A Historical Review of Measurement Techniques and Instrumentation for Characterizing the Colorimetric and Photometric Properties of Self-Luminous Displays and Other Output Devices

J. Rennilson
Advanced Retro Technology, Inc., Spring Valley, California

Abstract

The early beginnings of color in displays gave birth to a new industry, an industry dedicated to the accurate characterization of the photometric and colorimetric properties of these displays. Today this industry is international in scope totaling millions of dollars in sales. Coupled with this instrumentation are measurement techniques, guides and standards for their use. Both national and international organizations are preparing these standards backed by the respective national standards institutes. The development of both the instrumentation and the measurement techniques will be traced from their early beginnings up to the present fully automated systems. A brief review of sources for the guides, test methods and standards in use and in preparation will also be presented.

Introduction

The development of modern instrumentation for the measurement of color began with the first formulation of color metrics by E. Schrödinger[1] and R. Luther [2] in the 1920's. However the mathematical basis for modern color theory is generally attributed to J. Clerk Maxwell's investigations in the 1860's. This remarkable genius, to whom we owe much of today's theoretical knowledge of light and color was also an experimentalist. The first apparatus for measuring the equality of colors in both an additive and reflective mode was invented by him. The formulation of visual color matching functions and the mathematical basis of color measurement occurred both by Maxwell and his German contemporaries, Herman Grassmann and Herman von Helmholtz.

The history of instrumentation for colorimetric and photometric measurement may be separated into three historical eras.

The first was the period where visual observations were the only available means of assessment. This period began in the 1670's with Sir Issac Newton and continued up to the 1910-1920's when the first electrical detectors were used for color measurement. The visual method of comparison used the Maxwell color wheel and color box for matching one color to another. In 1894, A. König used the first spectral apparatus (Helmholtz/König) to determine the relative spectral responsivity functions of normal and annormal observers.

The introduction of the photoelectric detector, in the early decade of this century began the second period. With the international agreement on a standard colorimetric observer in 1931 the number of instruments from tristimulus colorimeters to spectrophotometers multiplied. The first spectrophotometer using a photoelectric detector stems from this period. Integration to yield CIE tristimulus values was obtained first by mechanical means, then later by electrical potentiometers. This period ended in the early 1950's.

With the input to the electronic computer using punched paper tape and cards the third period began. This period, within which we are today, is marked by the ease of computation through microprocessor control and analysis. New array detectors and convenient and compact tristimulus colorimeters make short work of the measurement process and allow the user the luxury of thoroughly characterizing the self-luminous device as well as the hard copy. Today both visual and electro-optical methods are merged in the field of color measurement. The realization of the fact that the instrument is subservient to the human observer has initiated a large effort in understanding color appearance and striving for a means to predict, from physical measurements of the stimulus, what the human observer will see. The remainder of this paper will highlight some of the more common instruments in each of these periods and conclude with the standards and methodology of colorimetric measurement in use today. Because of the quantity of instruments developed in these periods, no figures will be used in this text. The important ones, will however, be shown during the presentation.

The Visual Period

This era, as mentioned earlier, was initiated by Sir Issac Newton[3] in his Treatise on Light and Color and his many letters and rebuttals. His involvement in the making of glass prisms and lenses lead naturally to their use in generating the solar spectrum. The fact that a small hole approximately 1/4 inch in diameter was used as the entrance aperture of the prism lead Newton to draw erroneous conclusions as to the nature of color. If he had used a narrow slit instead, the physical sciences, at that time, might have taken a quantum jump. Nevertheless, his insight into the use of a lens to recombine the spectrum and his formulation of the hue circle led to the principle of color matching and their combinations. It was P. Bouguer[4] that first used the comparative technique to evaluate the intensities of two lights. Visual apparatus developed after Bouguer's time (Lambert, Rumford) all used this technique of "matching one stimulus against another" and adjusting one until a difference was undetectable. The technique of visual matching involves the comparison of lights for equal "brightness and color". In 1843, R. Bunsen[5] devised a method of comparisons using an opaque disc of white paper, the center area of which was made translucent by oil or wax. Light from one side thus illuminated the opaque side nearest the lamp while a lamp on the other side luminated the translucent center. By using mirrors and later prisms, Bunsen was able to see both sides and to adjust the position between the lamps such that the contrast between the opaque and translucent areas appeared equal. This fundamental principle that the eye is more sensitive to contrast than brightness we owe largely to Bunsen. Further development of designs based on this principle were used throughout the latter half of the 19th century. The most famous of these was the design by O. Lummer and E. Brodhun[6] in 1889. This photometer head formed the most accurate means of measuring the luminous intensity of light sources, even in the 1950's, and is still used today. Using a contrast Lummer/Brodhun photometer head and sources at the same color temperature, coefficients of variation of 1/2 to 1% are achievable. One important design which had it's prime application in colorimetry, was the first significant visual spectrophotometer, built by A. Konig[7] in 1885. It used polarization to establish equality of matching fields. The primary use of this apparatus was not to assess the color quality or adherence to a particular standard, but rather an understanding of how the human visual system works. In this effort he collaborated with Herman von Helmholtz[8].

The tristimulus method of assessing color began with J. Clerk Maxwell[9] and his color wheel. He used this device to establish the fundamentals of color matching. He also used a color box and mixed extended color lights as well as spectral colors. This work led to the very first projection of color photographs using three black and white positives behind three projectors with the same red, green and blue filters used to take the original photographs. An interesting application of a modern color wheel was developed over 120 years later by Applied Color Systems Inc. This color wheel used all the newest electronic technology and enabled an observer to establish a color match under a D65 Illuminant, after which, the formulation for the pigments were automatically determined. This wheel used seven primaries to expand the available color gamut. The variability of the human observer was thus taken into account as well as giving the customer the satisfaction of using a visual stimulus which they had control over. The usefulness of Maxwell's color wheel for illustrating color matching and color metrics has not diminished in these 130 years. A major advantage in using the color wheel is the greatly diminished aspect of object metamerism. When CRTs or even LCDs are used to create color matches, the degree of metamerism is, in many cases, very large.

Today in our over-indulgence with computers and it's associated mathematics, we sometimes loose sight of our goal. The physical measurement of the color stimulus is subservient to the visual sensation. In the end, the customer decides whether the color is acceptable or not. Physical measurement is a necessity today, but its tolerances must be determined by human observation.

The Physical Period

The second period began with the first use of electrical detectors to measure light. In the 1880's thermocouples and crude electrovoltaic cells were used to measure the amount of light incident from standard sources. The photometricists attempted to adapt these detectors to spectral and photometric equipment but found the poor repeatability and low sensitivity of these early devices to be far inferior to visual techniques. After the turn of the century a great improvement was made in photoelectric detection with the introduction of the multiplier phototube. This coincided with the desire to standardize on one visual response for the sake of international communication. The time-consuming visual measurements proved that to establish a system of color measurement for quality control in industry based on visual color matching, would never yield the efficiency necessary. The development of much more sensitive detectors gave the necessary impetus which led to the standard color observer. Now, it was possible to measure the color quantitatively and in a system which had international agreement. The 1924 and 1931 CIE meetings of the international community set in motion the development of new instruments to measure color.

The first application of physical detectors in color measurement was in color difference meters. These types of instruments were a necessity in the manufacturing of colored products of all kinds, from paints and textiles, to printing inks and photography. The need for absolute measurement of color, especially with the advent of color photography and printing, stimulated the instrumentation industry and the first recording spectrophotometer was developed by A. Hardy[10] in 1935. This instrument revolutionized the color community. Now for the first time, accurate data on the spectral reflectance/transmittance of objects could be reliably obtained. To compute tristimulus values and chromaticity coordinates under differing illuminants was, however, still a laborious task. This author remembers consuming more than one-half day in taking one spectral reflectance data at 5 nm intervals over the visible spectrum and computing by hand (with the aid of a mechanical calculator) the tristimulus values and chromaticity coordinates for two illuminants. Such labor intensive tasks led to mechanical integrators attached to the Hardy spectrophotometer and later electrical potentiometers. To speed up this process the photoelectric tristimulus colorimeter was developed by R. S Hunter[11] at the NBS in 1941. At first, the errors in detector fits to the CIE color matching functions (cmfs) allowed only close color differences to be accurately measured, thus the instrument was called a color difference meter. In Germany, A. Dressler and later H. G. Frühling[12] were able to commercially manufacture a detector/filter combination which closely fit the CIE cmfs allowing quick and convenient measurement of the CIE tristimulus values. Still the computation of color data was laborious and expensive.

During this era the expansion of color in all media exponentially increased. Black and white movie films were replaced by color and printed material demanded more and more color to illustrate their products. All of this required color control in the manufacturing process. Microphotometers and colorimeters were developed to satisfy the printing and photography industry. Quality control also depended on the generation of color atlases such as Munsell, Pantone, DIN and others. These atlases consisted of hundreds of solid colors made by a paint draw-down process and were used, and still are, to visually compare sample colors against one or more of the colors in the atlases. Subjective interpolation was used where the resultant color lies between two or more colors in the atlas. These colors were periodically measured with a spectrophotometer and CIE information on the colors were given along with the nomenclature of the atlas' color space.

The Microprocessor Period

The third period is of course, the present one which can be estimated to have started in the late 1950's and early 60's with the development of the integrated circuit and the transistor. Application of these devices to photometry and colorimetry was however somewhat slow. The sensitivity of the multiplier phototube and its widespread use in spectrophotometers and tristimulus colorimeters of that time, made introduction of these new solid-state detectors difficult. What did occur however, was the use of integrated circuits to speed up the processing time necessary for computation of the colorimetric information. The advent of silicon detectors has transformed the picture entirely. The microprocessor has made possible computations of photometric and colorimetric results in factions of seconds. Silicon array detectors make almost instantaneous measurement of spectral power distributions. Today many instruments can use deconvolution mathematics to automatically correct many systematic errors such as wavelength errors, detector non-linearities and many other errors which would have been almost impossible forty years ago.

This breakthrough in electronic technology has made colorimetric instrumentation so small that on-line process quality control is state-of-the-art. Processing of color data in real time is in-place in the printing industry, in some CRT manufacturers and now in LCD production. The new instrumentation has enabled us, for the first time, to examine the fundamentals of vision and to set acceptance limits based on the increased understanding of how the human visual system works. We have begun the integration of the psychophysical aspects of color sensation, color constancy, chromatic adaptation and the modeling of color appearance for self-luminous displays as well as hard copy. We can look forward in this period to a model which will approximate what we would see under specified conditions.

Guides, Test Methods and Standards

As our instrumentation has become more responsive to our demands, the requirement for documentation as to their use, limitations, and uniformity becomes paramount. In 1913, the lighting community recognized that because of world trade it was necessary to establish a standardizing organization to create uniformity in measurement and analysis dealing with lighting. Thus began the CIE or Commission Internationale de l'Eclairage. This organization is now a duly recognized international standardizing body responsible for light and color standards. In the field of characterization of self-luminous displays and output devices several organizations are active. The ISO has several technical advisory groups (TAGs) concerned with ergonomic aspects of displays. The International Electrotechnical Commission (IEC) has committees dealing with the electrical aspects and the CIE is now involved with characterization of displays. In the USA the consensus standard organization, American Society for Testing and Materials (ASTM), has a technical committee E-12 on Appearance. This committee has sub-committees involved in formulating guides, test methods and standard practices for appearance modes on surface materials as well as displays. The publications of interest are as follows:

ISO/CIE 10526, CIE Standard Colorimetric Illuminants
ISO/CIE 10527, CIE Standard Colorimetric Observers
CIE Publication 15.2, Colorimetry, 2nd Edition
CIE Publication 18.2, the Basis of Physical Photometry
CIE Publication 38, Radiometric and Photometric Characteristics of Materials and their Measurement
CIE Publication 41, Light as a True Visual Quantity: Principles of Measurement
CIE Publication 69, Methods of Characterizing Illuminance Meters and Luminance Meters
CIE Publication 63, The Spectroradiometric Measurement of Light Sources
CIE Publication 78, Brightness-Luminance Relations-Classified Bibliography
CIE Publication 87, Colorimetry of Self-luminous Displays, A Bibliography

CIE Technical Committees:
TC 1-27, Specification of Colour Appearance for Reflective Media and Self-luminous Display Comparisons
TC 1-32, Prediction of Corresponding Colours
TC 1-33, Colour Rendering
TC 1-34, Testing of Colour Appearance Models
TC 2-26, Measurement of Color Self-Luminous Displays: Final Report on "Guide to Characterizing the Colorimetry of Computer-Controlled CRT Displays"

ASTM E 1455, Standard Practice for Obtaining Colorimetric Data from a Visual Display Unit Using Tristimulus Colorimeters
ASTM E 1349, Standard Test Method for Reflectance Factor and Color by Spectrophotometry Using Bi-directional Geometry
ASTM E 1347, Standard Test Method for Color and Color-Difference Measurement by Tristimulus (Filter) Colorimetry
ASTM E 1341, Standard Practice for Obtaining Spectroradiometric Data from Radiant Sources for Colorimetry
ASTM E 1336, Standard Test Method for Obtaining Colorimetric Data From a Video Display Unit by Spectroradiometry

In conclusion, let me repeat what I stated at the beginning. We have made remarkable progress in our understanding and measurement of light and color in the rather brief period since Newton. It is important to recognize the history of this development and to study what has gone before, remembering the old Chinese proverb "When you drink, think of the source".

References

1 E. Schrödinger, Grundlinien einer Theorie der Farbmetrik im Tagessehen, *Ann. Physik* (IV) **63** (1920), pp. 397-456; 489-520.
2. R. Luther, Aus dem Gebiete der Farbreizmetrik, *Z. techn. Physik* **8** (1927), pp. 540-558.
3. I. Newton, Opticks, or a Treatise of the Reflections, Refractions, Inflections and Colours of Light. (1st Ed. 1704), *Dover Publ.* (1952).
4. P. Bouguer, Essai d'optique sur la gradation de la lumiere, (1729) Paris.
5. R. Bunsen, *Ann. d. Phys.*, **60,** (1843), p. 402.
6. O. Lummer and E. Brodhun, *Z. f. Instr.* **9**, 1889, pp. 23 and 41 and 12, (1892), p. 42.
7. A. König, Ein neues Spektralphotometer, *Wiedemanns Ann. Phys.* **53** (1894) pp. 785-792.
8. v. H. Helmholtz, Handbuch der physiologiscen Optik, *Hamburg/Leipzig: Voss*. 2 Aufl. (1896).
9. J. C. Maxwell, Experiments on colour as perceived by the eye, with remarks on colour-blindness, *Trans. Roy. Soc. Edinburgh*, **21** (1855), pp. 275-297.
10. A. Hardy, A new recording spectrophotometer, *J. Opt. Soc. Amer.,* **25** (1935), pp. 305-311.
11. R. S. Hunter, Photoelectric tristimulus colorimetry with three filters, *NBS Handbook* **77**, Vol III., (1942), pp. 529-575.
12. A. Dresler and H. G. Frühling, Über ein photoelektrisches Dreifarbenmessgeraet, *Licht* **8** (1938), pp. 238-242.

Other literature:

J. W. T. Walsh, Photometry, 3rd Ed. *Constable & Co. Ltd.*, 1958.

M. Richter, Die Entwicklung der Farbmetrik, *Die Farbe* **29** (1981), pp. 225-250.

H. Terstiege, Farbmessung, *Proc. 4th Cong. AIC* (1981) A8.