

## CHAPTER 3

### COLORIMETRY

#### 3.1 PREAMBLE

Colorimetry is the branch of color science concerned, in the first instance, with specifying numerically the color of a physically defined visual stimulus in such a manner that:

- (a) when viewed by an observer with normal color vision, under the same observing conditions, stimuli with the same specification look alike, (i.e., are in complete color-match),
- (b) stimuli that look alike have the same specification, and
- (c) the numbers comprising the specification are continuous functions of the physical parameters defining the spectral radiant power distribution of the stimulus.

The experimental laws of color matching as summed up in an empirical generalization, which we will refer to as the *trichromatic generalization*, provide the foundation for any system of colorimetry meeting these requirements. The concepts and terms currently employed in colorimetry are, in fact, to a large extent bound up with the trichromatic generalization.

Colorimetry is also concerned with the specification of small color differences that an observer may perceive when the differences in the spectral radiant power distributions of the given visual stimuli are such that a complete color match is not observed. For this purpose, *color-difference formulae* are used, which in current colorimetric practice are derived from a variety of different blocks of experimental data.

The *CIE Colorimetric System* comprises the essential standards and procedures of measurement that are necessary to make colorimetry a useful tool in science and technology.

#### 3.2 BASIC COLORIMETRIC CONCEPTS

The colorimetric concepts considered to be most basic and of most general use are discussed in this section. They provide the framework for the CIE Colorimetric System to be discussed in Section 3.3. For the convenience of the reader, the colorimetric terms and their definitions, as they are commonly used to describe succinctly the basic concepts, are collected in Table 1(3.2) of the Appendix. This table is not complete; other more comprehensive listings may be found in the current third edition of the *International Lighting Vocabulary* (CIE, 1970). The CIE has a fourth edition in preparation.

The terms given in Table 1(3.2) are classified as psychophysical terms of color and as such refer to color matching of two visual stimuli typically presented in the two halves of a bipartite visual field, and to judgments of similarities and degree of difference between the two stimuli. The psychophysical terms are distinguished from psychological terms of color, such as hue, saturation, and brightness, which apply to visual concepts that enable the individual observer to describe color perceptions. Chapter 6 on Uniform Color Scales deals with such concepts.

##### 3.2.1 Trichromatic Generalization

The experimental laws of color matching are summed up in the *trichromatic generalization*. This states that over a wide range of conditions of observation, many color stimuli can be matched in color completely by additive mixtures of three fixed primary stimuli whose radiant powers have been suitably adjusted. Other color stimuli have to be mixed with one of the primary stimuli before a complete color match with a mixture of the other two primary stimuli can be obtained. For some sets of primary stimuli, there remain yet other color stimuli that

have to be mixed with two of the three primary stimuli before a color match between this mixture and the third primary stimulus can be obtained. However, every color stimulus can be completely matched in color in one or another of these ways in terms of three fixed primary stimuli whose radiant powers can be adjusted by the observer to suitable levels. The choice of three primary stimuli, though very wide, is not entirely arbitrary. Any set that is such that none of the primary stimuli can be color matched by a mixture of the other two may be used. The different dispositions of the primary stimuli and their relevance to trichromatic matching will be discussed later [see Figures 5(3.2.3) and 1(3.2.4)].

The precise meaning of the term *additive mixture* in the above statement on trichromacy is made explicit by the following definition.

Additive mixture means a color stimulus for which the radiant power in any wavelength interval, small or large, in any part of the spectrum is equal to the sum of the powers in the same interval of the constituents of the mixture, constituents that are assumed to be optically incoherent.

If, in addition to the weaker or qualitative trichromacy principle enunciated in the foregoing paragraph, the results of color matching are also assumed to obey certain linearity laws, a stronger quantitative form of the trichromatic generalization is obtained. To these linearity laws of proportionality and additivity may be added two others, the laws of symmetry and transitivity, which, although they are generally tacitly assumed, it is desirable to make explicit. The four laws may be stated as follows:

(i) *Symmetry Law.*

If color stimulus **A** matches color stimulus **B**, then color stimulus **B** matches color stimulus **A**.

(ii) *Transitivity Law.*

If **A** matches **B** and **B** matches **C**, then **A** matches **C**

(iii) *Proportionality Law.*

If **A** matches **B**, then  $\alpha\mathbf{A}$  matches  $\alpha\mathbf{B}$ , where  $\alpha$  is any positive factor by which the radiant power of the color stimulus is increased or reduced, while its relative spectral distribution is kept the same.

(iv) *Additivity Law.*

If **A**, **B**, **C**, **D** are any four color stimuli, then if any two of the following three conceivable color matches

$$\begin{array}{c} \mathbf{A} \text{ matches } \mathbf{B}, \mathbf{C} \text{ matches } \mathbf{D}, \text{ and } (\mathbf{A} + \mathbf{C}) \\ \text{matches } (\mathbf{B} + \mathbf{D}) \end{array}$$

holds good, then so does the remaining match

$$(\mathbf{A} + \mathbf{D}) \text{ matches } (\mathbf{B} + \mathbf{C})$$

where  $(\mathbf{A} + \mathbf{C})$ ,  $(\mathbf{B} + \mathbf{D})$ ,  $(\mathbf{A} + \mathbf{D})$ ,  $(\mathbf{B} + \mathbf{C})$  denote, respectively, additive mixtures of **A** and **C**, **B** and **D**, **A** and **D**, and **B** and **C**.

The stronger form of trichromatic generalization of color matching as formulated above is a concise statement of what is implied in *Grassman's three laws of additive color mixture* (Grassman, 1853). Different formulations of Grassman's laws can be found in the literature. An example of a traditional formulation has been given by Judd and Wyszecki (1975). A mathematically formal and detailed exposition of Grassman's laws has been presented by Krantz (1975a).

Three considerations, ignored in the above exposition of

the trichromatic generalization, are:

- (a) the dependence of a match on the observational conditions under which the two color stimuli are compared,
- (b) the possible effects on a match of different previous exposures of the eyes to light,
- (c) differences in the color matches made by different observers.

All three factors as well as other aspects of color matching will be discussed in some detail in Chapter 5. However, a brief account of the main factors may be appropriate in this section.

**(i) Observational Conditions.** In matching, the two stimuli are

normally presented as contiguous light patches of similar shape and area. However, a color match of two stimuli of different spectral radiant power distributions, valid for a given observer when looking directly at the center of the matching field, will not generally remain valid if the observer looks to the side; and changing the area of the matching field may also upset the match. These viewing conditions must be fixed if critical color measurements are to be made.

In practical colorimetry, direct viewing of the matching field is of principal interest, and can be assumed unless it is expressly indicated otherwise. However, the angular size of the matching fields used varies widely, and this factor has been taken