A System for Communicating Color: Foundations and Rationale

M. S. Rea[1] and L. Deng[2]

[1]Lighting Research Center
Rensselaer Polytechnic Institute
21 Union Street
Troy, NY 12180
518-687-7100

www.lrc.rpi.edu

[2]GE Consumer & Industrial – Lighting
1975 Noble Road
Nela Park 335C
Cleveland, OH 44112
216-266-3198

www.gelighting.com/na/

Abstract

The term “color” can be used in two different ways. One way is to describe the subjective appearance of an object or a light source. The second way is to describe the physical characteristics of the stimulus. Throughout the last century attempts have been made to bridge these two domains with some, but not complete success. Perhaps a consequence of our inability to satisfactorily make this bridge between the subjective and the objective domains has been our inability to communicate color to consumers of light sources that provide different spectral power distributions. This paper offers a system for communicating one aspect of color, the color of radiant flux generated by a light source, to consumers. The philosophy underlying the proposed system is to provide a readily understandable means of communicating light source color to consumers while utilizing existing color metrics already familiar to lighting specialists.

Introduction

In one important sense, color is strictly a human experience and not an inherent property of radiant power. In this sense, color is the result of phototransduction and neural computation by a human observer. Thus, it is incorrect to refer, for example, to “red” and “blue” wavelengths or “red” and “blue” regions of the spectrum. In another, more practical sense, color is the result of formal, simplifying transformations of the spectral power distributions (SPDs) of light sources agreed to by industry through international consensus. Specifically, the Commission Internationale de l’Eclairage (CIE) has created an entire system of colorimetry that has been used throughout the world for more than half a century to describe the color of light sources.[1] Indeed, the CIE system of colorimetry has taken on a reality all its own, quite invaluable for international commerce but quite poor in representing human color experience. For example, brown and orange are distinct color experiences but both can have exactly the same color specification in the CIE system of colorimetry. Similarly, colorimetry defines colors regardless of the absolute amount of radiation, yet at low light levels color discrimination is poor or impossible.

One challenge for purveyors of light sources is to preserve the highly functional and ubiquitous methods of colorimetry while providing users and consumers with meaningful information about expected perceptions of color resulting from these light sources. The industry is committed to colorimetry, however, as the only orthodox foundation for that communication. It is beyond the scope of this paper, and probably even the current science of color, to introduce a new system of colorimetry that better represents the human experience of color. Rather, this paper lays out a proposed system for communicating one aspect of light source color to consumers while staying within the constraints of colorimetry presently used by the industry. In particular, this paper only addresses communicating expected color perceptions of the radiant flux generated by different “white” light sources. Responses by consumers to the proposed color communication system described here are discussed in a companion paper.[2]

Background

The SPDs of light sources are fundamental to every discussion of color. Formally, the SPD is defined in terms of the radiant power (P_λ) emitted by a light source at every wavelength interval (d_λ) and is measured in terms of watts (W) or joules per second (J/s) per wavelength interval**.** Figure 1 shows the SPDs of two light sources, one real source (CIE Illuminant A) and one imaginary.[3] Despite the marked differences in the physical characteristics of the flux generated by these two sources, the SPDs generated by these two light sources and incident on the retina are indistinguishable to a color-normal human observer at the same luminance. These two so-called metameric sources look the same because the net photon absorptions by the three human cone photopigments are identical. Indeed, an infinite set of SPDs will look identical to a color-normal observer as long as the respective absorptions by the three cone photopigments remain the same.

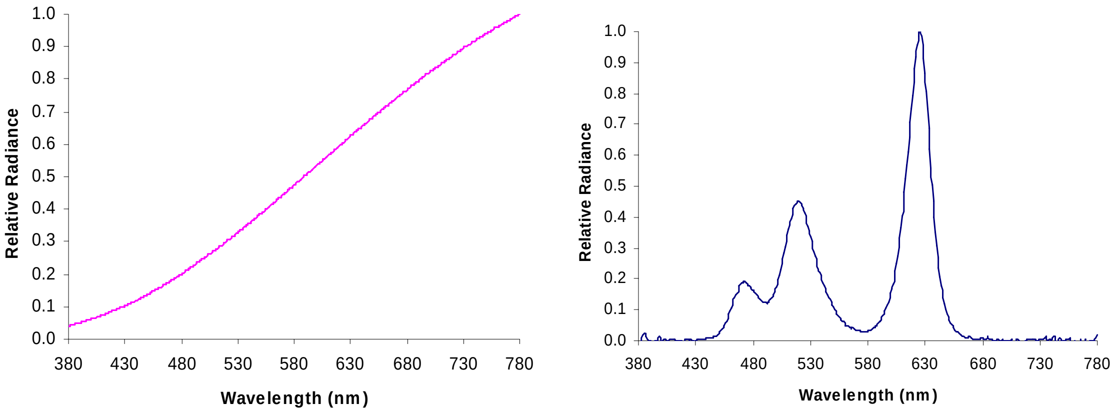

Figure 1. Two metameric spectral power distributions.
CIE illuminant A (left) and a hypothetical light source. (Adapted from NLPIP 2004.[3])

This trichromatic nature of human color vision greatly simplifies color specification of a light source and, indeed, forms the basis of colorimetry developed early in the previous century.[1] Helmholtz, following earlier observations by Young, showed, in effect, that the color appearance of all practical light sources of any SPD could be matched by mixtures of three carefully chosen, so called, primary light sources. In this way, it was possible to describe any light source in terms of just three numbers, each representing the amount of one primary needed to match that light source.

These empirical observations were subsequently confirmed experimentally and systematized into a set of linear equations weighting what are known as the three color matching functions.[1] Since the color matching functions were scaled by a set of linear equations, it was possible to transform the SPDs of three real primary light sources into imaginary primaries to obtain color matching functions with specific desirable aspects. One desirable feature of this system was that one of the three color matching functions ($\bar{y}$) was made identical to the photopic luminous efficiency function (V_λ), thereby providing a formal link between the CIE systems of photometry and colorimetry. But, again, this transformation did not alter the fact that every light source could now be completely defined in terms of the combined amounts of three primaries needed to make the radiant flux emitted from any light source appear indistinguishable from the combined primaries to a color normal observer. Another simplifying aspect of this system of colorimetry was that the relative amounts of the three primaries were normalized so that the sums of the three primaries needed to match a color added to unity. In this way any light source could now be specified in terms of the relative amounts of just two primaries, the third one being equal to one minus the sum of the other two. With this system any light source can be defined in terms of just two, so called, chromaticity coordinates and located in a two-dimensional plot known as the CIE chromaticity diagram. Figure 2 shows the three color matching functions designed by the CIE in 1931 to have these desirable features, and Figure 3 shows the CIE 1931 chromaticity diagram based upon those three color matching functions. The perimeter of the diagram in Figure 3 is defined by monochromatic, spectral wavelengths and by the straight line, known as the purple line, connecting the long- and short-wavelength limits of visible radiation.

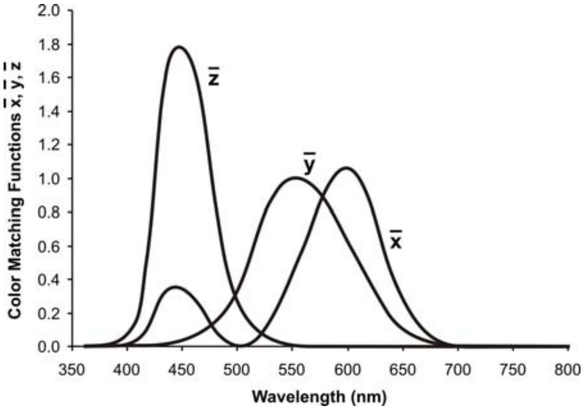

Figure 2. CIE 1931 color matching functions.

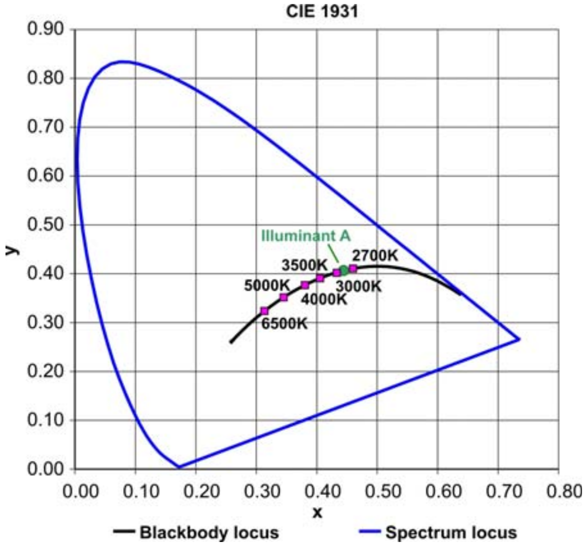

Figure 3. CIE 1931 chromaticity space with the blackbody locus and the chromaticities of several color temperatures, including CIE illuminant A. (Adapted from NLPIP 2004.[3])

In 1976 the CIE introduced another desirable feature into the system of colorimetry.[1] Again, since colorimetry is governed by a set of linear equations, it was possible to revise the color matching functions to provide a chromaticity diagram where distances between any two points in the chromaticity diagram were approximately equal in terms of perceptual differences. Although the 1976 system was intended to replace the 1931 system, the earlier system is still more commonly used by the lighting industry. Nevertheless, the CIE 1976 system will be used throughout the remainder of this paper.

Figure 4 illustrates the chromaticity coordinates of a wide and representative range of practical light sources manufactured as illuminants along with the blackbody locus in the 1976 CIE chromaticity diagram. It will be noted in Figure 4 that most practical sources lie close to the blackbody locus and, indeed, the blackbody locus has special significance as a reference line for all commercial “white” light sources used as illuminants. As an ideal blackbody is heated it begins to incandesce and the emitted radiation will appear red to a color-normal human observer. As the temperature increases, it will appear yellow-white and at still higher temperatures it becomes white, then blue-white. Each point along that transition from yellow-white to blue-white will have a specific, well characterized SPD and a so-called color, or more properly distribution temperature.[4] These color temperatures, in kelvins (K), are used as convenient short-hand descriptions of the color appearance of “white” light sources lying on the blackbody locus (Figure 4).

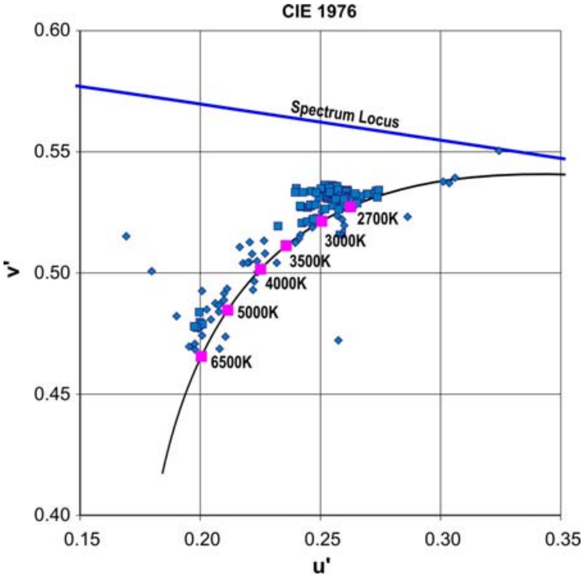

Figure 4. Chromaticities of 67 commercially available light sources in the CIE 1976 chromaticity space along with the blackbody locus and the chromaticities of several color temperatures. (Adapted from NLPIP 2004.[3])

Not every “white” light source lies on the blackbody locus, however, so the appearance of the radiated flux emitted by a practical light source is most often described by the industry in terms of its correlated color temperature. Correlated color temperature (CCT) is defined as the appearance of a real light most closely like that of the color temperature of an ideal source on the blackbody locus. Thus every practical light source can be, and almost always is, described in terms of its CCT, in K. For example, light emitted by a linear fluorescent lamp with a CCT of 3000 K will appear yellow-white to a color normal observer whereas that from a lamp with a CCT of 7500 K lamp will appear blue-white.

The system of communicating color appearance of “white” light sources through CCT specifications has actually worked quite well within the lighting industry, but only because there has been an additional step taken by the industry to ensure color consistency among light sources having the same CCT designation. Two light sources of the same CCT can, in principle, appear very different. Figure 5 illustrates the chromaticity coordinates of two imagined light sources, one green and one purple with identical CCTs. To preserve the simple CCT designation and communication system for commercial lamps, while simultaneously avoiding possible problems of the kind illustrated in Figure 5, the industry introduced color tolerance specifications for lamps having a specific CCT designation. This “hidden” system of color tolerance is based upon the MacAdam ellipse.[4,5,6] In the 1940s MacAdam, based upon psychophysical investigations of perceptible differences in color, introduced a set of ellipses in the CIE 1931 diagram that were purported to represent perimeters of just noticeable differences around a given light source’s chromaticity coordinates.[5,6] Although there have been several intellectual assaults on MacAdam’s proposal, these ellipses have become institutionalized by the lighting industry to characterize color tolerances. Depending upon the light source chromaticity coordinates, the sizes of the color tolerance ellipses varies in the CIE 1931 diagram. Figure 5 also shows the six current industry standards for color tolerances of fluorescent lamps, also ellipses, in the CIE 1976 diagram.[7] By industry consensus the chromaticity of every compact fluorescent lamp, less than 20 W, with a designation of 2700 K must fall within the ellipse on the far right. The chromaticities of all linear fluorescent lamps must fall within one of the five remaining ellipses in the CIE 1976 system to have a CCT designation. This extra "hidden" step to ensure color tolerances implicitly assures consumers that they will have the same color appearance of the radiant flux emitted from a linear fluorescent lamp of a given CCT, irrespective of the manufacturer or the time of purchase.

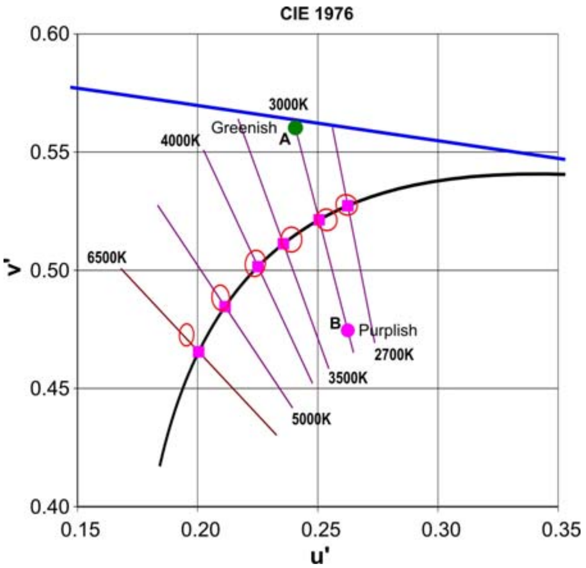

Figure 5. Chromaticities of two imaginary light sources of the same correlated color temperature (CCT), one green (A) and one purple (B), in the CIE 1976 chromaticity space along with the blackbody locus and several correlated color temperature lines. Also shown are the color tolerance circles corresponding to the MacAdam ellipses for linear fluorescent lamps. (Adapted from NLPIP 2004.[3])

This rather elegant and simple system of color communication has not, however, been embraced by manufacturers of other types of light sources. Figure 6 shows the "wild, wild west" of color tolerance in the compact fluorescent lamp (CFL) marketplace. Although all of the manufactures of these CFLs describe them in terms of CCT, consumers can clearly be disappointed because color tolerances have not been properly assured by the manufacturers in their CCT designations. The lighting industry in cooperation with the U.S. Department of Energy and the U.S. Environmental Protection Agency, through the ENERGY STAR® program, are currently working on a solution to this problem.

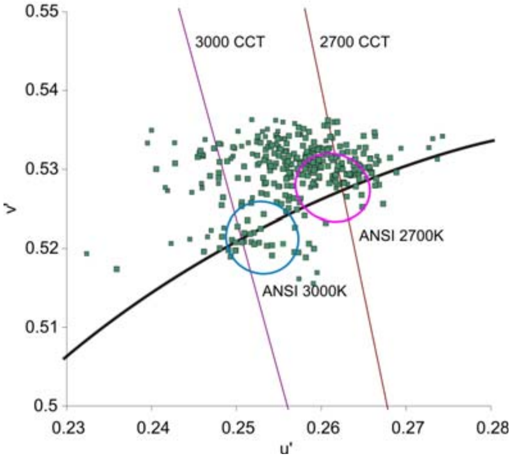

Figure 6. Chromaticities of commercially available compact fluorescent lamps plotted in the CIE 1976 chromaticity space along with the blackbody locus and the color tolerance circles corresponding to the MacAdam ellipses for 2700 K and 3000 K linear fluorescent lamps. (Adapted from NLPIP 2004.[3])

The proposed system

The proposed color communication system is designed to communicate the color of the radiant flux emitted by a light source in a simple way. It is supposed to be simple enough for consumers and non-specialists to quickly grasp, yet consistent with the current CCT color communication system and, of course, colorimetry and radiometry. In fact, the proposed system is a logical extension of the current CCT color communication system, including its "hidden" requirement of color consistency. Figure 7 illustrates the proposed system of color communication to be placed on a lamp package or on a point of purchase display. (As discussed in the companion paper by Leslie and Rea [2], the proposed system discussed here was subsequently modified based upon consumer and industry input.) Although this system was originally conceived as a method of communicating the color of radiant flux emitted by CFLs, the proposed system could be modified and used with any family of light sources that vary in CCT (e.g., metal halide or white LEDs).

Figure 7 shows six discs of different shades of white, from blue-white to yellow-white. Each of these discs is intended to communicate the possible colors of the radiant flux that could be emitted by that particular family of light sources (e.g., CFLs). A check mark on top of one disc indicates to consumers the color of the radiant flux emitted by the lamp in that particular package. So, for example, a CFL with a CCT of 3000 K would be sold with the six discs on the package and a check mark over the fifth (from the left) circle.

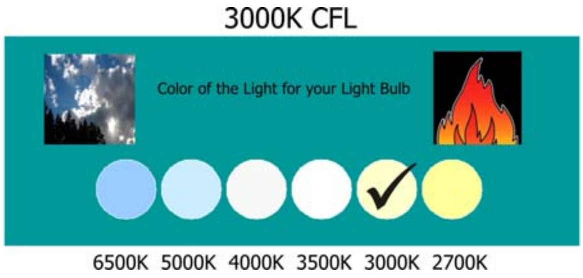

Figure 7. Proposed package illustration for a fluorescent lamp with a correlated color temperature (CCT) of 3000 K, indicated by the check mark. The colored discs in the illustration correspond to the six CCTs designated for linear fluorescent lamps by ANSI. The two icons, daylight and fire, are intended to represent the two extremes in chromaticity space for "white" light sources.

Again, the proposed color communication system was designed both to make it easy for consumers to grasp and to be consistent with current methods of communicating the color appearance of radiant flux emitted by light sources. To make the system easy for consumers to understand, three decisions were made. First, there are no numbers on the box corresponding to the CCT of the lamp. Second, the color of each disc roughly corresponds to the color appearance of radiant flux emitted by the lamps in that family. And, third, two icons, daylight and fire, are presented as anchors to the two ends of the range of colors available for that family of lamps.

To be consistent with the current method of communicating color with a CCT designation, the following constraints were placed on the proposed system. First, the order of the discs, blue-white on the left and yellow-white on the right, is consistent with the order of colors along the black body in the CIE colorimetric systems (1931 as well as 1976). Second, discs, rather than some other geometric form, were chosen because they resemble the nearly circular MacAdam ellipses in the CIE 1976 system of colorimetry that are used as the “hidden” criterion for color consistency in lamp CCT designation. The Japanese lighting industry uses rectangular regions rather than MacAdam ellipses to specify chromaticity;[8] labels based on these could use rectangles instead of discs to communicate color appearance. Third, six discs, rather than some other number, were chosen because there are six CCTs currently recognized by the industry for fluorescent lamps. Thus, each disc is intended to correspond with one of the six CCTs and corresponding MacAdam ellipses currently agreed to by the industry for fluorescent lamps and plotted in the CIE 1976 chromaticity space. Significantly too, the proposed system was designed to make color education more accessible to a wider range of people. Since the proposed system is closely tied to color orthodoxy, it is much easier for specialists and non-specialists to see a logical progression from the base spectroradiometric data, through colorimetry, to CCT and color tolerances, to the proposed system.

Finally, it should be noted that although the proposed system of color communication is intended for the lamp package, it is clearly necessary to support the proposed system with other reinforcing methods of communicating color. The companion paper by Leslie and Rea [2] discusses some of these options, including labeling on the lamp and at point of purchase displays.

Conclusions

The lighting industry has made significant progress in the specification of color over the last century. Most specialists within the industry have learned how to communicate to one another at several levels, from SPDs to CCTs, about light source colors. The industry has not, however, made significant strides in bridging color specification to color appearance and, perhaps, this failure to make a satisfactory bridge between these two domains of color has held the industry back in establishing a system of communicating color to consumers. Regardless of the reasons, the failure to extend color communications to non-specialists has diminished the ability of the industry to demonstrate the value color choices among lighting products offered to consumers. The system of color communication proposed here has both the strengths and the weaknesses inherent in the current system of colorimetry. Its strength is the logical extension of our current color communication system using CCT, but its weakness is the same as every system based on colorimetry; inherently colorimetry cannot accurately represent perceived colors.

A bridge between color perception and color specification will certainly not be established in the near future. This fact should not, however, deter lighting stakeholders from working together *now* to develop a meaningful system of communicating color to non-specialists. Indeed, failure to do so may further compromise success for a number of stakeholders in energy-efficient, high-quality lighting products. Envisioned following adoption of an industry-wide color communication system for consumers, consumers will have better lighting quality in their homes, environmental advocates will be better able to promote energy-efficient lighting products, and manufactures will be able to command better margins for innovative lighting products. Indeed, the adoption of an industry-wide system of color communication for consumers may be a first positive step from the current position of light source commoditization toward a more visionary set of value propositions for all lighting stakeholders.

Acknowledgements

Preparation of this manuscript was partially supported by the U. S. Environmental Protection Agency, the U. S. Department of Energy and the National Electrical Manufacturers Association. The authors would like to extend their thanks to John Bullough, Conan O'Rourke and Dennis Guyon of the Lighting Research Center for assistance in preparing this manuscript. The foundational work for this paper was conducted when the second author was employed as a research scientist at the Lighting Research Center.

References

1. CIE. 2004. *Colorimetry*, *3rd edition.* CIE No. 15.2004. Vienna, Austria: Commission Internationale de l'Éclairage.

2. Leslie, R. P. and Rea, M. S. 2006. A system for communicating color: What do consumers think? *EPRI Lighting Research Office 6th International Lighting Research Symposium*. Orlando, FL.

3. National Lighting Product Information Program (NLPIP). 2004. *Lighting Answers: Light Sources and Color*. Accessed 30 November 2005 at http://www.lrc.rpi.edu/programs/NLPIP/publicationdetails.asp?id=901&type=2

4. Wyszecki, G., and W. S. Stiles. 1982. *Color science: Concepts and Methods, Quantitative Data and Formulae*. New York: John Wiley & Sons.

5. MacAdam, D.L. 1942. Visual sensitivities to color difference in daylight. *Journal of the Optical Society of America*. 32, 247.

6. MacAdam, D.L. 1943. Specification of small chromaticity differences. *Journal of the Optical Society of America.* 33, 18.

7. American National Standards Institute. 2001. *American National Standard for Electric Lamps: Specifications for the Chromaticity of Fluorescent Lamps*, ANSI C78.376.2001. Rosslyn, VA: National Electrical Manufacturers Association.

8. Bullough, J.D. 2005. *Research matters: What's cooler than cool? Warm!* Lighting Design and Application. 33(2), 12.