.6–8.4*	8.0	*8.0–8.4*
6	4.6 PB		4.6 PB	*4* PB–*6* PB	4.6 PB		3.7	*3.3–4.1*	3.8	*3.2–4.1*	4.8	*4.2–5.8*	6.0	*5.6–6.0*	5.9		6.0	*5.6–6.0*
4	4.7 PB		4.7 PB	*4* PB–*6* PB	4.8 PB		3.7	*3.3–4.0*	3.8	*3.2–4.1*	4.8	*4.2–5.8*	3.9		4.0		3.9	*3.6–4.0*
2	4.9 PB		4.8 PB		4.9 PB		3.7	*3.2–4.0*	3.7	*3.1–4.1*	4.8	*4.2–5.7*	1.9	*1.6–2.0*	2.0	*1.6–2.0*	2.0	*1.6–2.4*

TABLE II.—*Continued.*

1929 Munsell Notation	Visual Estimates, Average and 80% Range																	
	Hue						Value						Chroma					
	White		Gray		Black		White		Gray		Black		White		Gray		Black	
H V/C	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range
PB 3/12	4.8 PB		4.6 PB	4 PB–5 PB	4.5 PB		2.8	2.4–3.2	2.9	2.5–3.3	3.8	3.4–4.9	11.7	10.8–12.0	11.9	12.0–12.4	11.9	11.6–12.4
10	4.8 PB		4.4 PB	3 PB–5 PB	4.7 PB		2.8	2.4–3.2	2.9	2.5–3.3	3.8	3.3–4.8	9.9	9.6–10.4	10.0	9.2–10.4	9.9	10.0–10.4
8	4.7 PB		4.6 PB	4 PB–5 PB	4.6 PB		2.7	2.4–3.2	2.8	2.4–3.1	3.8	3.3–4.8	8.2	8.0– 8.8	7.9	7.6– 8.4	7.9	8.0– 8.8
6	5.0 PB		4.6 PB	4 PB–5 PB	4.6 PB		2.7	2.4–3.1	2.9	2.5–3.1	3.7	3.3–4.7	5.7	5.2– 6.0	5.9	5.6– 6.0	6.0	5.6– 6.0
4	5.0 PB		4.7 PB		4.8 PB		2.7	2.2–3.0	2.8	2.4–3.1	3.6	3.2–4.5	3.9	3.6– 4.0	3.9	3.6– 4.0	4.0	3.6– 4.4
2	5.0 PB		4.7 PB		5.0 PB		2.7	2.2–3.0	2.8	2.4–3.1	3.6	3.2–4.5	2.0	1.6– 2.0	1.9	1.2– 2.0	1.9	1.2– 2.0
2/6	4.8 PB		4.7 PB		4.7 PB		1.9	1.7–2.2	1.9	1.7–2.1	2.6	2.1–2.8	6.0		6.2	5.2– 6.8	6.5	6.0– 6.8
4	4.8 PB		4.7 PB		4.8 PB		1.9	1.6–2.1	1.9	1.6–2.0	2.4	2.0–3.0	4.1	4.0– 4.4	4.4	4.0– 4.8	4.3	4.0– 4.8
2	4.9 PB		5.1 PB		5.0 PB		1.9	1.5–2.2	1.9	1.6–2.0	2.4	2.0–3.0	2.0	1.6– 2.0	2.1	1.6– 2.4	2.3	1.6– 2.8
10 PB 7/6	0.2 P		0.1 P		10.0 PB		6.8	6.2–7.1	7.2	7.0–7.3	7.6	7.2–8.0	5.8	5.2– 6.0	5.7	5.2– 6.0	5.6	5.2– 6.0
4	10.0 PB		0.1 P		0.1 P		6.8	6.2–7.1	7.2	7.0–7.3	7.6	7.2–8.0	3.9	3.6– 4.0	3.7	3.2– 4.0	3.8	3.2– 4.0
6/8	10.0 PB		0.1 P		10.0 PB		5.8	5.4–6.2	6.2	5.9–6.5	6.7	6.2–7.3	7.9	8.0– 8.4	7.9	7.6– 8.8	7.7	7.6– 8.0
6	10.0 PB		0.2 P		10.0 PB		5.8	5.3–6.2	6.2	5.9–6.4	6.7	6.3–7.3	6.0	5.6– 6.4	5.8	5.6– 6.4	5.8	5.6– 6.0
4	10.0 PB		0.2 P		10.0 PB		5.8	5.2–6.2	6.2	5.9–6.4	6.7	6.3–7.5	4.1	4.0– 4.4	3.9	3.6– 4.4	3.9	4.0– 4.4
5/10	9.9 PB		10.0 PB		10.0 PB		4.7	4.3–5.2	4.7	4.4–5.2	5.8	5.1–6.7	10.0	10.0–10.4	9.8	9.2–10.0	9.7	9.2–10.0
8	9.9 PB		10.0 PB		9.9 PB		4.8	4.3–5.2	4.7	4.3–5.2	5.8	5.3–6.7	8.0	7.6– 8.4	8.0	7.6– 8.4	7.9	7.6– 8.4
6	9.9 PB		10.0 PB		9.9 PB		4.8	4.2–5.2	4.7	4.5–5.2	5.8	5.4–6.7	6.0		5.9	5.6– 6.0	6.0	5.6– 6.0
4	9.9 PB		0.2 P		9.9 PB		4.7	4.1–5.2	4.7	4.4–5.2	5.8	5.4–6.7	4.0		4.1	4.0– 4.4	4.1	4.0– 4.4
4/10	10.0 PB		9.6 PB		10.0 PB		3.8	3.0–4.2	3.7	3.4–4.1	4.9	4.3–5.8	10.0	10.0–10.4	10.0	10.0–10.4	10.0	10.0–10.4
8	0.1 P		0.3 P		10.0 PB		3.8	3.7–4.3	3.7	3.5–4.2	4.9	4.5–5.9	8.1	8.0– 8.4	8.1	8.0– 8.4	8.1	8.0– 8.4
6	0.1 P		0.2 P		10.0 PB		3.8	3.1–4.2	3.8	3.4–4.2	4.9	4.3–5.7	6.1	6.0– 6.4	6.1	6.0– 6.4	6.1	6.0– 6.8
4	0.2 P		0.1 P		9.9 PB		3.8	3.0–4.2	3.6	3.2–3.9	4.9	4.3–5.6	4.0		4.1	4.0– 4.4	4.1	4.0– 4.4
3/10	0.1 P		9.9 PB		10.0 PB		2.9	2.3–3.3	2.8	2.4–3.2	3.8	3.3–4.6	10.3	10.0–10.8	10.3	10.0–10.8	10.3	10.0–11.6
8	0.2 P		9.9 PB		10.0 PB		2.9	2.2–3.3	2.8	2.4–3.2	3.8	3.3–4.2	7.9	7.6– 8.0	8.0	7.6– 8.0	8.1	7.6– 8.8
6	0.2 P		10.0 PB		10.0 PB		2.9	2.1–3.3	2.8	2.7–3.2	3.8	3.3–4.2	6.1	6.0– 6.4	6.0	5.6– 6.8	6.2	5.6– 6.8
4	0.3 P		10.0 PB		0.1 P		2.9	2.1–3.3	2.8	2.7–3.2	3.8	3.3–4.2	4.1	4.0– 4.4	4.2	4.0– 4.8	4.3	4.0– 4.8
2/6	*		*		*		1.8	1.5–2.2	1.9	1.6–2.0	2.4	2.1–2.7	5.5	4.4– 6.0	6.2	4.8– 6.8	7.5	6.0– 7.6
4	*		*		*		1.8	1.5–2.2	1.9	1.7–2.1	2.4	2.1–2.8	4.1	3.6– 4.4	4.2	3.6– 4.8	5.8	3.6– 5.6
P 8/4	5.2 P		5.4 P	5 P–7 P	5.1 P		7.9	7.8–8.2	8.2	8.0–8.3	8.3	8.0–8.5	4.4	4.0– 4.8	4.2	4.0– 4.8	4.3	4.0– 4.8
2	5.2 P		5.3 P		5.2 P		8.1	7.9–8.4	8.1	8.0–8.2	8.3	8.1–8.5	2.1	2.0– 2.4	1.9	1.6– 2.0	2.0	2.0– 2.4
7/6	5.2 P		4.8 P		5.1 P		6.8	6.4–7.3	7.2	7.0–7.4	7.5	7.3–7.9	6.5	6.0– 6.8	6.4	6.0– 6.8	6.4	5.6– 6.8
4	5.0 P		4.8 P		5.0 P		6.8	6.8–7.2	7.2	7.0–7.4	7.5	7.2–7.8	4.2	4.0– 4.8	4.1	3.6– 4.8	4.1	4.0– 4.8
2	4.9 P		4.9 P		5.0 P		6.7	6.2–7.1	7.1	7.1–7.4	7.5	7.2–8.0	2.2	2.0– 2.4	2.1	1.6– 2.4	2.1	2.0– 2.4
6/8	5.1 P		5.2 P		5.1 P		5.7	5.5–6.2	6.0	5.7–6.4	6.7	6.3–7.2	8.3	8.0– 8.8	8.1	8.0– 8.8	8.0	7.2– 8.4
6	5.0 P		5.2 P		5.0 P		5.7	5.3–6.0	6.0	5.7–6.3	6.7	6.3–7.2	6.2	6.0– 6.8	6.1	5.6– 6.4	6.0	6.0– 6.4
4	5.0 P		5.2 P		5.0 P		5.7	5.3–6.0	6.0	5.7–6.3	6.7	6.2–7.2	4.1	4.0– 4.4	4.1	4.0– 4.8	4.0	3.6– 4.4
2	4.8 P		5.2 P		5.2 P		5.8	5.5–6.1	6.0	5.6–6.2	6.7	6.3–7.2	2.2	2.0– 2.4	2.2	2.0– 2.4	2.2	2.0– 2.4
5/10	5.2 P		5.0 P		5.1 P		4.8	4.6–5.2	4.5	4.2–5.0	5.8	5.2–6.5	10.2	10.0–10.8	10.1	10.0–10.4	10.1	10.0–10.4
8	5.1 P		5.0 P		5.0 P		4.7	4.2–5.1	4.5	4.2–5.0	5.8	5.2–6.5	8.1	8.0– 8.4	8.1	7.6– 8.4	8.1	8.0– 8.4
6	5.1 P		5.0 P		5.1 P		4.7	4.7–5.1	4.5	4.2–5.0	5.8	5.2–6.5	6.1	6.0– 6.4	6.2	6.0– 6.8	6.1	6.0– 6.8
4	5.1 P		5.0 P		5.0 P		4.7	4.5–5.1	4.5	4.2–4.8	5.8	5.4–6.5	4.0		4.2	4.0– 4.4	4.2	4.0– 4.8
2	5.1 P		5.0 P		4.9 P		4.7	4.5–5.1	4.5	4.2–5.0	5.7	5.3–6.5	2.0		2.2	2.0– 2.4	2.1	2.0– 2.4
4/12	5.3 P	5 P–6 P	5.4 P	5 P–6 P	5.3 P		3.8	3.7–4.2	3.7	3.4–4.1	4.9	4.3–5.7	12.4	12.0–12.8	12.1	12.0–12.8	12.2	12.0–12.8
10	5.3 P		5.1 P		5.2 P	5 P–6 P	3.7	3.2–4.0	3.6	3.2–4.0	4.9	4.3–5.7	10.0	9.6–10.0	9.9	9.6–10.0	9.9	9.2–10.0
8	5.2 P		5.2 P		5.1 P		3.7	3.1–4.0	3.6	3.2–3.9	4.9	4.3–5.7	8.1		8.1	7.6– 8.4	8.0	8.0– 8.4
6	5.1 P	5 P–6 P	5.1 P		5.1 P		3.7	3.6–4.0	3.6	3.2–4.0	4.8	4.2–5.7	5.9	5.6– 6.0	5.9	5.6– 6.0	5.8	5.6– 6.0
4	5.1 P		5.1 P		5.2 P		3.7	3.7–4.0	3.6	3.2–4.0	4.9	4.3–5.7	4.0		4.0	3.6– 4.0	3.9	
2	5.1 P		4.6 P		5.0 P		3.7	3.6–4.0	3.5	3.2–4.0	4.9	4.3–5.7	1.9		2.0	1.6– 2.4	2.1	2.0– 2.8
3/10	5.2 P		5.3 P		5.5 P	5 P–6 P	2.9	2.2–3.2	2.9	2.4–3.2	3.8	3.3–4.4	10.0	10.0–10.8	10.6	10.0–10.8	10.4	10.0–10.8
8	5.1 P		5.2 P		5.3 P		2.8	2.2–3.1	2.7	2.4–3.0	3.7	3.2–4.0	8.1	8.0– 8.4	8.1	8.0– 8.4	8.1	8.0– 8.8
6	5.0 P		5.1 P		5.2 P		2.8	2.5–3.2	2.7	2.4–3.0	3.7	3.2–4.0	6.1	6.0– 6.4	6.1		6.0	6.0– 6.4
4	5.2 P		5.2 P		5.2 P		2.8	2.5–3.2	2.7	2.4–3.0	3.7	3.2–4.0	4.1	4.0– 4.4	4.2	4.0– 4.4	4.1	4.0– 4.4
2	5.1 P		5.3 P		5.3 P		2.8	2.3–3.2	2.7	2.4–3.0	3.7	3.3–4.0	2.0	2.0– 2.4	1.9	1.6– 2.4	2.0	1.6– 2.4
2/6	5.1 P		5.2 P		5.2 P		1.9	1.6–2.2	1.9	1.6–2.1	2.5	1.9–2.7	6.2	6.0– 6.4	6.7	6.0– 6.8	6.6	6.0– 6.8
4	5.1 P		5.2 P		5.1 P		1.9	1.6–2.1	1.8	1.6–2.1	2.5	2.2–2.8	4.1	3.2– 4.0	4.1	4.0– 4.8	4.0	3.2– 4.8
2	5.0 P		5.1 P		5.1 P		1.8	1.6–2.1	1.9	1.6–2.1	2.5	2.2–2.7	2.4	2.0– 2.8	2.8	2.0– 2.8	2.8	2.0– 3.2

TABLE II.—*Continued.*

1929 Munsell Notation	Visual Estimates, Average and 80% Range																	
	Hue						Value						Chroma					
	White		Gray		Black		White		Gray		Black		White		Gray		Black	
H V/C	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range
10 P 8/4	9.9 P		0.4 RP		0.2 RP		7.9	*7.8–8.1*	8.3	*8.0–8.4*	8.3	*8.1–8.5*	4.0		3.9		3.8	*3.2– 4.0*
7/8	0.3 RP		0.2 RP		0.2 RP		6.7	*6.4–7.2*	7.4	*7.2–7.3*	7.5	*7.2–7.9*	7.9	*7.6– 8.8*	7.8	*6.4– 8.4*	7.6	*7.2– 8.0*
6	0.2 RP		0.3 RP		0.1 RP		6.7	*6.6–7.1*	7.4	*7.2–7.4*	7.6	*7.2–7.9*	5.7	*5.2– 6.0*	5.6	*5.2– 6.0*	5.7	*5.2– 6.0*
4	0.3 RP		0.3 RP		0.2 RP		6.7	*6.6–7.1*	7.4	*7.2–7.4*	7.6	*7.2–7.9*	4.1	*4.0– 4.4*	4.0	*3.6– 4.4*	3.9	*3.6– 4.0*
6/8	0.2 RP		0.2 RP		10.0 P		5.7	*5.6–6.1*	6.2	*6.0–6.6*	6.7	*6.4–6.8*	8.0	*8.0– 8.4*	7.9	*7.6– 8.0*	7.9	*7.6– 8.4*
6	0.3 RP		0.2 RP		10.0 P		5.6	*5.4–6.1*	6.2	*6.0–6.4*	6.7	*6.4–7.3*	5.9	*5.6– 6.0*	5.9	*5.6– 6.0*	5.9	*6.0– 6.4*
4	0.1 RP		0.1 RP		10.0 P		5.6	*5.4–6.1*	6.2	*6.0–6.4*	6.8	*6.4–7.3*	4.0		4.0		4.0	*4.0– 4.4*
5/10	0.3 RP		0.5 RP	*10* P–*1* RP	0.4 RP	*10* P–*1* RP	4.7	*4.4–5.2*	4.8	*4.2–5.1*	5.8	*5.5–6.5*	10.1	*10.0–10.8*	10.1	*9.6–10.4*	10.0	*10.0–10.4*
8	0.3 RP		0.3 RP	*9* P–*1* RP	0.3 RP		4.7	*4.4–5.1*	4.7	*4.2–5.1*	5.8	*5.4–6.5*	8.0	*8.0– 8.4*	8.1	*8.0– 8.4*	8.0	
6	0.2 RP		0.3 RP	*10* P–*1* RP	0.3 RP		4.6	*4.4–5.1*	4.7	*4.2–5.1*	5.8	*5.4–6.5*	6.0	*5.6– 6.0*	6.1	*6.0– 6.4*	6.0	*5.6– 6.4*
4	0.1 RP		0.1 RP		0.1 RP		4.6	*4.3–5.1*	4.7	*4.2–5.1*	5.8	*5.4–6.5*	4.0	*3.6– 4.0*	4.1	*4.0– 4.8*	4.0	*4.0– 4.4*
4/10	0.2 RP		0.3 RP		0.1 RP		3.7	*3.3–4.3*	3.9	*3.7–4.4*	5.0	*5.5–6.6*	10.3	*10.0–10.8*	10.1	*10.0–10.4*	10.1	*10.0–10.8*
8	0.1 RP		0.3 RP		0.2 RP		3.7	*3.4–4.2*	3.8	*3.3–4.3*	4.9	*4.4–5.6*	8.0	*8.0– 8.4*	8.0	*7.6– 8.4*	7.9	*7.6– 8.0*
6	10.0 P		0.2 RP		0.2 RP		3.8	*3.2–4.2*	3.9	*3.6–4.4*	4.9	*4.4–5.6*	6.0	*5.6– 6.0*	6.0		5.9	*5.6– 6.4*
4	10.0 P		0.2 RP		9.8 P		3.6	*3.2–4.1*	3.8	*3.6–4.4*	4.9	*4.4–5.6*	4.0		4.0		3.9	
3/10	0.1 RP		10.0 P		9.9 P		2.7	*2.3–3.1*	2.9	*2.4–3.3*	4.0	*3.5–4.8*	10.0	*9.6–10.4*	10.1	*9.6–10.4*	10.1	*9.6–10.8*
8	0.1 RP		0.1 RP		0.2 RP		2.7	*2.3–3.1*	2.9	*2.4–3.3*	4.0	*3.4–4.8*	8.1	*8.0– 8.4*	8.2	*8.0– 8.8*	8.2	*8.0– 8.8*
6	10.0 P		0.1 RP		9.9 P		2.7	*2.3–3.1*	2.8	*2.4–3.3*	3.9	*3.3–4.0*	6.1	*6.0– 6.4*	6.2	*6.0– 6.4*	6.1	*6.0– 6.4*
4	0.2 RP	*10* P–*2* RP	10.0 P		0.3 RP		2.6	*2.1–3.1*	2.8	*2.4–3.3*	3.9	*3.3–4.0*	4.0	*4.0– 4.4*	4.1	*4.0– 4.4*	4.2	*4.0– 4.8*
2/6	*		*		*		1.8	*1.6–2.1*	1.9	*1.6–2.1*	2.4	*2.1–2.7*	5.8	*5.2– 6.0*	6.6	*6.0– 7.2*	7.7	*6.8– 7.6*
4	*		*		*		1.8	*1.6–2.1*	1.9	*1.6–2.2*	2.4	*2.1–2.7*	4.1	*4.0– 4.4*	4.5	*4.0– 4.8*	5.6	*4.4– 5.6*
RP 8/6	5.4 RP	*5* RP–*6* RP	5.2 RP	*5* RP–*6* RP	5.4 RP	*5* RP–*6* RP	8.0	*7.7–8.4*	8.1	*8.0–8.2*	8.3	*8.2–8.6*	5.6	*5.2– 6.0*	5.5	*4.8– 6.0*	5.5	*4.8– 6.0*
4	5.4 RP	*3* RP–*7* RP	5.2 RP	*5* RP–*7* RP	5.3 RP	*5* RP–*7* RP	7.9	*7.7–8.2*	8.0	*8.0–8.3*	8.3	*8.1–8.7*	3.8	*3.2– 4.0*	3.7	*2.8– 4.0*	3.8	*2.8– 4.0*
2	5.6 RP	*5* RP–*7* RP	5.2 RP	*5* RP–*6* RP	5.4 RP	*5* RP–*6* RP	8.1	*7.9–8.5*	8.3	*8.1–8.5*	8.3	*8.1–8.6*	2.1	*2.0– 2.4*	2.2	*2.0– 2.8*	1.9	*1.6– 2.4*
7/8	5.3 RP		5.3 RP		5.2 RP		6.8	*6.4–7.2*	7.4	*7.1–7.6*	7.6	*7.3–7.7*	7.6	*7.2– 8.0*	7.4	*6.8– 8.4*	7.4	*6.8– 8.0*
6	5.3 RP		5.3 RP		5.2 RP		6.8	*6.4–7.2*	7.3	*7.2–7.5*	7.6	*7.3–8.0*	5.7	*5.2– 6.0*	5.7	*5.2– 6.0*	5.7	*5.2– 6.4*
4	5.4 RP		5.3 RP		5.1 RP		6.8	*6.5–7.2*	7.4	*7.2–7.6*	7.6	*7.3–7.9*	3.8	*3.6– 4.0*	3.8	*3.2– 4.0*	3.8	*3.2– 4.0*
2	5.0 RP		5.2 RP		4.9 RP	*5* RP–*6* RP	6.8	*6.6–7.2*	7.4	*7.2–7.5*	7.6	*7.3–7.9*	1.8	*1.6– 2.0*	1.9	*1.6– 2.0*	1.8	*1.2– 2.0*
6/10	5.3 RP	*5* RP–*6* RP	5.4 RP	*5* RP–*6* RP	5.2 RP		5.7	*5.3–6.2*	6.1	*5.8–6.3*	6.7	*6.4–7.2*	9.6	*9.2–10.0*	9.7	*8.8–10.0*	9.8	*9.2–10.0*
8	5.3 RP	*5* RP–*6* RP	5.4 RP	*5* RP–*6* RP	5.2 RP		5.7	*5.3–6.3*	6.2	*5.8–6.3*	6.7	*6.4–7.2*	7.9	*7.2– 8.0*	7.8	*7.2– 8.0*	7.9	*7.2– 8.0*
6	5.3 RP	*5* RP–*6* RP	5.4 RP	*5* RP–*6* RP	5.2 RP		5.6	*5.3–6.2*	6.1	*5.8–6.3*	6.8	*6.4–7.5*	5.9	*5.6– 6.0*	5.8	*5.2– 6.0*	5.9	*5.6– 6.0*
4	5.2 RP		5.3 RP		5.1 RP	*5* RP–*6* RP	5.6	*5.4–6.0*	6.1	*5.8–6.3*	6.7	*6.3–7.5*	3.9		3.9	*3.6– 4.0*	3.9	
2	4.9 RP		5.3 RP	*5* RP–*7* RP	5.0 RP	*5* RP–*6* RP	5.6	*5.4–6.2*	6.1	*6.0–6.3*	6.8	*6.3–7.6*	1.9	*1.6– 2.0*	1.9	*1.6– 2.0*	1.9	*1.6– 2.0*
5/10	5.2 RP		5.3 RP		5.1 RP		4.7	*4.1–5.3*	4.7	*4.2–5.2*	5.9	*5.4–6.5*	10.0	*9.6–10.8*	9.9	*9.6–10.0*	9.9	*9.6–10.4*
8	5.1 RP		5.2 RP		5.1 RP		4.7	*4.1–5.2*	4.7	*4.2–5.1*	5.8	*5.4–6.5*	7.9		7.9		8.0	*8.0– 8.4*
6	5.1 RP		5.2 RP		5.0 RP		4.7	*4.1–5.2*	4.7	*4.2–5.1*	5.8	*5.4–6.5*	5.9	*5.6– 6.0*	5.9	*5.6– 6.0*	6.0	*5.6– 6.0*
4	5.0 RP		5.1 RP		5.1 RP		4.6	*4.1–5.2*	4.7	*4.2–5.1*	5.8	*5.4–6.5*	3.9		4.0	*3.6– 4.0*	4.1	
2	4.5 RP		4.6 RP		5.0 RP		4.6	*4.2–5.2*	4.7	*4.2–5.1*	5.9	*5.4–6.7*	1.9	*1.6– 2.0*	2.0	*1.6– 2.4*	2.0	*1.6– 2.0*
4/12	5.1 RP		5.3 RP		5.1 RP		3.8	*3.1–4.2*	3.8	*3.5–4.3*	5.0	*4.6–5.8*	11.9	*11.6–12.0*	11.9	*11.6–12.4*	12.1	*12.0–12.8*
10	5.1 RP		5.3 RP		5.1 RP		3.7	*3.1–4.1*	3.7	*3.5–4.3*	5.0	*4.6–5.8*	10.0	*9.6–10.4*	9.9	*9.6–10.4*	10.0	*9.6–10.8*
8	5.1 RP		5.1 RP		5.1 RP		3.7	*3.1–4.1*	3.7	*3.2–4.1*	5.0	*4.5–5.8*	8.0	*7.6– 8.0*	7.9	*7.6– 8.4*	8.0	*7.6– 8.4*
6	5.0 RP		5.1 RP		5.0 RP		3.7	*3.2–4.1*	3.8	*3.5–4.1*	5.0	*4.5–5.8*	6.0		6.0	*5.6– 6.0*	6.0	
4	4.9 RP		5.0 RP		4.9 RP		3.7	*3.2–4.1*	3.7	*3.2–4.1*	5.0	*4.5–5.8*	4.0	*3.6– 4.0*	4.0	*3.6– 4.0*	4.0	*4.0– 4.4*
2	4.7 RP		4.9 RP		4.8 RP		3.7	*3.2–4.1*	3.7	*3.2–4.1*	5.0	*4.4–5.2*	1.9	*1.6– 2.0*	2.0	*1.6– 2.0*	2.0	
3/10	5.5 RP	*5* RP–*6* RP	5.4 RP	*5* RP–*6* RP	5.3 RP		2.8	*2.4–3.3*	2.9	*2.5–3.1*	4.0	*3.5–4.8*	10.0	*9.6–10.0*	10.1	*9.6–10.4*	10.2	*9.6–10.8*
8	5.5 RP	*5* RP–*6* RP	5.3 RP		5.1 RP		2.7	*2.3–3.2*	2.8	*2.4–3.0*	3.8	*3.4–4.6*	7.9	*7.6– 8.0*	8.0	*8.0– 8.4*	8.2	*7.6– 8.4*
6	5.2 RP	*5* RP–*6* RP	5.3 RP		5.2 RP		2.7	*2.3–3.2*	2.8	*2.4–3.0*	3.8	*3.4–4.6*	5.9	*5.6– 6.0*	6.1	*6.0– 6.4*	6.0	*5.6– 6.8*
4	5.6 RP	*5* RP–*7* RP	5.4 RP		5.3 RP	*5* RP–*6* RP	2.7	*2.3–3.2*	2.8	*2.4–3.0*	3.8	*3.4–4.6*	3.9	*3.6– 4.0*	4.0	*3.6– 4.0*	3.9	*3.6– 4.0*
2	5.1 RP		5.4 RP	*5* RP–*8* RP	5.0 RP		2.7	*2.4–3.1*	2.7	*2.4–3.0*	3.8	*3.4–4.6*	1.9	*1.6– 2.0*	2.0	*1.2– 2.0*	2.0	
2/6	5.2 RP		5.0 RP		5.0 RP		1.9	*1.6–2.3*	1.9	*1.7–2.0*	2.4	*2.0–2.7*	6.0	*6.0– 6.4*	6.1	*6.0– 6.4*	6.2	*6.0– 6.8*
4	5.2 RP		5.0 RP		5.0 RP		1.9	*1.6–2.2*	1.9	*1.8–2.0*	2.4	*2.0–2.7*	4.1	*4.0– 4.4*	4.3	*4.0– 4.8*	4.4	*4.0– 5.6*
2	5.4 RP		5.6 RP	*5* RP–*9* RP	5.3 RP	*5* RP–*8* RP	1.8	*1.4–2.2*	1.8	*1.6–2.0*	2.4	*2.0–2.6*	2.0		2.1	*2.0– 2.4*	2.2	*2.0– 2.8*

TABLE II.—*Continued.*

1929 Munsell Notation	Visual Estimates, Average and 80% Range																	
	Hue						Value						Chroma					
	White		Gray		Black		White		Gray		Black		White		Gray		Black	
H V/C	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range
10 RP 8/6	10.0 RP		9.9 RP		10.0 RP		8.0	*7.9–8.3*	8.2	*8.0–8.2*	8.3	*8.1–8.6*	5.7	*5.2– 6.0*	5.6	*5.2– 6.0*	5.7	*5.2– 6.4*
4	9.7 RP		9.8 RP		9.7 RP		7.9	*7.8–8.1*	8.2	*8.0–8.2*	8.3	*8.1–8.6*	3.7	*3.2– 4.0*	3.8	*3.2– 4.0*	3.8	*3.2– 4.0*
7/8	9.8 RP		0.2 R		0.2 R		6.8	*6.6–7.2*	7.2	*7.1–7.3*	7.5	*7.3–7.9*	7.7	*7.2– 8.0*	7.7	*7.2– 8.0*	7.8	*7.2– 8.4*
6	9.9 RP		0.1 R		0.2 R		6.8	*6.8–7.2*	7.3	*7.1–7.2*	7.5	*7.1–8.1*	5.7	*5.2– 6.0*	5.7	*5.2– 6.0*	5.8	*4.8– 6.0*
4	9.6 RP		0.2 R		0.1 R		6.7	*6.6–7.2*	7.2	*7.1–7.2*	7.5	*7.1–7.9*	3.9	*3.6– 4.0*	3.9	*3.6– 4.0*	3.9	*3.2– 4.0*
6/10	10.0 RP		0.1 R		0.1 R		5.8	*5.6–6.5*	6.2	*5.9–6.4*	6.7	*6.2–7.3*	9.9	*9.6–10.4*	9.9	*9.2–10.4*	9.9	*9.2–10.4*
8	9.9 RP		0.1 R		0.1 R		5.7	*5.3–6.3*	6.1	*6.0–6.3*	6.7	*6.1–7.1*	7.8	*7.6– 8.0*	7.8	*7.2– 8.0*	7.8	
6	9.9 RP		10.0 RP		0.1 R		5.7	*5.3–6.3*	6.1	*6.0–6.3*	6.6	*6.1–7.1*	5.8	*5.2– 6.0*	5.7	*5.6– 6.0*	5.8	*5.6– 6.0*
4	9.5 RP	*9* RP–*10* RP	9.8 RP		10.0 RP		5.7	*5.1–6.3*	6.1	*6.0–6.3*	6.6	*6.1–7.1*	3.8	*3.6– 4.0*	3.9	*3.6– 4.0*	3.9	
5/10	10.0 RP		9.9 RP		9.9 RP		4.8	*4.4–5.3*	4.8	*4.2–5.2*	5.8	*5.3–6.3*	10.1	*10.0–10.8*	10.1	*10.0–10.8*	10.0	*9.6–10.4*
8	9.9 RP		9.8 RP		9.8 RP		4.8	*4.3–5.3*	4.7	*4.2–5.1*	5.7	*5.1–6.5*	8.0	*7.6– 8.0*	8.1	*8.0– 8.4*	8.0	*7.6– 8.0*
6	9.9 RP		9.9 RP		9.8 RP		4.7	*4.2–5.2*	4.7	*4.2–5.0*	5.7	*5.2–6.5*	6.0	*5.6– 6.0*	6.0	*5.6– 6.0*	6.0	*5.6– 6.0*
4	9.6 RP		9.8 RP		9.8 RP		4.7	*4.0–5.2*	4.7	*4.2–5.0*	5.7	*5.1–6.2*	3.8	*3.2– 4.0*	3.8	*3.2– 4.0*	3.9	*3.2– 4.0*
4/10	9.7 RP	*9* RP–*1* R	9.8 RP	*9* RP–*10* RP	9.8 RP		3.8	*3.5–4.3*	3.7	*3.2–4.1*	4.9	*4.3–5.7*	10.0		10.2	*10.0–10.8*	9.9	*9.6–10.4*
8	9.7 RP	*9* RP–*10* RP	9.9 RP	*9* RP–*10* RP	9.8 RP		3.8	*3.4–4.2*	3.7	*3.5–4.1*	4.9	*4.4–5.7*	8.0		8.1	*7.6– 8.4*	8.1	*8.0– 8.8*
6	9.6 RP	*9* RP–*10* RP	9.9 RP	*9* RP–*1* R	9.7 RP	*9* RP–*10* RP	3.8	*3.4–4.2*	3.7	*3.2–4.0*	4.8	*4.2–5.2*	6.1	*6.0– 6.4*	6.1	*6.0– 6.4*	6.1	*6.0– 6.4*
4	9.7 RP	*9* RP–*10* RP	9.4 RP	*8* RP–*10* RP	9.6 RP	*9* RP–*10* RP	3.8	*3.2–4.2*	3.6	*3.5–4.0*	4.8	*4.2–5.7*	3.9	*3.6– 4.0*	4.0	*3.6– 4.4*	3.9	*3.6– 4.4*
3/10	9.7 RP	*9* RP–*10* RP	9.7 RP	*9* RP–*10* RP	9.7 RP	*8* RP–*1* R	2.8	*2.4–3.1*	2.8	*2.4–3.0*	3.7	*3.2–4.3*	10.1	*9.6–10.4*	10.3	*10.0–10.8*	10.3	*10.0–10.8*
8	9.7 RP	*9* RP–*10* RP	9.7 RP	*9* RP–*10* RP	9.6 RP	*9* RP–*10* RP	2.8	*2.3–3.1*	2.7	*2.4–3.1*	3.6	*3.0–4.3*	7.9	*7.6– 8.0*	8.1	*7.6– 8.0*	8.2	*8.0– 9.2*
6	9.7 RP	*9* RP–*10* RP	9.7 RP	*9* RP–*10* RP	9.6 RP	*9* RP–*10* RP	2.8	*2.3–3.1*	2.8	*2.4–2.9*	3.6	*3.0–4.3*	6.0	*5.6– 6.4*	6.1	*6.0– 6.4*	6.1	*6.0– 6.8*
4	9.8 RP	*9* RP–*10* RP	9.6 RP	*9* RP–*10* RP	9.5 RP	*9* RP–*10* RP	2.8	*2.1–3.1*	2.7	*2.4–3.0*	3.6	*3.0–4.3*	3.8	*3.6– 4.0*	3.9	*3.6– 4.0*	3.9	*3.2– 4.0*
2/6	*		*		*		1.8	*1.6–2.2*	2.0	*1.7–2.2*	2.4	*2.1–2.5*	5.8	*5.6– 6.8*	6.7	*5.6– 6.8*	7.0	*6.0– 6.8*
4	*		*		*		2.0	*1.6–2.1*	2.0	*1.9–2.1*	2.5	*2.1–3.0*	5.2	*4.0– 6.4*	4.6	*3.6– 4.8*	5.2	*4.4– 5.6*

there are several general indications which are fairly apparent from inspection

Comparison with the 1929 notation of a given estimate of any attribute, is accomplished by looking along the appropriate row of the table. Wherever a difference is found it means that the consensus of the observers placed that particular sample at the new indicated position in Munsell color space. Thus G 5/6, as viewed on the white ground, appears somewhat misplaced in all dimensions and is better located by the notation 5.1G 4.7/6.4, as entered in the respective "white" columns. The notation of this sample on the gray ground was found to fall at 5.0G 4.6/6.4, as taken from the respective "gray" columns; and the notation for the black ground is 5.1G 5.8/6.3. The general indication from the table as a whole is that the averaged estimates usually approximate rather closely the 1929 Munsell notation and so support the validity of the latter. Still, minor adjustments of many samples may be expected to affect the final smoothing.

Inter-comparisons of the mean estimates from the different viewing grounds are facilitated by the arrangement of all relevant data in three adjacent columns. Thus in the case of G 5/6, the hue estimates from the three grounds are adjacently tabled in the same row, the figures being 5.1G, 5.0G, and 5.1G. Similarly, and further to the right in this same row, the comparative value estimates are 4.7, 4.6, and 5.8; and still further to the right, the chroma estimates are 6.4, 6.4, and 6.3. Comparisons of this character disclose no systematic differential influence of background on either hue or saturation, but it must be noted that such an influence could be reduced by the relativity of the judgments and the influence of color constancy (25–28, 37, 41, 85, p. 595). Briefly, that is because all the samples on a given chart are always seen in relation to each other and never on more than one background at a time. There is, however, a relatively marked and consistent effect in the case of value, and this effect is in the expected direction of simultaneous lightness contrast (58, 71, p. 546; 79, 82). Lightness variations are revealed which range in magnitude up to a full value step and more.

The variabilities, or 80 percent ranges, of the data in this table yield some idea of the spread of the individual estimates. The latter suggests, in conjunction with the size of n, that differences of a tenth or two in the means are usually not significant.

The several attributive units are so far from equivalent perceptually, that interattributive comparisons of variability are not valid psychologically; and intercomparisons of variability are best confined to the data of a given attribute. In regard to the influence of background on variability, for the given attribute, there seems to be no indication obvious on inspection. Little more can be said in advance of detailed analysis.

The reader should be cautioned that although the estimates in Table II are average estimates, they are not sufficiently reliable to be taken as standards at their face value. They remain to be smoothed and therefore should not be considered or used as standard data in their present form.

Preliminary Smoothing of Chroma

Preliminary smoothed data were made available by Nickerson in 1938 (60). These results are based on observations with charts on grounds of all three reflectances by about one-quarter of the subjects who eventually contributed to the review. Only the constant-value charts were used and only chroma was smoothed. Nevertheless, these earlier estimates are of considerable interest because they indicate some important adjustments in chroma, and they give the best definition of the ideal Munsell system yet available.

Procedure in smoothing

The samples at each of the seven value levels represented by the 1929 chromatic samples were plotted in the (x, y)-diagram of the I.C.I. coordinate system, utilizing for that purpose the Glenn-Killian data (16). The saturation estimates available at that date were summarized relative to each individual Munsell sample, and were plotted on the same diagram. Thus discrepancies between the 1929 Munsell notation and this 1938 visual consensus were revealed as spatial differences between plotted points at each value level.

Next, representative chroma contours were established by drawing smooth free-hand curves through the scattered Glenn-Killian points. Wherever such a point was not confirmed by the consensus of visual estimates the contour was correspondingly deflected. Not infrequently the average visual estimate was found to fall in the path of a smooth curve and to justify the drawing of a contour different from that suggested by the unadjusted data alone.

The chroma smoothing was affected by two further considerations both of which involved considerable judgment or freedom of choice on the part of the investigator. In drawing the iso-chroma contours at the given value level, limited concessions were made to the form of the concentric pattern of curves at that level, taken as a whole, according to the principle that the individual curves must bear a systematic relation to each other. Thus, if the chroma /6 contour has a shape differing from that of chroma /2, the chroma /4 contour must be transitionally related to them.

The other consideration involved the interrelationships between similar chroma contours on adjacent value levels. By drawing the several curves of each value level on a large separate sheet of translucent paper and by properly superposing these sheets, a guide was arranged to this intervalue-level smoothing. Here the changes seemed to be transitional from one level to the next, and especially marked in progressing from the middle levels toward either extreme. The end result of applying these two considerations was the desired tridimensionally smoothed system of iso-chroma contours.

Charted results

Greatly reduced reproductions of the final charts are shown in Figs. 7 to 14. In each figure, the small circles represent the plotted Glenn-Killian points and they bear the 1929 Munsell notations. The heavy elliptoid curves are the smooth iso-chroma contours corresponding to chroma /2, /4, /6, and so on. The origin of these concentric curves is the point representing I.C.I. Illuminant *C* which approximately represents the achromatic axis of the Munsell solid. Radiating

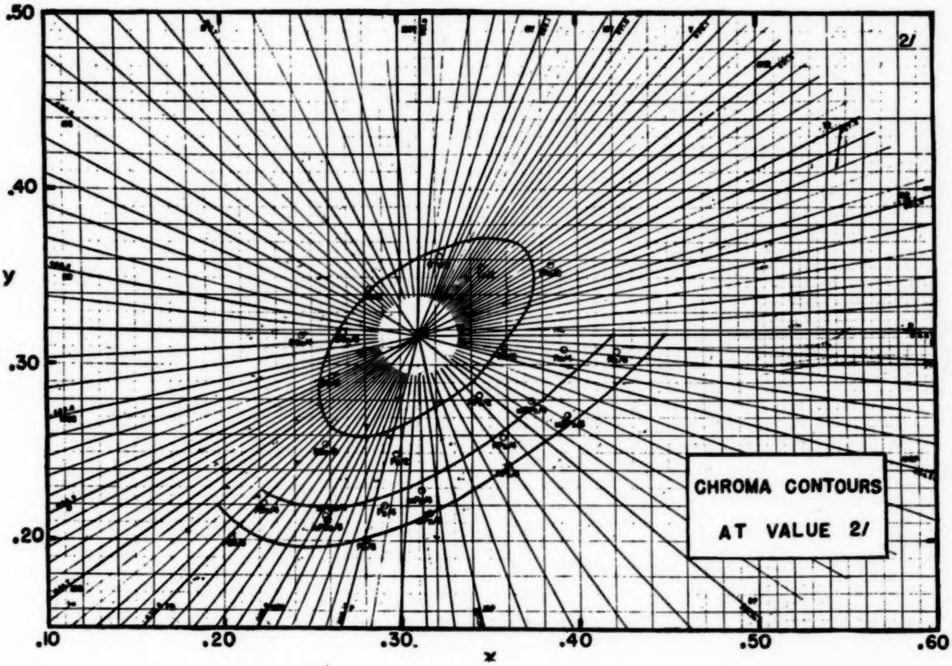

FIG. 7.

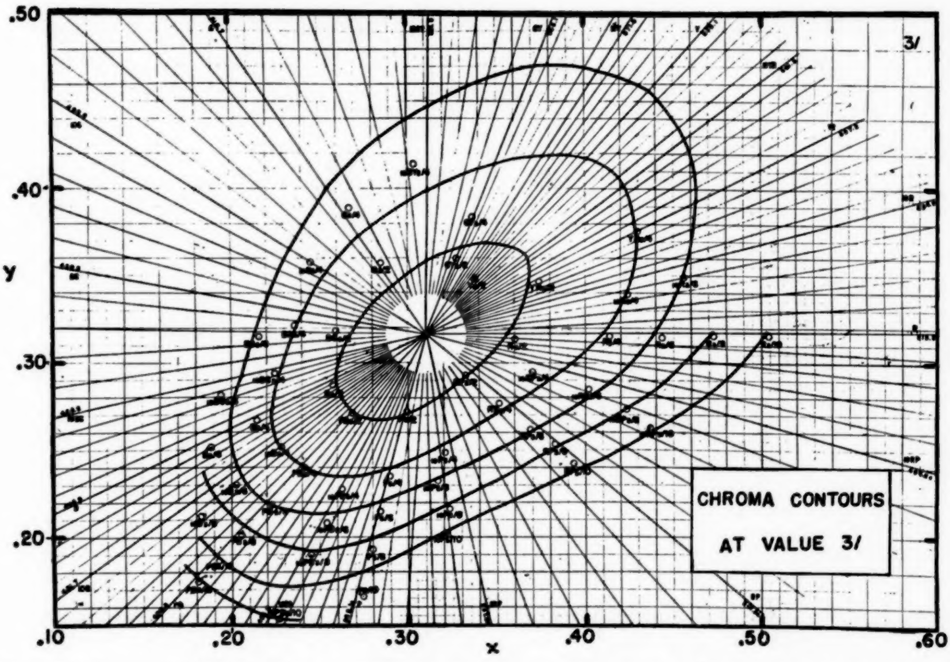

FIG. 8.

FIGS. 7–8. Representative iso-chroma contours at value levels 2/ and 3/ based on preliminary visual estimates of the constant-value charts.

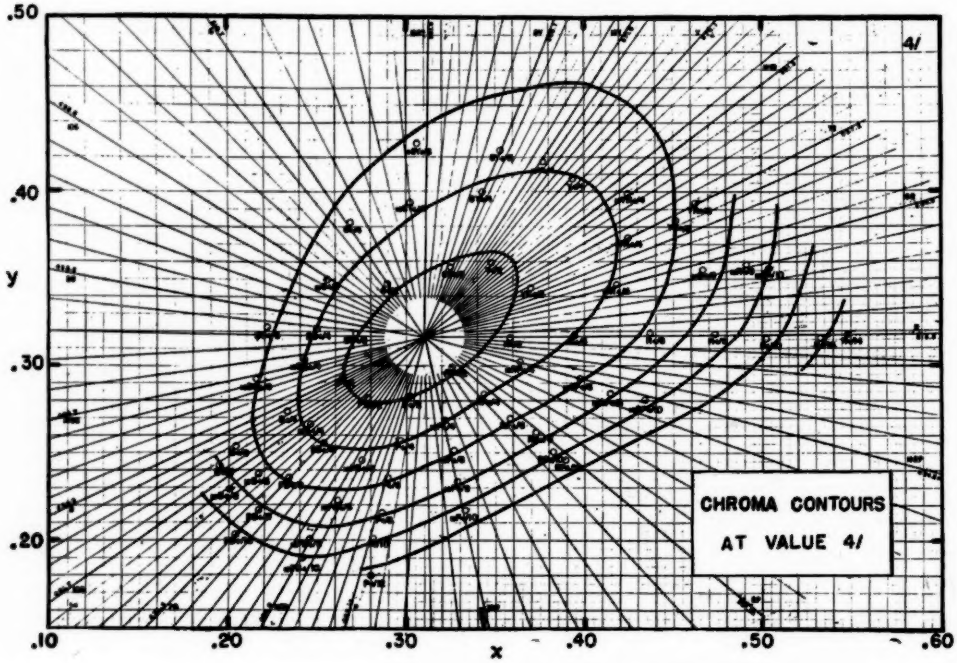

FIG. 9.

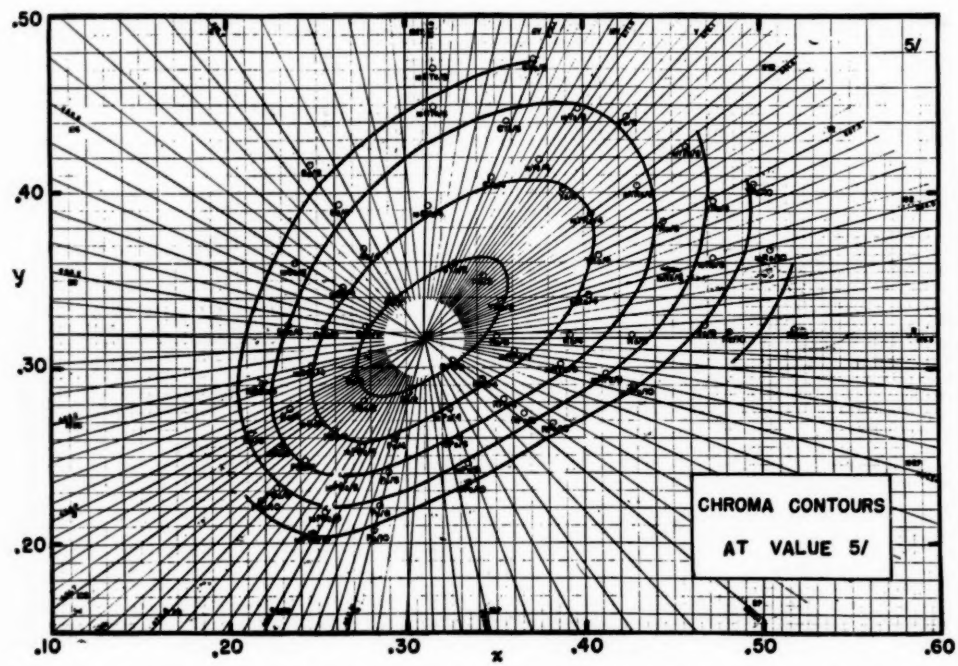

FIG. 10.

FIGS. 9–10. Representative iso-chroma contours at value levels 4/ and 5/ based on preliminary visual estimates of the constant-value charts.

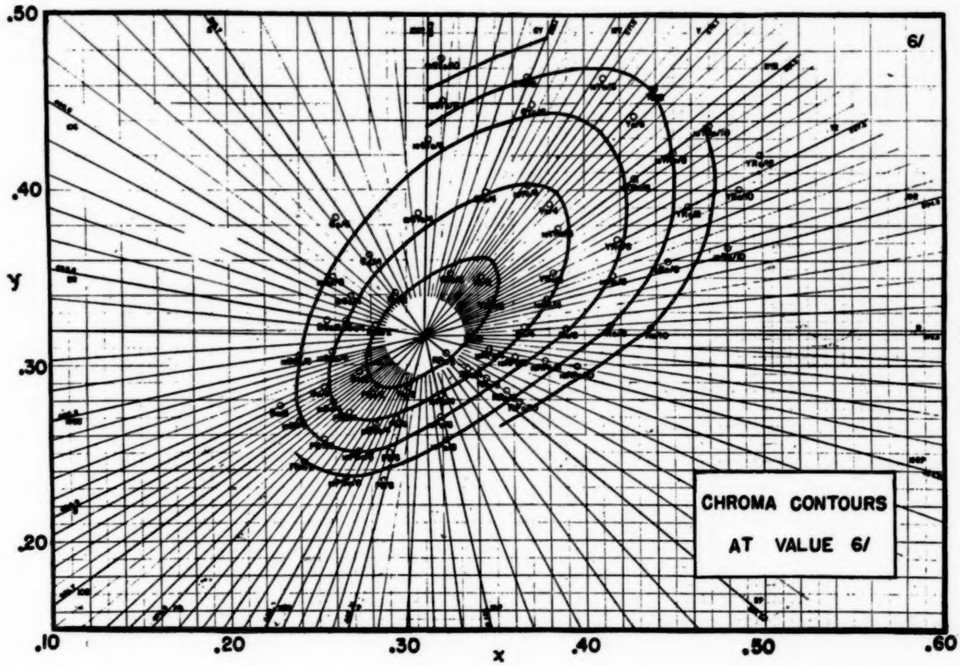

FIG. 11.

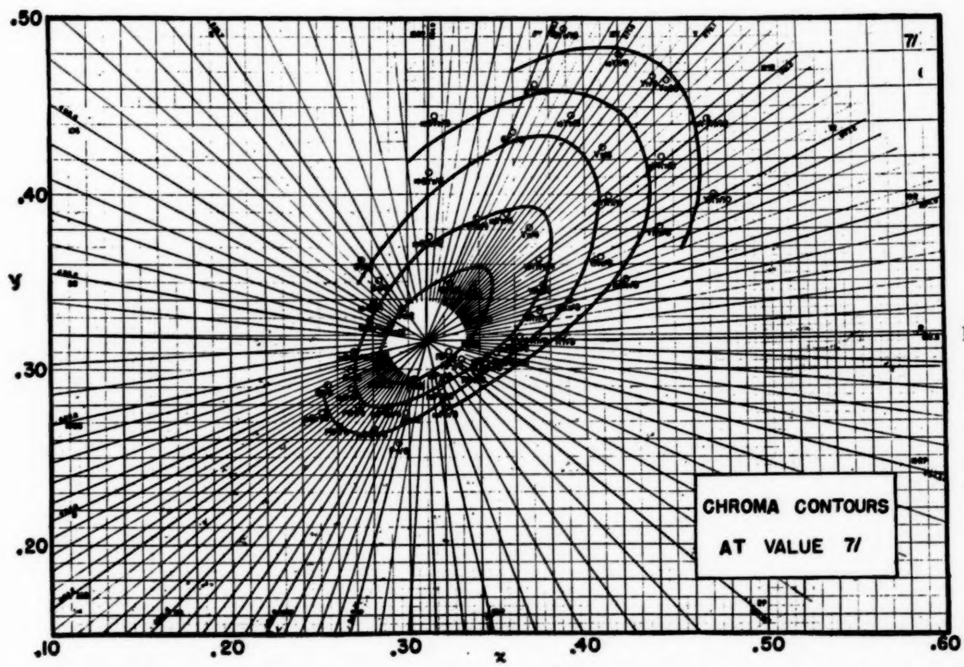

FIG. 12.

FIGS. 11–12. Representative iso-chroma contours at value levels 6/ and 7/ based on preliminary visual estimates of the constant-value charts.

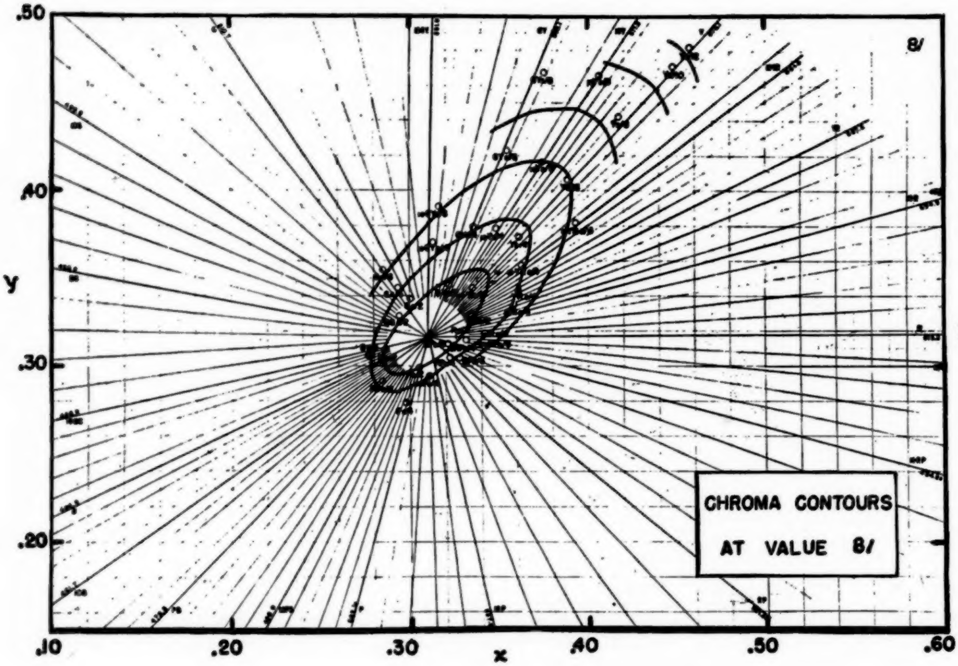

FIG. 13.

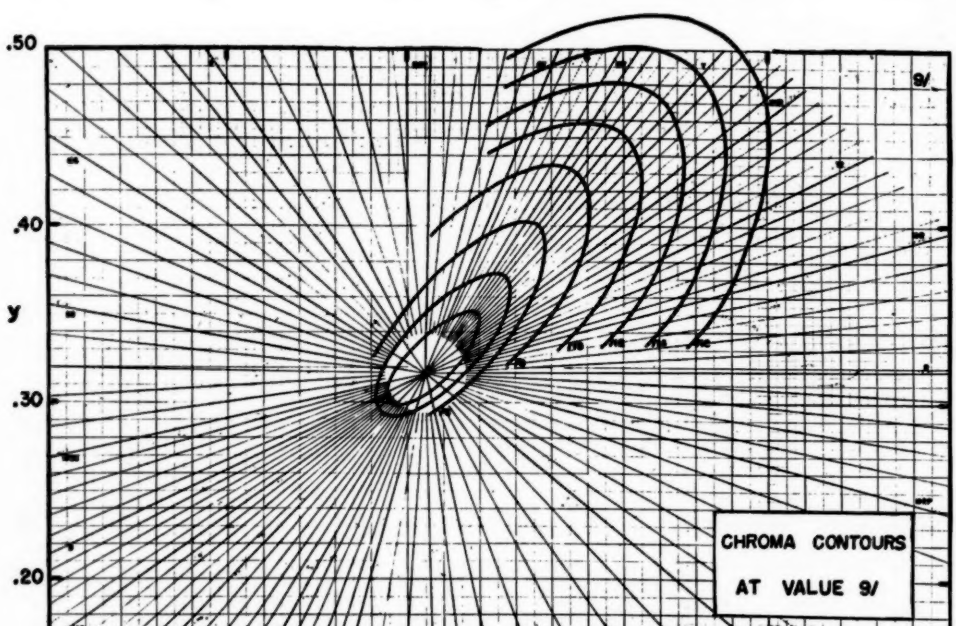

FIG. 14.

FIGS. 13–14. Representative iso-chroma contours at value levels 8/ and 9/ based on preliminary visual estimates of the constant-value charts.

from this origin are 100 lighter lines of average dominant wave-length. Twenty of these indicate approximately the average dominant wave-lengths of the 20 Munsell hues, while the remaining 80 are spaced arbitrarily at equal angles between them. Wave-length is shown for reference only, the relation between hue and dominant wave-length not being simple. Figure 14 differs from the others in that it is not based directly on data but simply represents at the 9/ value level the results of the intervalue smoothing.

Discussion

The iso-chroma contours at all value levels evince several distinctive characteristics. They are of a definitely elliptoid form with the major axis approximately coinciding with the Y to PB hue plane. There is an obvious broadening out of the contours in the first (10GY to R) as compared with the third (10P to B) quadrant, a tendency which is especially marked for higher chroma. Sections of contours lying in the first quadrant (10GY to R) show the greatest separation while those in the second quadrant (R to 10P) lie closest together. These sweeping departures from uniformly spaced concentric circles, may be ascribed reasonably to the I.C.I. system itself. They constitute a preliminary indication of the nature and magnitude of the general departures of the I.C.I. (x, y)-diagram from a uniform-chromaticity-scale system. This interpretation is admissible on the ground that our table of visual estimates has revealed no such irregularities in the Munsell system. On the other hand, the fact that the /2 chroma contour exhibits a tendency to a wider separation from the neutral point than the chroma contours do from each other, may represent a real irregularity in the Munsell spacing. As already mentioned, a number of observers had specially reported that the /0 to /2 chroma interval seemed too great. Other data on the relation of chroma to purity may be found elsewhere (12, 32, 62, 67, 69).

The experience gained in this preliminary smoothing of the chroma estimates from the constant-value charts should, for the final report, prove useful in the tridimensional smoothing of hue, value, and chroma from both the constant-value and constant-hue charts. Visual data for tridimensional smoothing are now available in Table II above.

Summary

This paper reports to date the work of the Optical Society of America subcommittee on the spacing of the Munsell colors. The ideal of this study is to produce a psychophysical specification of a system of surface colors corresponding as closely as possible to the true psychological color solid, but all along the general attitude of the subcommittee has been simply that any substantial improvement in spacing which might prove possible would be well worth while. The work of the subcommittee consists in revaluation by visual observations of the regular 400 Munsell samples of 1929, in order that they may conform more closely to the regular contours of the ideal solid. All samples were viewed against white, gray, and black grounds, independently.

A table is presented containing the averaged visual estimates of the numerous subjects who participated in the revaluation procedure. The unsmoothed corrections in the spacings are evident from a direct comparison of these data with the 1929 Munsell notation. The approximate validity of the latter is in general confirmed by the smallness and the distribution of the deviations.

Background reflectance is found to exert upon the lightness estimates a significant and systematic influence which is in the expected direction of simultaneous lightness contrast. There is evident from inspection no comparable general influence of background on either hue or saturation.

The plan is to smooth these averaged visual estimates in the I.C.I. colorimetric coordinate system for presentation in the final report. The smoothing operation is here illustrated by preliminary results for chroma, based on incomplete visual estimates with the constant-value charts.

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Proceedings of the Twenty-Fifth Annual Meeting of the Optical Society of America

ROCHESTER, NEW YORK, OCTOBER 3–5, 1940

IT was particularly appropriate that the twenty-fifth annual meeting should have been held in Rochester, the birthplace of the Society. For several years before the founding of the Optical Society of America in 1916, a local group of optical experts had been organized, and the national society grew out of this organization. During the process, the local group maintained its identity and is known today as the Rochester Section. The enthusiastic efforts of the local committee appointed by the Rochester section were largely responsible for making this meeting one of the most successful in the history of the Society.

The meeting was opened Thursday, October 3, at 9:30 A.M. by President Gibson with a session of contributed papers.

EVENING LECTURE

A lecture and demonstration of practical uses of the academically familiar phenomena of polarization by Mr. Edwin H. Land delighted those who knew what to expect as much as those who really preferred to believe in magic. For the latter, a sheet of ordinary-looking celluloid held in the hand could be black, white, red, or green at Mr. Land's whim. At the same time and in the same place could be seen a picture of the Taj Mahal or the kitchen sink depending upon the manner of holding the sheet material before the eyes.

For the more technically minded, the importance of this demonstration resided in the fact that only one projection lantern was used. This is made possible by controlling the degree of polarization of a polarizing surface in which the pictures are formed. A transparent sheet composed of oriented molecules of a long chain polymer is brought into contact with a solution containing a component which, when combined with the original molecule, produces a polarizing molecule. By controlling the number of these polarizing molecules, it is possible to achieve any desired degree of contrast in an image in terms of polarization if the image is viewed through a polarizing material. The advantages of projecting three-dimensional pictures by means of a single lantern are many. This was admirably demonstrated by a series of stereoscopic pictures representing subjects of all types. The demonstration closed with a stereoscopic picture projected in full color by means of a single lantern.

SYMPOSIUM OF INVITED PAPERS ON THE PROGRESS IN AMERICAN OPTICAL SCIENCE AND INDUSTRY

If for no other reason, the Rochester meeting would be memorable for its group of invited papers. These were presented by authors who combined unquestioned knowledge of their fields with the happy faculty of discussing their subjects in an extremely lucid manner. The program of these papers was as follows:

1. **A Quarter Century of Optics Reviewed,** HERBERT E. IVES, *Bell Telephone Laboratories.*
2. **Quality Control in the Manufacture of Optical Instruments—Twenty-Five Years' Progress,** W. W. GRAEPER, *Bausch & Lomb Optical Company.*
3. **Recent Developments in Photography,** C. E. K. MEES, *Eastman Kodak Company.*
4. **Producing Low Reflecting Glass,** C. HAWLEY CARTWRIGHT, *Corning Glass Works.*

Dr. Ives began by describing the transformation undergone by the concept of radiation from the time of Newton to the present. His discussion fascinated the imagination of the theorists as completely as it did those who think of radio as something to hear with and light as something to see with. In a most entertaining manner, he described the upset of the well-ordered wave theory after the discovery of the photoelectric effect and the resulting transformation of the subject into a paradise for the mathematician.

Physiological optics was represented by the speaker as a subject of slow and labored progress, which is still open to further chemical and physical interpretation. Helmholtz' theory of the visual purple and the theory of the visual violet, although attacked through a "clam's eye view," have been extended to the vertebrates. An international dispute has arisen out of the question whether the vitamin-deficient see "redder" than the well-fed people of America.

Developments in optical apparatus were found to be responsible for much of the progress during the last quarter-century. The controlled manufacture of ruled gratings, the discovery of supersonic gratings, the Schmidt camera, and aspheric lenses were given special mention.

Great advances in the measurement and specification of color have resulted from the development of photoelectric spectrophotometers and the concurrent development of a standard trilinear coordinate system. In the practical field, fluorescent lighting, photographic flash lamps, phototelegraphy, television, and the electron microscope are the most recent contributions of optics.

Advancement in science depends upon the perfection of the tools with which it works. Mr. Graeper assigned a large part of this responsibility in the optical industry to the methods of inspection employed by the optical instrument manufacturers.

Availability of materials, of course, is another factor in production, especially of those materials which are artificially producible. In this connection, the recent discovery of a deposit of a high quality calcite in one of our southwestern states is particularly interesting.

The fact that methods of manufacture in the last twenty-five years have culminated in a perfection of manufacturing techniques which equal the best inspection methods, may be regarded as both a challenge to inspection methods and a tribute to the quality control in manufacture.

Dr. Mees began his talk by comparing the size and weight of the equipment needed by the photographer in 1900 to that which he carries in 1940. The most important developments in photography during the last twenty-five years have been brought about through the cooperative efforts of physicists and chemists, but they have been made commercially possible because of the increased popular interest in photography. The things the amateur wanted were pictures easier to make, pictures in motion, and pictures in color. The technical developments which have fulfilled these wishes are: (1) improved methods of the optical sensitizing of emulsions; (2) the development of mechanized reversal processing; (3) the introduction of elaborate miniature cameras of high mechanical quality; and (4) the introduction of the integral tripack systems of color photography.

The improved methods of optical sensitizing arose from the development of the polymethine dyes, in which two nuclei are connected by a chain of methine groups. The absorption and sensitizing spectra of these dyes depend upon the length of the chain and the weight of the nuclei. The new dyes increase the sensitivity of slow, fine-grain emulsions more than they do that of high speed emulsions; and this makes it possible to prepare films of satisfactory speed having an image structure which allows a considerable degree of enlargement. This development has greatly encouraged the use of miniature cameras.

The growth of amateur cinematography has been dependent upon the excellent results obtained by reversal processing carried out on continuous developing machines using automatic compensation for the second exposure.

On the optical side, the growth of amateur cinematography and of miniature cameras has led to the introduction of lenses of very much higher aperture than those used previously, and this has been assisted by the introduction of improved glasses, particularly glasses of low dispersion and high refractive index.

The use of the integral tripack has been very successful in color photography, and the majority of all substandard motion pictures are now made in color. In other branches of photography, the use of color processes is constantly increasing.

To make things disappear was once a conjuror's trick, but Dr. Cartwright demonstrated for his audience that optical advancement has made this magic possible without legerdemain. Glass is visible because of the light it reflects; it becomes invisible when it is sufficiently transparent.

H. Dennis Taylor in 1892 observed that camera lenses were "faster" after they became tarnished. Several methods for artificially tarnishing glass were subsequently developed. A more physical approach to the problem was made in 1936 by J. Strong, who evaporated films of CaF_2 and realized the value of a film material having an index of refraction intermediate between that of air and the glass. In 1938, K. Blodgett showed that the thickness of the film was of paramount importance and succeeded in reducing the reflection of monochromatic light to zero by the application of "skeletonized" films of metallic stearates. In 1938, Cartwright and Turner applied evaporated films of the metallic fluorides to glass under conditions which satisfied the correct index and thickness requirements. The metallic fluorides have unusually low indices of refraction, and a satisfactory result for photography is obtained by their approach to the ideal index. The correct thickness of the film is obtained by observing the reflection of light during the condensation of the metallic fluorides.

Although the thickness can be correct for only one wave-length of light, reflection is greatly reduced throughout the entire visible spectrum. Metallic fluoride films can be made sufficiently rugged for camera lenses and the reduced reflections from the six to ten air-glass surfaces noticeably increase the speed. The perfection of a camera lens is further increased by the absence of flare and ghost images that normally appear under adverse lighting conditions.

Dr. Cartwright projected an interesting series of "before and after" pictures, all of which demonstrated the increase in image sharpness and contrast. Perhaps the most striking of these were the photographs taken with the coronograph of Professor D. Menzel.

Annual Dinner and First Award of the Adolph Lomb Medal

On Friday evening, members of the Society and their wives were the guests of the Bausch & Lomb Optical Company at a dinner held at the Oak Hill Country Club. Nearly four hundred were in attendance. The toastmaster, Mr. C. S. Hallauer, first called on Mr. Carl Bausch, who told of the measures instituted by his company to supply the increasing need for optical glass and optical parts during this active period of preparation for national defense. The toastmaster then called on President Gibson, who introduced the charter members of the Society in turn. He also read letters from several charter members who were unable to be present because of illness.

Dr. W. B. Rayton was then asked to recount for the benefit of new members the events that led to the formation of the Optical Society of America. From his various anecdotes relating to the early days, it was abundantly evident that considerable growth and progress has been made during the quarter-century. He paid special tribute to Mr. Adolph Lomb, a charter member and treasurer of the Society until his death in 1932.

President Gibson then explained the purpose of the Board of Directors in establishing the Adolph Lomb Medal and read the conditions of award adopted at the Board meeting in October, 1939. Past President R. C. Gibbs, the chairman of the committee to nominate a candidate to receive the first award then spoke as follows:

"After canvassing a representative group of members of the Society for suggestions of suitable nominees and after a careful study of the scientific achievements of the various persons on the list thus assembled, the committee made a unanimous nomination for an award. This nomination was transmitted to the Board of Directors, which, by a unanimous vote on March 2, 1940, officially awarded the Adolph Lomb Medal for 1940 to David Lewis MacAdam.

"Born in Philadelphia, July 1, 1910, Dr. MacAdam attended the public schools in Upper Darby, Pennsylvania, and Lehigh University, receiving the B.S. degree from the latter in 1932. He then spent four years in graduate study at the Massachusetts Institute of Technology, where he received the Ph.D. degree in 1936. Since that time he has been a member of the staff of the Physics Department of the Research Laboratories at the Eastman Kodak Company in Rochester, New York.

"Dr. MacAdam's scientific contributions have been embodied in twenty-one published papers or reports. A survey of these contributions shows five studies of major importance which may be considered as the bases for this award.

"1. Dr. MacAdam developed the theory of the maximum visual efficiency of colored materials and, on the basis of appropriate computations, prepared tables showing the maximum visual efficiency as a function of excitation purity for twenty-four dominant wave-lengths. He studied and examined the general type of spectrophotometric curve which yields a maximum value for the visual efficiency for materials exhibiting a given chromaticity when illuminated with light of a specified quality, and presented a new proof of the validity and uniqueness of this type of curve.

"2. In a study of 'Photometric Relationships Between Complementary Colors,' he presented formulas and tables for the interconversion of colorimetric and excitation purities, and reviewed the complementary relations between colors having maximum visual efficiencies.

"3. In a review of the 'Photographic Aspects of the Theory of Three-Color Reproduction,' he examined the significance of the concept of photographic spectral sensitivity and emphasized the desirability of emulsions having contrast independent of wave-length. He also determined the limits within which it is possible or desirable to increase purity by an increase of contrast.

"4. In a report on 'Subtractive Color Mixture and Color Reproduction' he showed how the analytical form of a simple rule for predicting the colors of mixtures of certain dyes can be incorporated into the theory of color reproduction, and derived formulas for use in printing a subtractive reproduction, and in the simultaneous introduction of partially negative spectral sensitivities.

"5. More recently he has undertaken to investigate the 'Noticeability of Color Difference in Daylight' which has now culminated in a report presented at this meeting of the Society. He has developed and carried out an extensive series of color-match observations and has examined in detail the probable errors to be expected and encountered in such color matching.

"Mr. President: It gives me great pleasure, on behalf of the Committee and of the officers of the Society, to present at this time Dr. David Lewis MacAdam as a person highly qualified to receive the Adolph Lomb Medal because of his noteworthy contributions to optics."

After President Gibson had formally bestowed the medal, Dr. MacAdam responded briefly as follows:

DAVID L. MACADAM

"Mr. President: I realize that I must not take the time that would be necessary to express adequately my appreciation of the award which you have just bestowed upon me. May I say simply that I feel greatly honored at being chosen to receive the first award of this symbol of encouragement for young men entering the field of optics. I thank you sincerely."

BUSINESS SESSION

A brief business session of the Society was held Saturday morning, October 5, at 9:45 A.M., President Gibson presiding. Formal reports of the Secretary, Treasurer, and Editor of Publications for the calendar year 1939* were received and placed on file. Informal reports covering the period from January 1, 1940 to the time of the annual meeting in 1940 were also presented.

President Gibson called attention to the fact that the term of appointment of Arthur C. Hardy as Secretary of the Society would expire at this annual meeting. He also called attention to the report of a Nominating Committee, which had been circulated in accordance with the provisions of the By-Laws. On a motion from the

* Published in the J. Opt. Soc. Am. **30**, 259–264 (1940).

floor which was carried unanimously, the President was instructed to cast one ballot for Arthur C. Hardy. He thereupon declared Arthur C. Hardy elected Secretary for the term October, 1940 to October, 1941.

The President called attention also to the unusually fine program that had been arranged for this meeting and declared his intention to dispatch letters of appreciation to those who had been responsible for the arrangements. By a motion which was carried unanimously, the President was instructed to send telegrams expressing regrets to the charter members who had been unable to attend the meeting.

Contributed Papers

Sessions for the reading and discussion of contributed papers continued throughout Saturday, October 5, the authors' abstracts of these papers being appended.

Registration

The total number of members who registered at this meeting was 208. Much of the success of the meeting was due to the efforts of a committee appointed by the Rochester Section and consisting of the following: Leon V. Foster, *Chairman*, R. E. Burroughs, A. A. Cook, A. Doyle, George Gardner, H. F. Kurtz, R. Miller, B. Noyes, Brian O'Brien, F. H. Perrin, C. M. Tuttle, and T. R. Wilkins.

Among the special events arranged by this committee were trips to the Research Laboratories of the Eastman Kodak Company, to the Bausch & Lomb Optical Company, and to many other places of interest. A complimentary luncheon at the Taylor Instrument Company on Friday was followed by an inspection tour of the plant. An unusually attractive program for the entertainment of the ladies was arranged by a committee under the chairmanship of Mrs. Brian O'Brien.

Meeting of the Board of Directors

A meeting of the Board of Directors was held on Wednesday, October 2, 1940. Minutes of the meeting are appended.

Arthur C. Hardy, *Secretary*

Minutes of the Sixteenth Meeting of the Board of Directors of the Optical Society of America, Incorporated

Hotel Sagamore, Rochester, New York, October 2, 1940

BESIDES the transaction of routine business and the receiving of reports from chairmen of committees and representatives, the following items of general interest to members of the Society were taken up.

Announcement by Secretary

Results of Letter Ballots

1. Award of first Adolph Lomb Medal to David L. MacAdam.
2. Appointment of Clifton M. Tuttle as a member of the Committee on Meetings and Programs.
3. Appointment of (Mrs.) Blanche Bellamy to the Colorimetry Committee.
4. Resolution setting time and place of next O. S. A. meeting (to be held jointly with the American Physical Society in Cambridge, Massachusetts, February 21 and 22, 1941).
5. Appointment of Special Committee to Cooperate with A. I. P. in planning the Tenth Anniversary Meeting of the Founder Societies in October, 1941.

Membership

The Secretary reported that since the last meeting of the Board four members had died, forty-two new members had been elected as of January 1, 1940, and eight as of January 1, 1941.

Transfer from Associate to Regular Membership

The following were transferred from associate to regular membership:

Frederick W. Brock	1194	Robert H. Park	1219
Willoughby M. Cady	1191	Earle E. Richardson	1232
H. Keffer Hartline	1210	Charles P. Shillaber	1244
F. C. Hutchings	1026	John Spence	1188
Edwin E. Jelley	1230	J. A. Van den Akker	1242
Theodore F. Karwoski	1217	George Wald	1208
C. N. Nelson	1231	S. Rains Wallace	1226

Financial Status of the Society

The Treasurer gave an informal report which showed that the financial condition of the Society continued satisfactory.

Election of Editor

George R. Harrison was unanimously elected Editor of the Journal for the term October, 1940, to October, 1944.

Committee Appointments

To Consider and Report Upon New Contract with the American Institute of Physics:

F. C. Gibbs, *Chairman*

L. B. Tuckerman	H. F. Kurtz

To Report at the February, 1941 meeting on the possibility of awarding an Adolph Lomb Medal in October, 1942:

W. B. Rayton, *Chairman*,

R. C. Gibbs	Selig Hecht
G. R. Harrison	F. L. Mohler

To report at the February, 1941 meeting on the possibility of awarding an Ives Medal in 1941:

Rudolf Kingslake, *Chairman*

Jesse W. Beams	P. E. Klopsteg
H. E. Ives	A. G. Worthing

Emeritus Membership

On the basis of a report submitted by a Committee Appointed to Consider the Matter of Emeritus Memberships, it was voted to amend Article I of the By-Laws as follows:

By inserting in Section 1, Classes of Membership: the word "Emeritus."

By inserting after the third paragraph of Section 3, Eligibility: the paragraph:

"Any person who has retired from active work, has reached the age of 65 years, and has been a member for at least 20 years is eligible for emeritus membership. Other members may, by a two-thirds (2/3) vote of the Board of Directors, be declared eligible for emeritus membership."

By inserting after the fourth paragraph of Section 5, Election to Membership: the paragraph:

"Any eligible member may, at his own request, be transferred to emeritus membership by the Secretary."

And by inserting after the second paragraph of Section 6, Duties and Privileges: the paragraph:

"Emeritus members shall have all of the privileges of their former membership status, except the right to receive the Journal and other publications of the Society."

A.I.P. Representative

Arthur C. Hardy was nominated to succeed himself as O. S. A. representative on the Governing Board of the American Institute of Physics.

ARTHUR C. HARDY, *Secretary*

Program of Sessions

(Titles and Abstracts of Papers)

1. Refractive Indices of Liquid Aliphatic Organic Compounds. Maurice L. Huggins, *Research Laboratories, Eastman Kodak Co.*

The molal refraction, defined by a Gladstone-Dale type of equation, $R=V(n_D-1)$, where V is the molal volume and n_D is the refractive index for the Na D lines, is, for a *normal* paraffin, a rectilinear function of the chain length. For *any* paraffin, the molal refraction is, practically within experimental error, the sum of "bond refractions," each of which has a magnitude depending on the kinds of atom (hydrogen; primary, secondary, tertiary or quaternary carbon) joined by the bond. The molal refraction of an *unsaturated* aliphatic hydrocarbon can be computed from that for the corresponding saturated compound by subtracting a characteristic constant for each double or triple bond (the size of the constant depending somewhat on the number of R groups attached to the multiply bonded atoms) and adding another constant if two multiple bonds are adjacent to or conjugated with each other. The molal refraction of many *derivatives* of aliphatic hydrocarbons can be computed quite accurately by adding appropriate constants, characteristic of the substituting atoms or groups, to the refractions calculated for the corresponding unsubstituted compounds. Constants have been derived for chlorides, bromides, iodides, amines, alcohols, ketones, aldehydes, acids, esters, ethers, thio-ethers, etc. Equations are presented for the calculation, for compounds of the various classes discussed, of molal refractions from the structural formulas.

2. The Regulation of Tungsten and Mercury Lamps. Harold Stewart, *University of Rochester.*

Certain radiometric problems attempted here have required the regulation of high intensity tungsten lamps and of mercury arc lamps. Voltage, current, resistance, radiation, and power d.c. regulators were developed for tungsten lamps. Voltage regulation was chosen. A 1500-watt 115-volt tungsten lamp in series with a resistance bank of heater coils is connected to the 220-volt line. In parallel with the resistance bank are six power tubes. Differences in the lamp voltage from a reference voltage are put into a two-stage d.c. amplifier and the output is applied to the grids of the power tubes in such a way as to increase the power tube current when the lamp voltage decreases. Fluctuations in the voltage output of the local generator are several percent, but regulation of lamp voltage is about 1/400 of one percent. However the radiation output of the lamps is not better than 1/10 of one percent due to several causes within the lamp itself. The radiation output of the type H5 mercury arc lamps has been regulated to better than 1/10 of one percent for short periods (30 minutes) by a photoelectric regulator. Six power tubes are connected in parallel with the lamp across the secondary of the lamp's transformer. Light from the lamp falls on a photo-cell in series with 100 megohms which operates into a one-stage feed-back amplifier. The output of the feed-back amplifier goes to the input of a three-stage d.c. amplifier the output of which controls the voltage on the grids of the power tubes in such a way as to decrease the current in the power tubes when the photo-current decreases. Without the regulator, radiation fluctuations are several percent. When the regulator is to be used for long periods a thermopile or other such device is used as a reference standard.

3. Factors Contributing to the Discrepancy Between Subjective and Skiascopic Determinations of the Refraction of the Eye.* Glenn A. Fry, *Ohio State University.*

An eye can be rendered artificially emmetropic by placing before it an ophthalmic lens which corrects the spherical and astigmatic errors of refraction. When such an eye is subjected to skiascopic examination at a distance of, say, 40 cm, the eye can be made to fixate a target in the same plane as the skiascope, and although the subject reports that the target is seen clearly, the skiascope will indicate that the eye is under-accommodated. Conceivably, the following factors might contribute to this discrepancy between subjective and skiascopic criteria of the state of refraction: (1) displacement of the skiascope from the line of sight; (2) the lazy lag of accommodation; (3) spherical aberration; (4) chromatic aberration. The paper reports an investigation of the relative roles played by these factors. A special type of skiascope and an instrument called an aberrometer have been designed for carrying out the investigation. These two instruments make it possible to evaluate the roles played by the different factors. The displacement of the skiascope from the line of sight was not found to be an important factor, and the discrepancy between the subjective and skiascopic determinations of the eye involves to a certain extent all the other factors mentioned above.

* To be submitted to J. O. S. A.
Bibliography: J. P. C. Southall, "Optical principles of skiametry," J. Opt. Soc. Am. **13**, 245–266 (1928).

4. Ophthalmic Lens Testing Instrument. A. Ames, Jr. and Kenneth N. Ogle,* *Dartmouth Medical School.*

In the study of the importance of the relative sizes and shapes of the ocular images in the two eyes to binocular vision, it is necessary to have an instrument with which the optical properties of lenses, as used with the eyes, can be completely determined. Since no existing instrument was adaptable, this necessitated the building of one. The present paper briefly describes the instrument from the point of view of measuring power, astigmatism, peripheral aberrations, prismatic deviation, magnification and distortion for the lens used with the stationary and mobile eye. An example of the measurements is given. (There are two such instruments at the present time—one at Dartmouth, Department of Research in Physiological Optics, and the second at the American Optical Company in Southbridge, Massachusetts.)

* Presented by Mr. Ogle.

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5. Photographic Analysis of Some Unexplored Visual Phenomena. WILLIAM A. GARDNER, *Columbia University.*

If an observer fixate a stationary point along the track of a speeding automobile, he will apparently see the spokes of the rotating wheels. This effect has been tentatively ascribed to stroboscopic vision, or to subjective factors. Photographs (with camera speed slow, relative to automobile velocity) show this same effect, proving that it depends on objective factors. Experiments reveal that apparent spoke visibility is limited to the lower hemisphere, that the eye must rigorously fixate a nearby stationary point, and that the effect is independent of velocity, lighting, or angle of vision. Photographs, exactly duplicating the visual impressions, are obtained by keeping the camera shutter wide open during the transit of the experimental wheel. Analysis shows that this effect depends entirely on mechanics. The apparent "spokes" are, in reality, the locus of maximum overlap (and therefore of maximum brightness) of the cycloids formed by the combined rotation and translation of each spoke. The summation of these cycloids forms a static pattern (progressively created by the combined rotation and translation of the wheel), which glides across the sentient retina or the sensitive film. Instead of demanding a stroboscopic theory of vision, therefore, this "cycloid effect" favors a theory of continuity of vision analogous to the continuous sensitivity of the camera film with wide-open shutter. A comparable illusion was described in 1821, whereby the spokes of a rapidly rolling carriage wheel, when viewed through a series of fixed vertical slits, appeared curved. Roget, in 1824, explained this effect as due to mechanical factors, and showed that the same phenomenon could be produced by a stationary rotating wheel when viewed through a transversely moving system of slits. This "Roget effect" is experimentally duplicated, and seen as a startling fixed pattern of variably curved vertical lines. Photographs made with wide-open camera shutter produce an image identical with that seen by the eye. The "cycloid effect" and the "Roget effect" are examples of the manner in which both eye and camera build up, by a summation of mechanically produced images, a retinal (or optical) pattern, which has wholly objective causality, but wholly subjective (or photographic) existence.

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6. A Supersonic Cell Fluorometer. H. B. BRIGGS, *Bell Telephone Laboratories.*

A method will be described for the measurement of the rise and decay of luminescence in phosphors excited by cathode-ray beams. It is particularly suited to the investigation of phosphors classed as fast, i.e., those in which the major changes in intensity occur in a few microseconds. The problem is to measure the intensity of the emitted light at definite time intervals after the excitation has started or stopped, and during periods sufficiently short so that no major changes in intensity occur within the measuring interval. This is accomplished by utilizing the properties of a supersonic cell arranged to produce the Debye-Sears diffraction effect. The high speed shutter action is obtained by modulating the supersonic wave train to produce short steep sided pulses. Time intervals in the decay process are measured in terms of distances traversed by the sound waves in water. Light intensities sufficient for direct measurement in terms of photoelectric cell response are obtained by synchronizing the periodic excitation of the phosphor with the diffracting wave pulses in the liquid. The phase relation between the excitation of the phosphor and the diffracting wave pulses may be continuously varied by moving the supersonic cell to increase or decrease the distance from the quartz crystal generating the sound waves to the section of the liquid traversed by the light beam. Several methods of using the device will be described, and some results obtained by these methods will be shown.

7. Interference Phenomena with a Moving Medium.* HERBERT E. IVES AND G. R. STILWELL, *Bell Telephone Laboratories.*

An experimental study of interference patterns set up on a mercury surface when the source of ripples is in motion with respect to the surface. Ripples are produced by air jets interrupted by sector disks in the air supply, and the ripple patterns, or the standing wave patterns, are photographed by intermittent and steady illumination. The air jets, light source and camera are arranged on a lathe bed so as to move with velocities which are a large fraction of the ripple velocity. The Fresnel biprism is simulated by two jets, and it is shown that the interference pattern with a moving medium is altered from that for a stationary medium in a manner which is corrected by the Fitzgerald contraction and the Larmor-Lorentz change of frequency. Stationary interference phenomena produced by the simultaneous occurrence of both capillary and gravity waves of different velocities are shown to call for the Fresnel drag coefficient to nullify effects of motion of the medium. The amplitudes of the "biprism" or double jet interference fringes are unaltered by motion of the medium. The question of the rate of flow of energy in front of and behind a moving source is discussed.

* The present paper will appear in full in J. Opt. Soc. Am.

Symposium of Invited Papers

Progress in American Optical Science and Industry

8. A Quarter Century of Optics Reviewed. HERBERT E. IVES, *Bell Telephone Laboratories.*

9. Quality Control in the Manufacture of Optical Instruments—Twenty-five Years' Progress. W. W. GRAEPER, *Bausch & Lomb Optical Company.*

10. Recent Developments in Photography. C. E. K. MEES, *Eastman Kodak Company.*

11. Producing Low Reflecting Glass. C. HAWLEY CARTWRIGHT, *Corning Glass Works.*

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12. Changes in Lens Characteristics with Temperature. A. FRANCIS TURNER, *Bausch & Lomb Optical Co.*

The calculation of the change of correction of a lens with temperature requires, besides data on the coefficient of expansion of the metal of the mount, also a knowledge of the coefficient of expansion of the glass, together with its temperature variation of index and dispersion. Measured data on glass for low temperatures are lacking. Using published[1] results obtained above room temperature one calculates, for instance, a decrease in focal length in a simple imaging system of a few hundredths percent per 50°C decrease in temperature. Although such temperature effects are small, they cannot always be ignored in the design of optical instruments, as for use in airplanes where −40°C may be encountered. A need is felt by the industry for more low temperature data on optical glasses.

[1] E.g., *Int. Crit. Tab.* Vol. II.

13. Chemical Methods for Increasing the Transparency of Glass Surfaces. FRANK L. JONES AND HOWARD J. HOMER,* *Mellon Institute.*

The amount of light transmitted by a lens or prism can be increased by suitable chemical treatment of the polished surface. The effect was described by Taylor in 1892, Kollmorgen in 1916, and Wright in 1921. The general use of treated lenses was delayed because of a lack of knowledge of the physical and chemical principles involved in the process. The chemical treatment involves the formation of a transparent surface film of silica by the removal of the higher refractive index oxides to a depth approximately equal to one-fourth the wave-length of the light for which maximum transmission is desired. Such removal is possible without damage to the surface polish if the solvent does not dissolve silica. The surface film is not noticeably different from the base glass in hardness. The gain in light transmission and the decrease in surface reflection is slightly less than that produced by evaporated films of materials of lower refractive index than silica. Solvents that will remove higher refractive index materials from a glass surface include water, fused salts, alkaline phosphate solutions, salt solutions and acid solutions. A dilute acid solution such as 1 percent nitric acid is suitable for most optical glasses with the exception of crown glass. The treatment time is short for glasses containing large amounts of lead or barium and long for borosilicate glasses. The solution speed for a given glass approximately doubles for each 10°C rise in temperature. Freshly prepared glass surfaces react with the solution at a uniform rate that depends on the glass composition, the solution composition, and the temperature. When a silica surface film has been formed, it may be processed in various ways that will render the surface unreactive so that a second treatment will not appreciably change the thickness of the film. Glass surfaces not freshly prepared are usually unevenly reactive due to accidental stabilizing of the surface by handling or processing.

* Bausch & Lomb Optical Company's Industrial Fellowship, Mellon Institute.

14. An Automatic Telescope Control. ARTHUR C. HARDY, *Massachusetts Institute of Technology.*

During the progress of some tests on the flatness of window glass, it became desirable to determine the deviation experienced by a small parallel bundle of rays traversing the glass normally to its surface. Measuring this deviation by means of a collimator and telescope is unsatisfactory because modern drawn glass is of such high quality that the maximum deviation is usually less than a few minutes of arc. It would, therefore, be necessary to use a telescope having an entrance pupil of such size as to mask the local variations in the deviation over the glass surface. This problem was satisfactorily solved by using a photoelectric cell to control the telescope. Light from a tungsten lamp enters a collimator whose slit is replaced by a circular aperture. At the image of this aperture, where cross-hairs would normally be located, there is a sort of photometric field consisting of two pieces of Polaroid placed side by side with their axes at right angles. Behind this photometric field is a single piece of Polaroid which is rotated in its own plane at a rate of thirty revolutions per second. When the image of the circular diaphragm is exactly centered on the dividing line of the photometric field, the rotation of the second Polaroid produces no variation in the light flux transmitted by the system. If the image is decentered, a sixty-cycle current is produced in the output circuit of an amplifier actuated by a photoelectric cell, the phase of the current depending upon which half of the photometric field receives the greater amount of light. This current is used to operate a motor in a manner previously described.[1] The motor drives a tangent screw which controls the telescope and another screw which controls a recording pen.

As a piece of glass is moved through the beam, a record is made on an adding machine tape six inches in width. The advantage of this method is due chiefly to the fact that the telescope is not required to have a resolving power as high as the angular deviation which it measures. This comes about because the photoelectric cell is able, with this arrangement, to determine very accurately when the diffraction pattern produced by the objective has been bisected by the dividing line of the photometric field. The telescope objective used in these tests had a focal length of one meter, and it was fitted in most cases with a diaphragm having a circular aperture only 0.1 inch in diameter. The uncertainty in the setting was of the order of ±2 seconds. This optical system could readily be adapted to such purposes as the guiding of an astronomical telescope or the recording of galvanometer deflections.

[1] A. C. Hardy, J. Opt. Soc. Am. and Rev. Sci. Inst. 18, 109 (1929).

15. Optical Properties of Evaporated and of Burnished Vitreous Quartz in the Extreme Ultraviolet. RICHARD TOUSEY, *Tufts College.*

The specular reflectivities of quartz evaporated onto crystalline and onto vitreous quartz, and of burnished (slowly polished) vitreous quartz have been measured at 45°, 60°, 75°, and 85° incidence within the wave-length range 910A to 1436A. Values of refractive index and extinction coefficient have been computed from these reflectivities.[1] These results will be compared with similar data for crystalline quartz and for vitreous quartz etched in KOH,[2] which, having almost no surface layer, are as near "ideal" surfaces as possible. These data indicate that a burnished surface of vitreous quartz does not closely resemble an ideal surface of either crystalline or vitreous quartz, while one produced by evaporation is very unlike either ideal surface. The strong selective reflection at 1190A and the weaker one at 1070A, characteristic of both crystalline and etched vitreous quartz, are greatly reduced for vitreous quartz by burnishing the surface. The extinction coefficient curve for a typical burnished surface is fairly smooth, with the hump at 1190A only one-third as high as for etched vitreous quartz. The surface produced by evaporation shows practically no selective reflection at all whether condensed on crystalline or vitreous quartz. The extinction coefficient for evaporated quartz rises rapidly from near zero at 1436A to a value of 0.6 at 1216A. From this wave-length to 1026A it runs practically constant. As a check on this work and on the reflection method for determining the extinction coefficient, the transmission values of an evaporated surface of quartz have been measured directly to 1100A by using LiF as a support. These are in agreement with the extinction coefficient curve as determined by reflection.

[1] R. Tousey, J. Opt. Soc. Am. 29, 235 (1939).
[2] Lord Rayleigh, Proc. Roy. Soc. 160, 507 (1937). R. Tousey, Phys. Rev. 57, 29A, 1060 (1940).

16. Measurement of Numerical Aperture. R. BRUCE HORSFALL, JR., *Bausch & Lomb Optical Company.*

The customary definition of numerical aperture is adequate, and techniques of measurement are well known in the case of well corrected systems such as microscope objectives. In dealing with uncorrected or poorly corrected lenses such as condensers, there are deficiencies which may lead to misunderstanding and disagreement. Techniques of measurement approximating conditions of most frequent use are recommended as standards. It is suggested that condensers be tested by comparison with objectives of known N.A., using an unrestricted source for uncorrected condensers and a source which will just fill the objective field for corrected condensers. Mention is made of the term "Aplanatic Aperture" used by Carpenter-Dallinger[1] and a suggested revision of definition is proposed.

[1] C. B. Carpenter, revised by W. H. Dallinger, "The Microscope and its Revelations," eighth edition, pp. 307–315.

17. An Improved Radiation Pyrometer.* T. R. HARRISON AND WM. H. WANNAMAKER, *The Brown Instrument Company.*

In the development of a new radiation pyrometer, the following characteristics were required: (1) constancy of calibration with different distance-to-target diameter ratios up to twenty to one; (2) freedom from ambient temperature errors; (3) freedom from transient errors while ambient temperature is changing; (4) reasonably high electromotive force; (5) practically complete response within from two to four seconds. The thermoelectric type was found to be the most adaptable and dependable for general use. Consideration of ambient temperature effects, which is of much importance in modern industrial practice, was carried out by aid of mathematical analysis. In one assumed case, with a very sensitive type of thermopile losing heat from its hot junction by radiation alone, it is shown that an increase in operating ambient temperature of 180°F (from 80°F to 260°F) results in a drop in output voltage of 38 percent for a constant furnace temperature of 1300°F. The corresponding error in reading is 315°F. At a furnace temperature of 3000°F the decrease in voltage is 17 percent and the error in reading is 387°F. Under similar conditions with a less sensitive thermopile having a conduction factor of 3×10^{10}, this 180°F increase in operating ambient temperature would result in a decrease in output voltage of from 12.2 percent to 12.5 percent for any furnace temperature between the two values mentioned. The error in reading would range from 58°F to 162°F over the stated span of furnace temperatures. The constancy of ratio of e.m.f.'s with the latter case makes that case suitable for compensation by means of a nickel wire shunt connected across the thermopile terminals. This method was adopted. Other methods of compensation are considered. Test data show the degree of perfection realized in the various respects indicated. Special features of construction are shown, rendering the pyrometer practically free from the usual transient errors accompanying changes in the temperature of the pyrometer. All of the thermopile junctions are spot-welded and the construction is arranged throughout to withstand high ambient temperatures.

* The present paper will appear in full in Rev. Sci. Inst.

18. Calibration Data on General Electric Recording Spectrophotometer. J. L. MICHAELSON AND W. R. FANTER, *General Electric Company.*

Due to the general interest shown by members of the Optical Society of America in spectrophotometry, it has occurred to the authors that it would be interesting to present calibration data obtained from various General Electric spectrophotometers. Therefore, during the past two years we have recorded rather complete data on the performance of these instruments, which will be presented.

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19. The Importance of Optically Clean Absorption Cells in the Determination of the Concentration of Dye Solutions. S. Q. DUNTLEY, *Massachusetts Institute of Technology.*

Spectrophotometric transmission data are often used in determining the strength of dye solutions. Customarily, effects due to the presence of the absorption cell and to the solvent are compensated by placing a duplicate cell filled with undyed solvent in the comparison beam of the photometer. It is the purpose of this paper to investigate the errors in dye strength determinations which may result when this compensation is imperfect. Such imperfect compensation may occur during a series of measurements due to contamination of the outer cell surfaces by fingerprints, spilled dye solution, etc. By the application of differential calculus to Beer's law, it can be shown that the greatest change in transmission for a given percentage change in dye concentration occurs when the transmission is 37 percent. It can further be shown that the errors arising from imperfect cell compensation can be slightly reduced by using a lower value of transmission. However, it is never possible to reduce the error to negligible proportions by this device. For example, with a pair of cells which, when filled with solvent, yield an apparent transmission factor of 99 percent, the resulting error in $\Delta C/C$ is greater than 50 percent even when the sample transmits no more than 15 percent. This leads to the conclusion that the use of concentrated solutions does not excuse the operator from checking the condition of his cells before each measurement. The treatment is extended to show the effect of imperfect cell compensation on data taken with the "five times," cam available for the Hardy recording spectrophotometer.

20. The Viewing Angle of Reflectometry. ELLIOT Q. ADAMS, *Lamp Development Laboratory, General Electric Company, Nela Park.*

Many instruments for the rapid measurement of the reflectance of matte surfaces provide for illumination, or viewing, at an angle of 45°, although it has been known for some time that the angle of equivalence with diffuse illumination is, for most matte surfaces, appreciably greater than 45°. Thus A. H. Taylor and C. H. Sharp, in discussing[1] the Taylor absolute reflectometer, speak of viewing at 50°, while McNicholas[2] reports: "Thus for matt samples of the kind herein studied (of not extremely low reflectance), one would be quite safe in choosing an angle of observation of 55° and assuming an accuracy of 1 or 2 percent." It appears not to have been pointed out that there is *a priori* reason for illuminating at an angle of approximately this value: If diffuse illumination is to be replaced by illumination from a finite number of points, the nearest equivalence will be secured by locating the sources at the corners of a regular polyhedron, i.e., of a regular tetrahedron, octahedron or cube, the number of sources being, respectively, 4, 6 and 8. For an opaque plane surface, the sources behind the plane will not contribute to the illumination, hence may be omitted. If the remaining sources are so located as to make equal angles with the normal to the surface, and *if* the reflectance of the surface *does not vary with azimuth*, the normal brightness will, by symmetry, be unchanged if the 2, 3 or 4 sources are replaced by a single source of the total luminous intensity, at the location of one of them. The angle from the normal will be, in each case, that between the threefold and fourfold axes in the cubic crystallographic system. This angle is $\tan^{-1}\sqrt{2}=54°44'8+''$. To the degree of accuracy of the reciprocity principle, the apparent reflectance will be the same for normal illumination and viewing at an angle of 54°44′8″.

[1] A. H. Taylor and C. H. Sharp, Trans. Ill. Eng. Soc. **15**, 811 (1920).
[2] H. J. McNicholas, Bur. Stand. J. Research **1**, 29 (1928).

21. An Extreme Case of the Performance of the Eye *versus* that of the Spectrophotometer.* I. H. GODLOVE, *E. I. duPont de Nemours and Company.*

The addition of small amounts of Crocein Scarlet to Tartrazine was supposed by Draves[1] to be a case where the eye can detect smaller additions than a spectrophotometer; but it was shown by Nutting,[2] using the Hardy spectrophotometer,[3] that the reverse is true if the measurements are not confined to a single wave-length, as was done by Draves. This case is one in which the two spectral absorption curves involved are very different in shape. The opposite extreme, where the curves have similar shapes, includes cases where, at least under industrial working conditions, the spectrophotometer cannot detect as small additions as the eye. This extreme is illustrated by mixtures of Pontacyl Carmines 2B and 6B Conc., which are not chemically identical but have very similar spectral absorption curves. For equal weights of standardized dyes, the long wave portions of the curves for the solutions can be practically superimposed, the short wave portions being parallel; somewhat different relations hold for the reflection curves of dyeings. Two very experienced dye testers find that 2.5 percent of the latter dye mixed with the former can be seen to change the color of the skeins, but the mixture would usually be passed as not "off-shade," while a 5 percent admixture would cause positive rejection. Using the curves of the buffered solutions of the two dyes normally employed by us for spectrophotometric standardization, the hue change due to a 25 percent admixture of the latter dye probably can be detected by inspection of the curves; but the curve due to a 10 percent admixture (with 90 percent of the 2B type) is so close to that of the former unmixed dye that, when the two curves are drawn by the fountain pen of the Hardy-G. E. instrument,[4] they overlap too much to be separated. Making computations on the ICI system of colorimetric specification, the 10 percent addition is found to cause a change of about 0.0014, 0.0004 and 0.0017 in the x, y and Y values, respectively. These values were obtained when all errors due to weighing and hygroscopicity of samples and to making up solutions were eliminated; some other errors were eliminated by reading directly on the instrument counter at selected wave-lengths. If these differences are considered as errors due to a single impurity of known character, and the indicated precautions are taken, then the performance of the instrument, using solutions, becomes comparable to that of the eye, using dyed skeins. But these conditions are ones which cannot be used in routine standardization. In particular, the number and nature of the impurities are often unknown and variable; also, it is inconvenient to eliminate errors by measurements on the standard every time the corresponding lot comes up, or by reading on the counter. The time element, as well as serious difficulties of "levelness" and incompleteness of "exhaust," makes measurements on skeins or pieces wholly impracticable; but measurements of this sort will be reported. It is our experience that the majority of cases fall between the two extremes discussed; but enough fall near the "similar-curve" extreme to make standardization "for shade" (chromaticity) frequently very unsatisfactory when compared to standardization by "dye testing."

* The present paper will appear in full in J. Opt. Soc. Am.
[1] C. Z. Draves, J. Opt. Soc. Am. **21**, 336–46 (1931).
[2] R. D. Nutting, J. Opt. Soc. Am. **24**, 135–8 (1934).
[3] A. C. Hardy, J. Opt. Soc. Am. **18**, 96–117 (1929).
[4] A. C. Hardy, J. Opt. Soc. Am. **25**, 305–11 (1935); J. L. Michaelson, J. Opt. Soc. Am. **28**, 365–71 (1938).

22. Noticeability of Color Difference in Daylight. DAVID L. MACADAM, *Eastman Kodak Company.*

The probable error of two component additive visual color matching has been adopted as the most reproducible criterion of the noticeability of color differences. The probable errors of matching a series of colors are proportional to the corresponding just noticeable differences, within the rather great uncertainties of the latter. An apparatus has been employed in which the color of each half of a two-degree circular field can be varied corresponding to the points along any of a very great number of straight lines in the chromaticity diagram. The luminance of each half of the test field remains constant for all of the additive mixtures of the light from any two of a set of over one hundred color filters, all of which have equal luminous transmittances for the quality of light incident upon them in the instrument. A surrounding field of forty degrees diameter can be uniformly illuminated to any desired luminance and chromaticity. Over 18,000 color matches have been made by one observer, with 15 millilamberts luminance in the test field and 7.5 millilamberts of daylight quality (ICI illuminant C) in the surrounding field. The probable errors of determination of position along specified straight lines in the chromaticity diagram can be shown as functions of the positions on those lines corresponding to the chromaticities of the colors matched. The probable errors of purity determinations for representative dominant wave-lengths and their complementaries (including purples) reveal a direct relation between the noticeabilities of purity differences for nearly neutral complementary chromaticities. The noticeabilities of chromaticity differences along straight lines close to the spectrum locus and the boundary of the purples are very simple functions of distance along those lines. A curve for the probable error of wave-length matching under conditions of automatically constant luminance of the spectrum has been deduced from the observed data and shows only two minima, at about 486 mμ and 582 mμ. The probable errors of matching white (illuminant C) with mixtures of complementary colors can be represented by points on an ellipse around the point representing white in the chromaticity diagram. Similar ellipses represent the observed probable errors of all kinds of two-color mixtures matching eighteen other chromaticities well distributed over the chromaticity diagram. The major characteristics of all of the curves and loci representing the results for the principal observer have been confirmed by less extensive series of color matches by other observers.

23. $X-Z$ Planes in the 1931 ICI System of Colorimetry. ELLIOT Q. ADAMS, *Lamp Development Laboratory, General Electric Company, Nela Park.*

The Maxwell triangle usual in colorimetry is predicated on a symmetrical relationship among the three components of the Young-Helmholtz theory. There is no reason to treat them symmetrically; the Munsell color system is one of cylindrical coordinates about the axis of value, the 1931 ICI system attaches all the luminosity to the Y component, and observations of chromaticity differences are made after equating brightness. By plotting X and Z values for colors of the same luminous reflectance (albedo, Munsell value) it is found that a suitably chosen ratio of scales (threefold greater for X) gives a nearly uniform radial and circumferential spacing of the Munsell colors, centered about the neutral color of equal value. For measurements made under ICI standard illuminant C (as were those of Glenn and Killian) normalization by division by (respectively) X and Z for standard illuminant C gives X_c and Z_c, and a scale-factor of approximately $2\frac{1}{2}$. Plotting Z_c-Y against X_c-Y brings the neutral color for each value of luminous reflectance to the origin of coordinates. Approximate register of colors of equal hue and chroma, and unequal value, is obtained by converting X_c, Y, and Z_c to V_x, V_y, V_z using the Munsell-Sloan-Godlove value function, and plotting V_z-V_y against V_x-V_y. These subtractions are the mathematical representation of inhibitory nervous connections (synapses) in the retina, according to the author's theory of color vision.

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24. Change of Color with Change of Particle Size.* I. H. Godlove, *E. I. duPont de Nemours and Company.*

The previously developed theories[1] of the change in the three attributes of surface color, which accompany a change in size of pigment particles, have been elaborated and corrected, and have been tested by application to a great many cases observed in the laboratory and found in the literature. Excellent agreement of the theory with the facts is found. The chief color changes are: (1) the increase in lightness due to decreased absorption by particles of decreasing size; (2) the dulling due to the greater surface reflection of light not absorbed; and (3) certain hue changes predictable from the changes with increased subdivision of particles, or with decreased thickness of absorbing layer, known to occur in the absorption or transmission curves of solutions of corresponding color. The hue changes are describable as those resulting from the assumption that most of the reflected light from pigment surfaces is due to light transmitted through the particles; and they are in the direction corresponding to decreased absorption in the wave-length region of the characteristic maximum absorption, as the particle size decreases. It is further found that, roughly speaking, subdivision of the particles has the same effect on the hue as admixture of black or white pigment to the chromatic one, or changing from oil film or wet pigment to dry powder in air, except that, especially on addition of certain white pigments, a blue-violet component due to scattering of light by very small particles is blended with the main component of the reflected light.

* The present paper will appear in full in J. Opt. Soc. Am.
[1] Merwin, Proc. Am. Soc. Test. Mat. **17** (ii), 494–530 (1917).

25. A New Polarimeter Using Sheet Polarizing Elements. Roger S. Estey, *Spencer Lens Company.*

A new polarimeter will be described which employs Polaroid material in the polarizer and analyzer. A narrow strip is superimposed on a large disk of this material to form a three-part field in the polarizer. This, like the Lippich half-shade device, can be set to a selected sensitivity and can be used with light of any wave-length. The analyzer contains a disk of Polaroid material which is mounted in a cone bearing and is controlled by a worm gear and worm. The position of the analyzer can be read to 0.1 degree by reference to a graduated drum on the worm shaft. Sample tubes 200 mm long and shorter can be accommodated. In an instrument of this grade, sheet polarizing material offers many advantages. The end point device is simple, easy to mount and to adjust. The glass plates between which the Polaroid sheeting is laminated serve also as splash plates. In the material selected, the polarization is practically complete through the middle of the visible spectrum and is still adequate near the limits of visibility. If one attempts to match the fields when the instrument is illuminated with white light a residual color difference is evident. Because of the rotatory dispersion of the sample it is useless to attempt measurements under these conditions with any polarimeter. When the instrument is used with monochromatic light these color differences disappear. The use of an orange filter to modify the light from a tungsten lamp is common practice with simple polarimeters designed primarily to measure glucose and albumen in urine. In this application the rotatory dispersion has a small effect on the color of the field because the total rotation is so small (5°–10°). Nevertheless it is desirable to supply a filter which will control the wave-length limits of the transmitted band with sufficient accuracy to ensure that measurements made with this illumination will have the same values as reference measurements made with sodium light. A similar problem arises with filters designed to approximate the effect of other wave-lengths. Data on such filters will be presented.

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