Evolution of Color Science through the Lens of OSA

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The Optical Society (OSA) was the dominant professional society in the evolution of color science, both through its many technical committees and through the Journal. This chapter highlights some of the many significant activities and publications that occurred through the 1950s.

OSA established the Committee on Colorimetry in 1919 chaired by I. G. Priest from the National Bureau of Standards and during its first year circulated a preliminary draft [1]. The committee's first report was published in the Journal in 1922, authored by the current chairman and president of the Society, L. T. Troland [2]. This remarkable 64-page report outlined the basis of photometry and colorimetry, including visibility and color-matching function data (referred to as the OSA excitation curves), terminology for visual description, chromaticity diagrams, complementary wavelengths, standard illuminants, color temperature, optimal color filters for trichromatic color reproduction, visual colorimetry, and transformation of primaries. All of these concepts would be central to establishing the 1924 $V\lambda$ visibility curve and the 1931 CIE colorimetric system, XYZ and xyY. The Colorimetry Committee was a driving force in the evolution of modern colorimetry, culminating with the book *The Science of Color* published in 1953 [3]. The book indicates the breadth of expertise of the committee and that color science is multi-disciplinary as it includes physics, optics, physiology, psychophysics, and history beginning with our first use of colored materials hundreds of thousands of years ago.

The first color order system that was based on extensive psychophysics was the Munsell system. The Munsell Value scale quantified visual compression by establishing the relationship between incident light and perceived lightness [4]. It has been used to support Steven's exponential model of visual compression and relate luminance factor to CIE lightness, L^*. An OSA committee performed extensive research leading to the current definition of the Munsell system [5]. These data were used by Adams to derive the precursor to CIELAB [6]. The Munsell system is a cylindrical system, and as a consequence, neighboring samples are not equidistant. In addition, samples of constant hue vary in either lightness or chroma, but not both simultaneously as occurs in common coloration. In the late 1940s an OSA committee, chaired by D. B. Judd from the National Bureau of Standards, was established to develop a new color order system where samples were equidistant in all three dimensions based on a regular rhombohedral crystal lattice structure to [7]. The OSA Uniform Color Scales were the result thirty years later. Both systems are still used to develop and evaluate colorimetric-based color spaces for visual uniformity.

Any quantitative color description of objects depends on measuring the spectral reflectance factor. A breakthrough occurred during the 1930s when A. C. Hardy, a professor at the Massachusetts Institute of Technology, developed the first recording spectrophotometer whose illumination geometry was optimized for measuring materials via an integrating sphere where the specular component could be included or excluded, the latter correlating with the appearance of glossy materials [8]. General Electric manufactured the Hardy spectrophotometer. By the late 1940s, it was possible to interface the instrument to an automatic tristimulus integrator [9], and as a result, color measurements were reported as a spectral graph and CIE tristimulus values. One drawback of this approach was the high cost. Hunter made color measurement much more accessible with the development of a color-difference meter using color filters and three photodetectors, first presented at an OSA Annual Meeting in 1948 [10].

When the CIE system was promulgated in 1931, there were three standard sources, A, B, and C, representing incandescent, sunlight, and daylight, respectively. Source C was produced by filtering incandescent lighting with bluish liquid filters. Such a light was very deficient in UV and short-wavelength visible radiation compared with natural daylight. Measurements of daylight, principal component analysis, and a very clever approach to calculate the eigenvector scalars for a specific correlated color temperature resulted in the CIE D series illuminants [11, 12]. Today, CIE illuminants D50 and D65 are used extensively in color reproduction and color manufacturing, respectively.

All specifications include tolerances, and as early as 1932 [13], the Journal began publishing research demonstrating the CIE system's lack of uniformity with respect to color discrimination, research proposing linear and nonlinear transformations that improved correlation, and psychophysical data from discrimination experiments. At the forefront of this research was D. L. MacAdam, a student of Hardy at MIT, who went on to have a distinguished career at the Eastman Kodak Research Laboratories. In the early 1940s, he built an apparatus to measure color-matching variance that resulted in the "MacAdam ellipses," still used as a discrimination dataset [14]. His research and leadership resulted in the 1960 uv and 1976 u′v′ uniform chromaticity scale diagrams and the 1976 L*a*b* and L*U*V* uniform color spaces.

An interesting research topic was designing color reproduction systems that could be related to colorimetry by linear transformation. During the late 1930s, Hardy and Wurzburg [15], MacAdam [16], and Yule [17] laid the groundwork for today's color management for both additive and subtractive imaging systems.

We all use manufactured products meeting a color specification. Predicting and controlling a recipe is invaluable for coloration systems where the colorants and media both absorb and scatter light. The theory proposed in 1931 by P. Kubelka and F. Munk and published in the Journal in 1948 [18] continues to be used successfully in textiles, plastics, and coatings. In 1942, J. L. Saunderson demonstrated its effectiveness for the coloring of plastics, particularly by accounting for refractive index discontinuities at the surface [19].

Today, color science has evolved from tristimulus XYZ, through L*a*b* and L*u*v*, to color-appearance spaces such as CIECAM97s and CIECAM02. A key requirement of such spaces is accounting for the effects of chromatic adaptation. Such research began in the 1950s and the seminal experiments by R. W. Burnham, R. M. Evans, and S. M. Newhall from Eastman Kodak remain reliable and viable data [20].

I will end my highlight tour with Ref. [21], which describes how MacAdam created separation plates for printing both the color gamut of a set of offset printing inks and a spectrum. A 19-page article appeared in the 3 July 1944 issue of *Life* magazine, titled "Color: it is the response of vision to wave lengths of light" [22]. This remarkable article includes colored images of a dispersed spectrum, additive and subtractive mixing, principles of selective absorption of colored filters, spectral reflectance curves of a lemon and a tomato, the Hardy recording spectrophotometer, the visible spectrum, the Munsell system, an afterimage demonstration using the American flag, and several other optical illusions. The 1931 CIE system was used to calibrate the color separations where dominant wavelength represented the spectral hues and, in turn, mixtures of the printing inks. Incredibly, I have MacAdam's copy of the article. The article summarizes color science and, indirectly, the tremendous impact the OSA has had on its evolution.

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