January 1, 1934

PUBLICATIONS on COLORIMETRY AND SPECTROPHOTOMETRY from the National Bureau of Standards

Part I
Publications primarily related to Colorimetry.

Part II
Abstracts, reports, letter circulars, etc., not included in Part I.

Part III
Miscellaneous publications, not included in Parts I and II.

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Publications primarily related to Colorimetry

   The law is verified with light from the Nernst glower and with red, green, and blue light, respectively, for total angular openings between 288° and 10°.


5. *Ives, Herbert E.,* The daylight efficiency of artificial illuminants, B.S. Bull., vol. 6, p. 231, 1909-10. (S125)


8. *Nutting, P.G.,* A photometric attachment for spectrometers, B.S. Bull., vol. 7, p. 239, 1911. (S155)
   By means of the attachment a spectrometer may be converted into a spectrophotometer; the original instrument is described.

   Color is specified by the monochromatic method; an early form of instrument is described and typical results given.

    The variations found among Lovibond red glasses of the same nominal grade are illustrated and discussed.


14. *Specification of the transparency of paper and tracing cloth, B.S. Circular No. 63, 1917. (C63, 5%) Transparency is specified by measuring the contrast ratio, B/W, where B and W are the brightnesses resulting when the material is placed over black and white (MgO) surfaces, respectively.

15. *Priest, Irwin G., and Peters, Chauncey G., Measurement and specification of the physical factors which determine the saturation of certain tints of yellow, B.S. Tech. Paper No. 92, 1917. (T92) Saturation of yellow samples is indicated by the ratio, reflectance for 578 mμ divided by reflectance for 436 mμ.

16. *Coblentz, W.W., and Emerson, W.B., Relative sensibility of the average eye to light of different colors and some practical applications to radiation problems, B.S. Bull., vol. 14, p. 167, 1918-19. (S303, 15%) Determinations were made on 125 observers by the flicker method. (See also ref. 34.)


19. *Gibson, K.S., Photo-electric spectrophotometry by the null method, B.S. Sci. Papers, vol. 15, p. 325, 1919-20. (S349, 5%) This method has been superseded by the more rapid method described in a later publication. (See ref. 35.)

The transmission of soya bean oil in the visible spectrum is found to be of a similar type to that of cotton seed oil.

21. *Gibson, K.S., Tyndall, E.P.T., and McNicholas, H.J., The ultra-violet and visible transmission of various colored glasses, B.S. Tech. Paper No. 148, 1920. (T148, 104) Spectral transmission curves are given for over 50 different kinds of glasses. Methods of measurement are briefly described and a chart is given by which transmittances for varying thicknesses may be obtained if known at any one thickness.

22. *Priest, Irwin G., Gibson, K.S., and McNicholas, H.J., An examination of the Munsell color system. I. Spectral and total reflection and the Munsell scale of value, B.S. Tech. Paper No. 167, 1920. (T167) Data are given on 20 samples selected from the Atlas of the Munsell Color System (1916). It is shown that the "Munsell value" of these samples is closely proportional to the square root of their reflection for noon sunlight.


On page 482 of this publication is shown the variation in color of direct sunlight from sunrise to sunset in February.


A maximum variation of approximately 0.7 of a Lovibond red unit was found among sixteen glasses, all of nominal grade 7.6, when tested in combination with Lovibond 35 yellow.


The method is more completely described in ref. 36.
28. *Priest, Irwin G., The spectral distribution of energy required to evoke the gray sensation, B.S. Sci. Papers, vol. 17, p. 231, 1922. (S417, 10\) It is found that the average dark-adapted observer calls a Planckian stimulus at 5200\(^\circ\)K gray.


30. *Priest, Irwin G., Measurement of the color temperature of the more efficient artificial light sources by the method of rotatory dispersion, B.S. Sci. Papers, vol. 18, p. 121, 1922-23, (S443, 5\); also Jour. Opt. Soc. Am. and Rev. Sci. Inst., vol. 5, p. 27, 1922. The spectral-centroid method of determining color temperature is described and applied to the rotatory-dispersion instrument and to certain standard lamps; data are given on incandescent lamps at 2,850\(^\circ\)K and 3,100\(^\circ\)K, and on the carbon arc (cored carbons, 3,420\(^\circ\); uncored, 3,780\(^\circ\)K). Intercheck was made with Nela Research Laboratory to test the accuracy of calibration. (See also ref. 36.)

31. Optical Society of America Committee on Colorimetry, L.T. Troland, Chairman,* Report for 1920-21, Jour. Opt. Soc. Am. and Rev. Sci. Inst., vol. 6, p. 527, 1922. This is an important comprehensive treatment of colorimetry, including authoritative discussions of nomenclature, methods of color specification, methods of interconversion, and tables of data required for colorimetric computation. The report lists standard conditions for observation, gives excitation data long used as standard, also wave lengths of complementaries and spectral chroma scale. The Lovibond, Munsell, Ridgway, and Ostwald color systems are described. The following methods of colorimetry are interrelated by way of excitation data; spectrophotometry, monochromatic analysis, trichromatic analysis, rotatory dispersion systems, and Planckian distribution analysis.


Determinations were made on 52 observers by the so-called step-by-step, equality-of-brightness method. Comparisons are made with the results obtained by other investigators. A study of all available data leads to a new set of recommended values for the average normal observer under standard photometric conditions. (See also ref. 39.)

The method described has been extended throughout the visible spectrum and into the infra-red with the caesium cell as detector. A thermo-electric method is also described.

The rotatory dispersion colorimetric photometer is described in detail; by its use the color temperature of incandescent illuminants and the various phases of daylight may be determined and their relative intensities measured under color-match conditions. The colors of various illuminants are classified on the color-temperature and spectral-centroid scales. (See also ref. 30.)

The reliability is tested by measuring the transmission of rotating sectored disks of accurately known aperture; a formula and chart are given for computing the probable error of the transmission from the instrumental readings. (See also refs. 62 and 78.)

An elaborate "monochromatic colorimeter" is described; explicit directions for its use, instrumental calibrations and checks, and tests of performance and accuracy, are also given.
39. Gibson, K.S., The relative visibility function, Proc. of the Int. Comm. on Ill., 6th Meeting, Geneva, 1924 (University Press, Cambridge, Eng.), pp. 67 and 232, 1926. The material in B.S. Sci. Paper No. 475 (ref. 34) is summarized. The Gibson-Tyndall recommended values for the relative visibility function were provisionally adopted by the International Commission on Illumination in 1924, were incorporated in the so-called 1931 I.C.I. standard observer (see ref. 91), and were accepted in 1933 by The Advisory Committee on Electricity and Photometry of The International Bureau of Weights and Measures.

40. Gibson, K.S., Spectral characteristics of test solutions used in heterochromatic photometry, Jour. Opt. Soc. Am. and Rev. Sci. Inst., vol. 9, p. 113, 1924. Spectral and luminous transmissions are given for the yellow and blue solutions used to test observers for heterochromatic photometry; the Y/B ratio is computed on the basis of various visibility functions.


43. Optical Society of America Progress Committee for 1922-23, K.S. Gibson, Chairman; Report on spectrophotometry, Jour. Opt. Soc. Am. and Rev. Sci. Inst., vol. 10, p. 169, 1925. The report includes sections on nomenclature, spectrometry, photometry, visual instruments, and auxiliary methods; the calibration and use of spectrophotometers are discussed in considerable detail; a brief but fairly complete review of visual instruments is presented; the applications of spectrophotometry are briefly considered.

44. *Frehafer, M. Katherine, and Snow, Chester L., Tables and graphs for facilitating the computation of spectral energy distribution by Planck's formula, B.S. Miscellaneous Pub. No. 56, 1925. (M.6, 354) Large scale graphs are given for temperatures between 1,000° and 24,000°K and for every 10 μ in wave length between 400 and 760 μ. Energy distributions corresponding to C0 different from the adopted value (14,350) may also be determined with slight additional labor. A table is given of the complete function in a form which facilitates extension to higher and lower wave lengths and temperatures. (See also refs. 65 and 75.)

46. Lloyd, Morton G.* Traffic signals, Proc. Int. Ass'n. Municipal Electricians, 30th Meeting, Detroit (Int. Ass'n. Munic. Elect., West New York, New Jersey), p. 154, 1925. This paper includes the colorimetric specifications for luminous and non-luminous traffic signals as adopted by a Sectional Committee of the American Engineering Standards Association; the former were approved by the American Standards Association as the "American standard colors for traffic signals". (See ref. 61 in Part II.)


It is shown that (1) for a given illuminant there is a linear relation between the thickness of the filter and the spectral centroid of the transmitted light, (2) for a given filter there is a linear relation between the spectral centroids of the incident and transmitted light, when the color temperature of the former is varied.


Data are given on the colors of natural sunlight and Abbot-Priest sunlight.


The Priest purity formulas are applied to non-spectral (purple) colors; Ives' definition rather than Troland's is followed.


The Judd formulas for colorimetric purity are derived; routine methods of computation and sources of error affecting previous published results are discussed; extension is made to purple colors according to the Ives and the Troland definitions; and inverse formulas are derived for computing trilinear coordinates from values of purity and dominant wave length.


Filters are described for isolating or absorbing various spectral regions in the ultra-violet, visible, and infra-red.


57. Judd, Deane B., and Walker, Geraldine K., A study of 129 Lovibond red glasses with respect to the reliability of their nominal grades, Oil and Fat Industries, vol. 5, p. 16, 1928. The routine method of comparing test glasses with standard glasses is described; inconsistencies as high as one unit are revealed in the maker's marks for these red glasses, which are given to tenths of a unit.
58. Priest, Irwin G., Tests of color sense of A.O.C.S. members and data on sensibility to change in Lovibond red, Oil and Fat Industries, vol. 5, p. 63, 1928. A method of testing observers for chromaticity sensibility is described; it is found that 0.1 standard Lovibond red unit is close to the least difference perceptible with certainty at 35-yellow plus 7.6-red.


The Helmholtz reciprocity law is applied to the theory of reflectometry; it is shown that reflectance for any angular distribution of illumination may be derived from the uni-directional reflectances for completely diffused illumination. Apparatus is described and measurements presented of samples of various materials chosen to cover a wide range of reflectance and gloss. Comparative measurements are also reported by the methods of Sharp and Little, Karrer, and Taylor.

The König-Martens spectrophotometer and the auxiliary equipment constructed at the Bureau are described in detail; the theory of the instrument and its use in practice are discussed, particularly those factors affecting the reliability of the data obtained.

Heating by 25°C a 35-yellow glass (or a combination of 35-yellow with 7.2-red) was found by the spectrophotometric method to cause a slight reddening—about the same as that produced by adding 0.2-red.
The construction and adjustment of the spark apparatus are described; improvements in the optical design of the sector photometer are suggested.

The wave lengths for the energy tables extend from 320 to 760 μ by steps of 10 μ and the temperatures extend from 2,000° to 3,120° by steps of 20°K. \( C_0 = 14330 \). The luminosities embody the Gibson-Tyndall recommended values adopted by the International Commission on Illumination (ref. 39). (See also refs. 44 and 75.)


The luminous transmissions obtained directly by flicker and equality-of-brightness photometry are compared with those obtained by spectrophotometric measurement and computation with standard visibility data. The practicability and propriety of using this latter procedure as a basis for standard values is shown. Seven laboratories cooperated in this work.

The glasses are specified by their equivalent in terms of standard Lovibond yellow and red and by the transmission for sunlight. No serious errors in the grades of these glasses were found.

This paper deals with coordinate systems for representing tristimulus specifications, some for practical, others for theoretical purposes; it gives the variation in luminosity coefficients of the primary stimuli with change in coordinate system.


The subject is reviewed from its beginning, near 1900, to 1930. The advantages and limitations of amplified-current instruments are discussed, in addition to the various types of errors to which all spectrophotometric methods, including the photoelectric, are liable.


Precision is raised considerably by increasing the field size or by decreasing the width of a black line separating the two halves of the field; it is raised somewhat by using both eyes instead of one, or by decreasing the width of a non-contrasting dividing line, or by using fields in the same plane.


A change in coordinate system reveals that Hecht's first curves do not accurately express normal mixture data although they seem to do so from direct comparison.

75. *Davis, Raymond, and Gibson, K.S., Filters for the reproduction of sunlight and daylight and the determination of color temperature, B.S. Miscellaneous Pub. No. 114, 1931. (M114, 458)

The color of the Planckian radiator may be reproduced over the range from that of the incandescent lamp (yellow) to approximately 19,000°K (blue); the color temperatures of incandescent lamps may be determined by means of these filters. Detailed spectrophotometric analyses are given both of the filter components and of a considerable number of complete filters; the effects of time, temperature, impurities, and other factors are discussed and illustrated; details regarding selection of chemicals and preparation of solutions and cells are given. Tables of spectral energy distribution of the Planckian radiator with C0 = 14350 are included, covering the temperature range from 2,000° to 20,000°K and the wavelength range from 350 to 720 µm; values of the trilinear coordinates (r, g, b) are also given for the Planckian radiator from 1,600° to 20,000°K, computed on the basis of the O.S.A. excitations and with Davis-Gibson mean sun as basic stimulus. (See also refs. 79 and 82.)


78. Gibson, K.S., Spectrophotometry at the Bureau of Standards, Jour. Opt. Soc. Am., vol. 21, p. 564, 1931. The various spectrophotometric methods used in the Colorimetry Section are described and data given showing the degree of agreement obtained in the measurement of spectral transmission by the visual, photoelectric, and thermoelectric methods.


80. *Davis, Raymond, A correlated color temperature for illuminants, B.S. Jour. Research, vol. 7, p. 659, 1931. (RF385, 106) A method is described for computing the approximate temperature of the Planckian stimulus most nearly matching any reasonably similar stimulus. Tables facilitating this computation are given for temperatures from 1,600° to 20,000°K.

81. Judd, Deane B., Comparison of Wright's data on equivalent color stimuli with the O.S.A. data, Jour. Opt. Soc. Am., vol. 21, p. 699, 1931. It is found that these new data refer to an observer of definitely heavier macular pigmentation and exhibit other significant differences; individual differences between normal observers are, however, considerably greater than either of these. Revision of the O.S.A. data is discussed.

Description is also given of the Davis-Gibson 2,848°-to-4,800°K filter; this and the 2,848°-to-6,500°K filter, with illuminant at 2,848°K, were adopted by the International Commission on Illumination in 1931 as standard illuminants B and C for colorimetric purposes.


The formula is general in the sense that any point in the plane may be taken to represent the heterogeneous stimulus instead of just the center of the Maxwell triangle and in the sense that any coordinate system obtained by homogeneous, linear transformation of the data may be used instead of some particular coordinate system. Purity of the stimulus is discussed in relation to saturation of the color evoked.


The (r,g)-plot of the O.S.A. color triangle is found to make a better "sensation" diagram than other forms of plotting. The difference in r-coordinate or that in the g-coordinate, whichever is the greater, is taken as a measure of the degree of chromaticity difference; this is somewhat better than actual distance on the plot.


The least perceptible difference in color temperature is found to be proportional to the square of the color temperature from 1,700° to 11,000°K, as indicated by previous fragmentary data.


Adding white light to both sides of the field decreases sensibility to wave-length difference for wave lengths greater than 480 µ, and for those less than 480 µ it first decreases, then increases, then finally decreases it.
The saturation scale is given by specifying in terms of dominant wave length and purity the series of stimuli exhibiting equal saturation steps.

Reciprocal temperature is proposed because it forms a uniform chromaticity scale and because computations involving the Wien formula for spectral distribution of energy deal directly with reciprocal temperature. (In particular, the additive value of a blue or yellow filter in changing the apparent reciprocal color temperature of a source is expressed simply as a difference in reciprocal color temperature.)

Report No. 3. Spectral and luminous transmissions and derivation of new values of A.R.A. transmission for the 22 "limit" glasses selected by Committee VI, A.R.A., at Corning, November 5-6, 1931 and engraved "J.C.M. 11-6-31".
Report No. 4. Chromaticities and luminous transmissions, with illuminants at 1,900°K and 2,848°K, for the 22 "limit" glasses described in Report No. 3.
Report No. 5. Tentative specifications for railway signal colors.

This report makes available in convenient form the properties of the standard observer recently recommended for colorimetric purposes by the International Commission on Illumination. These data supersede the values published in the 1922 report of the committee on colorimetry (Ref. 31) known as the O.S.A. excitation data. Forms are given for computing trilinear coordinates (trichromatic coefficients), dominant wave length, colorimetric purity, and luminous transmission (or reflectance) from spectrophotometric data. Tables of the data needed are included for the 1931 I.C.I. standard illuminants A, B, and C.

This is a French translation of a report prepared by the author. The glasses are to be used as standards in the heterochromatic photometry of incandescent illuminants.
PUBLICATIONS ON COLORIMETRY AND SPECTROPHOTOMETRY
FROM THE NATIONAL BUREAU OF STANDARDS

Part II

Abstracts, reports, letter circulars, etc., not included in Part I

If the abstract has been superseded by a more complete publication, the number in parentheses following the date gives such publication reference in Part I.


15. Optical Society of America Committee on Colorimetry, Irwin G. Priest, Chairman; Report for 1919. (Not published; manuscript copy may be borrowed from Bureau of Standards library. See Jour. Opt. Soc. Am., vol. 4, p. 186, 1920.)


23. Priest, Irwin G., The complete scale of color temperature and 
it's application to the color grading of daylight and arti-
(36)

24. Priest, Irwin G., Progress on the determination of normal gray 
p. 72, 1923. (28)

ous conditions upon the determination of the normal stim-
7, p. 73, 1923. (28)

26. Priest, Irwin G., Apparatus for the determination of hue sensi-
bility (wave length differences perceptible by difference 
in hue) and the visibility of radiant energy, Jour. Opt. 

27. Priest, Irwin G., The colorimetry and photometry of daylight 
and incandescent illuminants by the method of rotatory 
75, 1923. (36)


29. Priest, Irwin G., Gibson, K.S., and Munsell, A.E.O., A compar-
ison of experimental values of dominant wave length and 
purity with their values computed from the spectral dis-

30. Priest, Irwin G., Apparatus for the determination of color in 
terms of dominant wave length, purity, and brightness, 
1924. (38)

31. Priest, Irwin G., McNicholas, H.J., and Frehafer, M. Katherine, 
Some tests of the precision and reliability of measure-
ments of spectral transmission by the König-Martens spec-
vol. 8, p. 30, 1924. (37)

32. Priest, Irwin G., Gibson, K.S., and Munsell, A.E.O., The speci-
ification of color in terms of dominant wave length, 


55. Winters, S.R., Colors in relation to business, Trade Winds (The Union Trust Co., Cleveland, Ohio), vol. 6, p. 16, 1927.

56. Davis, Raymond, and Gibson, K.S., Reproducible liquid filters for the determination of the color temperatures of incandescent lamps, Phys. Rev. (2), vol. 29, p. 916, 1927. (75)


77. Judd, Deane B., Thomas Young's theory of color vision and the hue change by addition of white light, Jour. Opt. Soc. Am., vol. 20, p. 156, 1930. (See also ref. 58, above.)


96. *Color and legibility, B.S. Letter Circular, LC-351 (revised), July 1933.


Miscellaneous publications, not included in Parts I and II.

Numerous papers of primary importance in other fields, such as photometry, radiometry, and dyes, are not listed here. For complete list consult B.S. Circular No. 24 and supplements, or see letter circulars listed below.


8. *Coblentz, W.W., and Emerson, W.B., Glasses for protecting the eyes from injurious radiations (3rd edition), B.S. Tech. Paper No. 93. (T93, 10¥)


   While designed particularly for use in radio work, this table will be found equally useful in the visible range of radiation, e.g., if used intelligently with proper placing of the decimal point, it may serve to convert wave lengths in millimicrons to frequency in trillions per second (fresnels).


43. *Color for school furniture, B.S. Simplified Practice Recommendation No. 111, 1930. (R111-30, 5¢)

44. Scott, W.M., and Appel, W.D.* Bibliography of color with special reference to textiles and dyes, Am. Assoc. Textile Chemists & Colorists 1930 Yearbook, p. 146. (Supplementary bibliographies are published in subsequent yearbooks.)


47. *Foundry patterns for wood (color systems for), B.S. Commercial Standard No. 19, 1932. (CS19-32, 10¢)


51. *Procedure for the measurement of the reflectance of manila rope fiber for light of wavelength 500 millimicrons, B.S. Letter Circular, LC-393, November 1933.

