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Color Vision and Self-Luminous Visual Technologies

Color vision is a complicated phenomenon triggered by visible radiation from the observer's environment imaged by the eye on the retina and interpreted by the human visual brain [1]. A visual display device constitutes an interface between a supplier of electronic information (e.g., a television channel or a computer) and the human observer (e.g., a person watching TV or a computer user) receiving the information stream converted into light. The characteristics of the human component of this interface (i.e., the features of the human visual system such as visual acuity, dynamic luminance range, temporal sensitivity, color vision, visual cognition, color preference, color harmony, and visually evoked emotions) cannot be changed as they are determined by biological evolution.

Therefore, to obtain an attractive and usable interface, the hardware and software features of the display device (e.g., size, resolution, luminance, contrast, color gamut, frame rate, image stability, and built-in image processing algorithms) should be optimized to fit the capabilities of human vision and visual cognition. Accordingly, in this chapter, the most relevant characteristics of human vision – especially those of color vision – are introduced with special respect to today's different display technologies.

The other aim of this chapter is to present a basic overview of some essential concepts of colorimetry [2] and color science [3–5]. Colorimetry and color science provide a set of numerical scales for the different dimensions of color perception (so-called correlates for, for example, the perceived lightness or saturation of a color stimulus). These numerical correlates can be computed from the result of physical light measurement such as the spatial and spectral light power distributions of the display. Using these numerical correlates, the display can be evaluated and optimized systematically by measuring the spectral and spatial power distributions of their radiation – without cumbersome and time-consuming direct visual evaluations.

Illumination, Color and Imaging: Evaluation and Optimization of Visual Displays, First Edition.
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1.1 Color Vision Features and the Optimization of Modern Self-Luminous Visual Technologies

This section summarizes the most important features of color vision for the evaluation and optimization of self-luminous color displays including the photoreceptor structure of the retina, the spatial and temporal contrast sensitivity of the human visual system, color appearance and color difference perception, the components of visual performance and ergonomics (legibility, visibility, and conspicuity of colored objects), and certain features arising at a later stage of human visual information processing such as cognitive, preferred, harmonic, and emotional color phenomena. The important issue of interindividual variability of color vision will also be dealt with in this section.

1.1.1 From Photoreceptor Structure to Colorimetry

Human color vision is trichromatic [1]. This feature has its origin in the retinal photoreceptor structure consisting of three types of photoreceptors that are active at daytime light intensity levels: the L-, M-, and S-cones. Rods constitute a further type of retinal photoreceptors but as they are responsible for nighttime vision and partially for twilight viewing conditions, they are out of the scope of this book. Displays should ensure a high enough general luminance level (e.g., higher than 50–100 cd/m^2, depending on the chromaticity of the stimulus) for the three types of cones to operate in an optimum state for the best possible perception of colors. Generally, above a luminance of about 100 cd/m^2, rods produce no signal for further neural processing and it is possible to predict the matching and the appearance of colors from the cone signals only.

L-, M-, and S-cones constitute a characteristic retinal cone mosaic. The central (rod-free) part of the cone mosaic can be seen Figure 1.1.

As can be seen from Figure 1.1, the inner area of the central part (subtending a visual angle of about 0.3° or 100 μm) is free of S-cones resulting in the so-called small-field tritanopia, that is, the insensitivity to bluish light for very small central viewing fields. There are on average 1.5 times as many L-cones as M-cones in this region of the retina [1]. L- and M-cones represent 93% of all cones, while S-cones represent the rest (7%).

Spectral sensitivities of the three types of cones [1] are depicted in Figure 1.2, while a more extensive database of the characteristic functions describing human color vision can be found on the Web [1)]. These cone sensitivities were measured at the cornea of the eye; hence, they include the filtering effect of the ocular media and the central yellow pigment on the retina (so-called macular pigment). Sensitivity curves

1) Web Database of the Color & Vision Research Laboratory, Institute of Ophthalmology, University College London, London, UK, www.cvrl.org

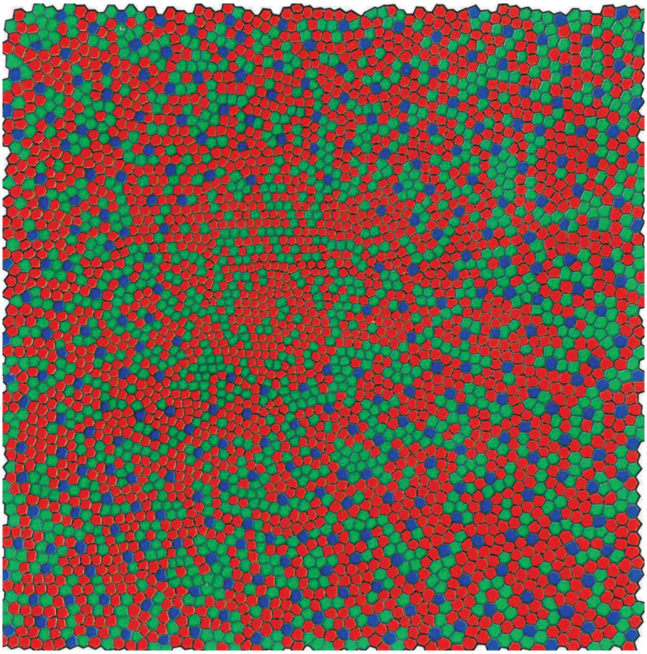

Figure 1.1 The cone mosaic of the rod-free inner fovea, that is, the central part of the retina subtending about 1°, that is, about 300 μm. Red dots: long-wavelength sensitive cone photoreceptors (L-cones). Green dots: middle-wavelength sensitive cones (M-cones). Blue dots: short-wavelength sensitive cones (S-cones). *Source*: Figure 1.1 from Sharpe, L.T., Stockman, A., Jägle, H., and Nathans, J. (1999) Opsin genes, cone photopigments, color vision and color blindness, in Ref. [1], pp. 3–51. Reproduced with permission from Cambridge University Press.

were adjusted to the average relative numbers of the L-, M-, and S-cones, that is, 56, 37, and 7%, respectively.

As can be seen from Figure 1.2, the spectral bands of the L-, M-, and S-cones provide three initial color signals like the CCD or CMOS array of a digital camera. From these initial color signals, the retina computes two chromatic signals (or chromatic channels), L − M (red–green opponent channel) and S − (L + M) (yellow–blue opponent channel), and one achromatic signal, L + M. The latter signal is called luminance signal or luminance channel. As can be seen from Figure 1.2, the maxima of the L-, M-, and S-sensitivity curves in Figure 1.2 occur at 566, 541, and 441 nm, respectively [1]. Note that these spectral sensitivity curves are expressed in quantal units. To express them in energy units, the logarithm of the wavelength should be added to each value and the curve renormalized [1].

For stimuli subtending a visual angle of 1–4°, the spectral sensitivity of the luminance channel is usually approximated by the $V(\lambda)$ function, the spectral luminous efficiency function for photopic vision also defining the CIE standard photometric observer for photopic vision (the basis of photometry) [2]. The $V(\lambda)$

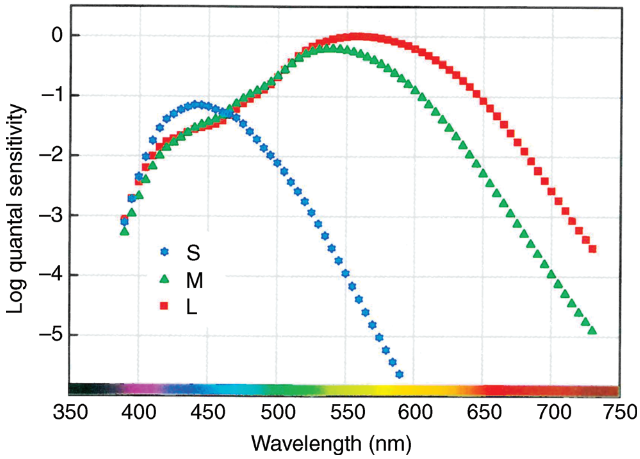

Figure 1.2 Spectral sensitivities of the three types of cones measured in quantal units (to obtain energy units, add log(λ) to each value and renormalize [1]) as measured at the cornea of the eye, thus containing the filtering effect of the ocular media and the macular pigment. Sensitivities adjusted to average relative numbers of L-, M-, and S-cones (i.e., 56, 37, and 7%, respectively). *Source*: Figure 1.1 from Sharpe, L.T., Stockman, A., Jägle, H., and Nathans, J. (1999) Opsin genes, cone photopigments, color vision and colorblindness, in Ref. [1], pp. 3–51. Reproduced with permission from Cambridge University Press.

function seriously underestimates the spectral sensitivity of the luminance channel at short wavelengths[1)].

Due to historical reasons, the spectral sensitivities of the three types of cones (Figure 1.2) are currently not widely used to characterize the radiation (so-called color stimulus) reaching the human eye and resulting in color perceptions. Instead of that, for color stimuli subtending a visual angle of 1–4°, the so-called color matching functions of the CIE 1931 standard colorimetric observer [2] are applied, while interindividual variability cannot be neglected (see Section 1.1.6). These color matching functions are denoted by $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ and constitute the basis of standard colorimetry. At this point, we would like to direct the attention of the interested reader to the recent updates of photometry and colorimetry[1)] [6].

To describe the color matching of more extended stimuli, that is, for visual angles greater than 4° (e.g., 10°), the so-called CIE 1964 standard colorimetric observer is recommended [2]. These color matching functions are denoted by $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $\bar{z}_{10}(\lambda)$. Latter functions are compared with the $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ functions in Figure 1.3.

The aim of colorimetry is to predict which spectral power distributions result in the same color appearance (so-called matching colors) in a single (standard) viewing condition, that is, directly juxtaposed 2° stimuli imaged to the central retina for an average observer of normal color vision. In this sense, two matching colors have the same so-called *XYZ* tristimulus values. *XYZ* tristimulus values are recommended to be the basis of CIE colorimetry [2].

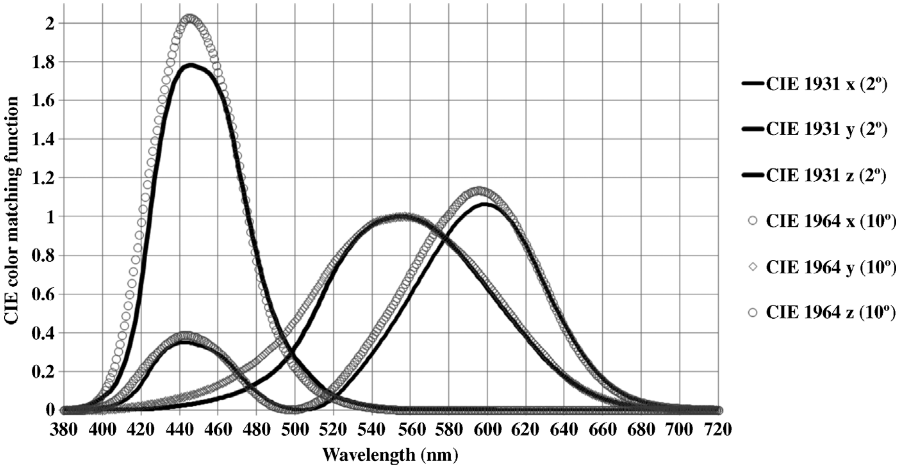

Figure 1.3 Black curves: color matching functions of the CIE 1931 standard colorimetric observer [2][1)] denoted by $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ intended to describe the matching of color stimuli subtending a visual angle of 1–4°. Open gray circles: color matching functions of the CIE 1964 standard colorimetric observer [2][1)] denoted by $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $\bar{z}_{10}(\lambda)$ intended to describe the matching of color stimuli subtending greater than 4°.

To compute the *XYZ* tristimulus values, the spectral radiance distribution of the color stimulus $L(\lambda)$ measured by a spectroradiometer on a color patch (a color sample reflecting the light from a light source or a self-luminous light emitting surface) shall be multiplied by one of the three color matching functions ($\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$), integrated in the entire visible spectrum (360–830 nm), and multiplied by a constant k (see Equation 1.1).

$$\begin{aligned} X &= k \int_{360\ \mathrm{nm}}^{830\ \mathrm{nm}} L(\lambda)\bar{x}(\lambda)\mathrm{d}\lambda \\ Y &= k \int_{360\ \mathrm{nm}}^{830\ \mathrm{nm}} L(\lambda)\bar{y}(\lambda)\mathrm{d}\lambda \\ Z &= k \int_{360\ \mathrm{nm}}^{830\ \mathrm{nm}} L(\lambda)\bar{z}(\lambda)\mathrm{d}\lambda \end{aligned} \tag{1.1}$$

For reflecting color samples, the spectral radiance of the stimulus ($L(\lambda)$) is equal to the spectral reflectance ($R(\lambda)$) of the sample multiplied by the spectral irradiance from the light source illuminating the reflecting sample ($E(\lambda)$). Equation 1.2 expresses this for diffusely reflecting materials.

$$L(\lambda) = \frac{R(\lambda)E(\lambda)}{\pi} \tag{1.2}$$

The value of k is computed according to Equation 1.3 [2].

$$k = \frac{100}{\int_{360\ \mathrm{nm}}^{830\ \mathrm{nm}} L(\lambda)\bar{y}(\lambda)\mathrm{d}\lambda} \tag{1.3}$$

As can be seen from Equation 1.3, for reflecting color samples, the constant k is chosen so that $Y = 100$ for ideal white objects with $R(\lambda) \equiv 1$.

For self-luminous objects (such as self-luminous displays), the value of k can be chosen to be 683 lm/W [2]. Then the value of Y will be equal to the luminance of the self-luminous object. In case of a self-luminous display, the peak white of the display is often visible as a background or as a white frame around an image. In this case, it makes sense to compute the relative tristimulus values of the color stimulus appearing on the self-luminous display by dividing every tristimulus value of any color stimulus (X, Y, and Z) by the Y value of peak white (i.e., by peak white luminance) and multiplying by 100. The CIECAM02 color appearance model anticipates such relative tristimulus values (see Section 2.1.9).

For color stimuli with visual angles greater than 4°, the tristimulus values X_{10}, Y_{10}, and Z_{10} can be computed substituting $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ by $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $z_{10}(\lambda)$ in Equation 1.1. As can be seen from Figure 1.3, the two sets of color matching functions, that is, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ and $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $\bar{z}_{10}(\lambda)$, differ significantly. The consequence is that two matching color stimuli subtending a visual angle of, for example, 1° generally will not match if their size is increased to, for example, 10°.

The so-called chromaticity coordinates (x, y, z) are defined by Equation 1.4.

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}, \quad z = \frac{Z}{X+Y+Z} \tag{1.4}$$

The diagram of the chromaticity coordinates x, y is called the CIE 1931 chromaticity diagram or the CIE (x, y) chromaticity diagram [2]. Figure 1.4 illustrates how color perception changes across the x, y diagram.

As can be seen from Figure 1.4, chromaticities are located inside the curved boundary of quasi-monochromatic radiations of different wavelengths (so-called spectral locus) and the purple line. White tones are positioned in the middle range of the diagram with increasing saturation toward the spectral locus. Perceived hue changes (purple, red, yellow, green, cyan, and blue) when going around the region of white tones in the middle of the x, y diagram.

1.1.2
Spatial and Temporal Contrast Sensitivity

The user of the display would like to discern visual objects such as letters, numbers, or symbols from their background and perceive the fine spatial structure of objects, for example, analyze the colored textures of different objects in a photorealistic image, discern a thin colored line of a diagram with colored background, or recognize a complex Asian letter based on its composition of tiny strokes. To be able to do so, the user needs an appropriate display hardware and image rendering software respecting the spatial frequency characteristics of the achromatic (L + M) and chromatic (L − M, S − (L + M)) channels of the human visual system.

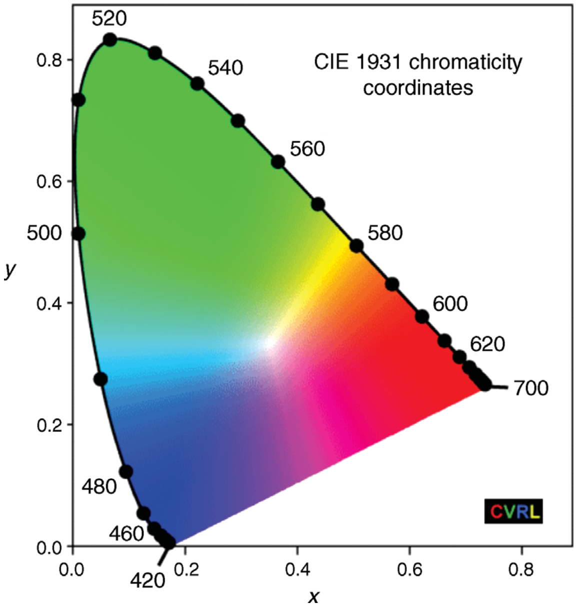

Figure 1.4 Illustration of how color perception changes across the CIE (*x*, *y*) chromaticity diagram [2]. The curved boundary of colors with three-digit numbers (wavelengths in nanometer units) represents the locus of monochromatic (i.e., most saturated) radiation. Source: Figure 7 from Ref. [7]. Reproduced with permission from Wiley-VCH Verlag GmbH & Co. KGaA.

To understand these spatial frequency characteristics, it is essential to learn how the human visual system analyzes the spatial structures of the retinal image. L-, M-, and S-cone signals are processed by different cell types of the retina including the so-called ganglion cells. Ganglion cells process the signals from several cones located inside their receptive fields. Receptive fields of ganglion cells are built to be able to amplify the spatial contrasts (i.e., edges) of the image in the following way.

Every receptive field has a circular center and a concentric circular surround. Stimulation of the center and the surround exhibits opposite firing reactions of the ganglion cell: it is firing when the stimulus is in the center ("on-center cell"), while it is inhibited when the stimulus is in the surround. The other type of ganglion cell ("off-center cell") is inhibited when the stimulus is in the center and firing when the stimulus is in the surround. This way, spatially changing stimuli (contrasts or edges) increase firing, while spatially homogeneous stimuli generate only a minor response (see Figure 1.5).

On the human retina, achromatic contrast (i.e., spatial changes of the $L + M$ signal) is detected according to the principle of Figure 1.5. Similar receptive field structures produce the chromatic signals for chromatic contrast, that is, spatial changes of the $L - M$ or $S - (L + M)$ signals. But in this case, the spectral sensitivity of the center differs from the spectral sensitivity of the surround due to the different combinations of the L-, M-, and S-cones in the center and in the surround. This receptive field structure is called double opponent because there is a spatial

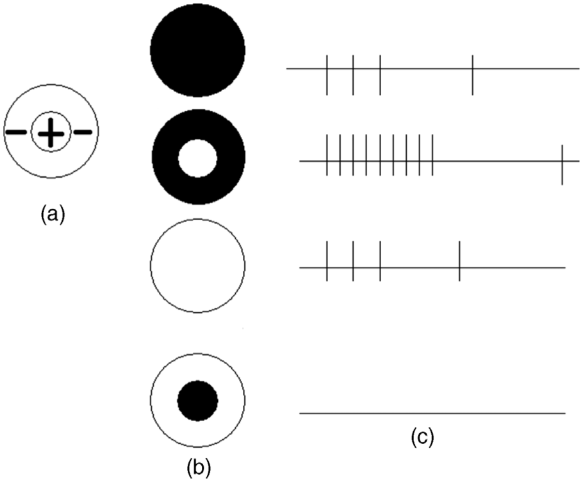

Figure 1.5 (a) Schematic representation of the receptive field of an "on-center" ganglion cell: +, center; −, surround. (b) Black: no light; white: light stimulus; from top to bottom: (1) no light over the whole receptive field; (2) contrast – light on the center, no light on the surround; (3) light over the whole receptive field; (4) light on the surround. (c) Firing rate, from top to bottom: weak, strong, weak, no response [8].

opponency (center/surround) and a cone opponency (L/M or S/(L + M)). Table 1.1 summarizes its possible cone signal combinations.

To produce chromatic signals for homogeneous color patches, a so-called single-opponent receptive field (with cone signal opponency but no spatial opponency) is responsible. In this kind of receptive field, the center and the surround (containing the combinations of Table 1.1) overlap in space [9].

It is the size and sensitivity of the receptive fields and the spatial aberrations of the eye media (cornea, lens, and vitreous humor) that determine the spatial frequency characteristics of the achromatic and chromatic channels [8]. In practical applications including self-luminous displays, the basic question is how much achromatic or

Table 1.1 Possible combinations of L-, M-, and S-cone signals in the center and in the surround of the receptive field structure producing the signals of the chromatic channels to detect chromatic contrast (chromatic edges).

Chromatic channel	Cell type	Center	Surround
L − M	On-center	+L	−M
L − M	Off-center	−L	+M
L − M	On-center	+M	−L
L − M	Off-center	−M	+L
S − (L + M)	On-center	+S	−(L + M)
S − (L + M)	Off-center	+(L + M)	−S

chromatic contrast is needed to detect a visual object of a given size corresponding to a given spatial frequency (see Sections 3.3 and 4.4). Size is usually expressed in degrees of visual angle, while spatial frequency is expressed in cycles per degree (cpd) units. For example, 10 cpd means that there are 10 pairs of thin black and white lines within a degree of visual angle.

Contrast (C) can be measured either by the contrast ratio, that is, the signal value (e.g., L + M or L − M) of the object (S_O) divided by the signal value of its background (S_B) (i.e., S_O/S_B), or by the so-called Michelson contrast $(S_O - S_B)/(S_O + S_B)$. Contrast sensitivity (CS) is defined as the reciprocal value of the threshold value of contrast needed to detect the object. Achromatic contrast sensitivity is a band-pass function of spatial frequency increasing up to about 3–5 cpd and then decreasing toward high spatial frequencies. For about 40 cpd (corresponding to a visual object of about 1 arcmin) or above, achromatic contrast sensitivity is equal to zero. This means that it is no use increasing the contrast (even up to infinity, that is, black on white) if the object is smaller than about 1 arcmin. This is the absolute limit of (foveal) visual acuity. Below this limit, generally more contrast is needed for higher spatial frequencies to be able to detect an object, as can be seen from Figure 1.6.

In Figure 1.6, the spatial frequency of the pattern increases from top to bottom and contrast increases from left to right. For each spatial frequency, there is a horizontal threshold position where the pattern can just be detected. These visual threshold positions correspond to the achromatic contrast sensitivity function plotted in Figure 1.7.

As can be seen from Figure 1.7, achromatic contrast sensitivity is higher for higher retinal illuminance levels (e.g., 2200 Td) because at such a high level, the visual system is operating in its optimum (i.e., truly photopic) state of adaptation. The conventional unit of retinal illuminance is the troland (Td), the product of photopic luminance in cd/m^2 and the pupil area in mm^2. Replacing the grayscale sinusoidal pattern of Figure 1.6 by pure chromatic transition patterns (without achromatic contrast), the contrast sensitivity of the chromatic channels becomes visible. An example can be seen in Figure 3.19b. The latter example shows a combination of L − M contrast and S − (L + M) contrast without any achromatic contrast. Chromatic contrast sensitivity functions of the L − M and S − (L + M) channels are compared with the achromatic contrast sensitivity function (at a high retinal illuminance level) in Figure 1.8.

As can be seen from Figure 1.8, while the L + M (luminance) contrast sensitivity function exhibits band-pass nature, chromatic functions are low-pass functions. Chromatic contrast sensitivity is limited to a narrow spatial frequency range up to 8 cpd. Even for lower spatial frequencies, chromatic contrast sensitivity is low compared to achromatic contrast sensitivity (see Section 3.3). This knowledge is exploited to develop image and video compression algorithms (e.g., JPEG, MPEG) for digital still and motion images and the dataflow in digital TV and cinema (see Section 4.4.3). The low contrast sensitivity of the S − (L + M) channel can be used to watermark video sequences without noticing it visually (see Section 4.4.4).

Concerning temporal contrast sensitivity, increasing the temporal frequency (measured in Hz units) of temporally modulated stimuli, first flicker is perceived

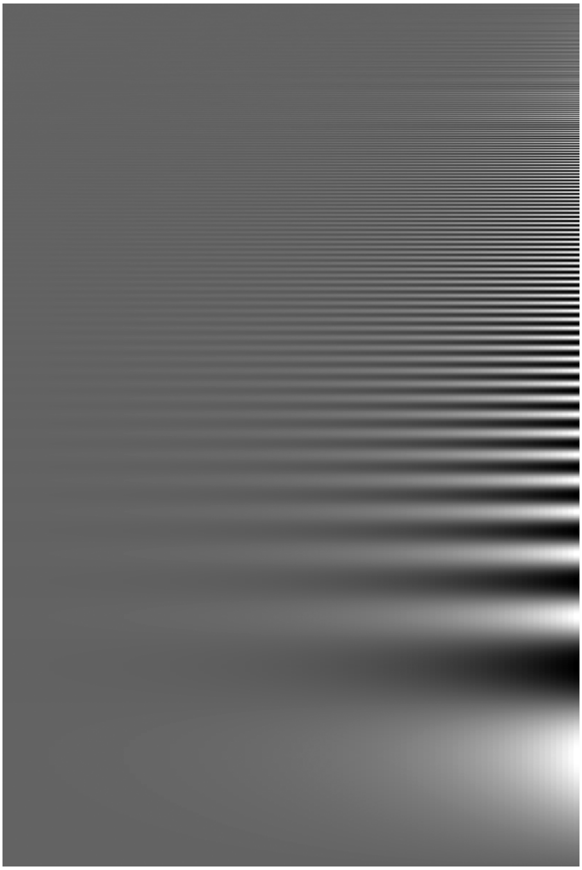

Figure 1.6 Demonstration of achromatic contrast sensitivity (so-called Campbell–Robson contrast sensitivity chart). The spatial frequency of the pattern increases from top to bottom. Achromatic contrast increases from left to right. For each spatial frequency, there is a horizontal threshold position where the pattern can just be detected corresponding to the achromatic contrast sensitivity function plotted in Figure 1.7. Try to reconstruct this position as a function of spatial frequency visually and draw the contrast sensitivity function of your own eye [8].

and then, for higher temporal frequencies, a constant stimulus appears. The transition point between the two is called critical flicker frequency (CFF) playing an important role in the visual ergonomics of displays (see Section 3.1). The temporal contrast sensitivity of the achromatic (luminance) channel exhibits band-pass nature, while the temporal contrast sensitivity of the chromatic channels is a low-pass function (see Figure 1.9).

As can be seen from Figure 1.9, the temporal contrast sensitivity of the chromatic channels is much less than the temporal contrast sensitivity of the achromatic channel. Critical flicker frequency of the chromatic channels is equal to about 6–7 Hz, while the critical flicker frequency of the achromatic channel is equal to about

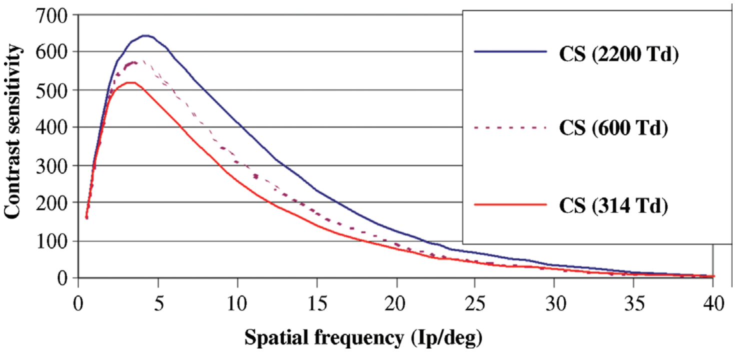

Figure 1.7 Achromatic contrast sensitivity functions for different values of retinal illuminance level (in Td units). Retinal illuminance corresponds to the luminance of the stimulus (in cd/m^2) scaled by the pupil area (in mm^2). Abscissa: spatial frequency in cpd units; ordinate: achromatic contrast sensitivity (relative units) [8].

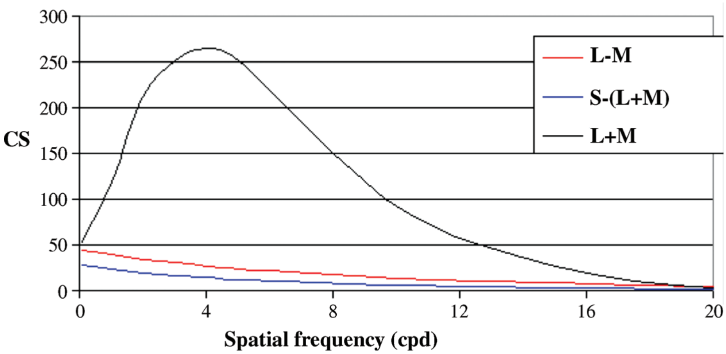

Figure 1.8 Chromatic contrast sensitivity functions of the L − M and S − (L + M) channels compared with the achromatic contrast sensitivity function (at a high retinal illuminance level). Abscissa: spatial frequency in cpd units; ordinate: contrast sensitivity (relative units) [8, 10].

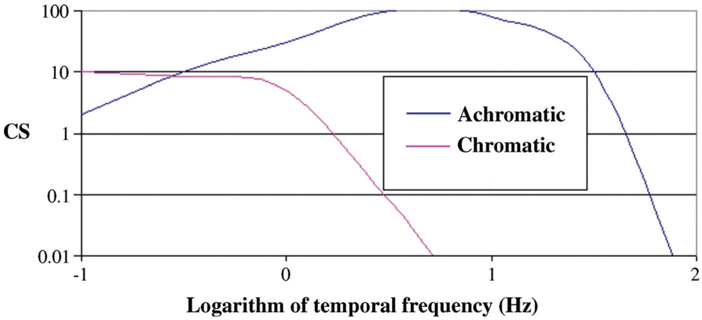

Figure 1.9 Temporal contrast sensitivity functions of the achromatic (luminance) and chromatic channels. Abscissa: temporal frequency of the altering stimulus in Hz units; ordinate: contrast sensitivity (relative units) [8].

50–70 Hz depending on luminance level and stimulus eccentricity. This knowledge is essential to measure the $V(\lambda)$ function to be able to "switch off" the influence of the more sluggish chromatic channels. Modern displays and film projectors use high frame rates to avoid any flicker artifact even for higher luminance levels and peripheral perception (see Section 4.4.1).

1.1.3
Color Appearance Perception

The description of color stimuli in the system of tristimulus values (X, Y, and Z) results in a nonuniform and nonsystematic representation of the color perceptions corresponding to these stimuli. More specifically, the relevant psychological attributes of perceived colors (i.e., perceived lightness, brightness, redness–greenness, yellowness–blueness, hue, chroma, saturation, and colorfulness) cannot be expressed in terms of XYZ values directly. To model color perception, numerical correlates have to be derived from the XYZ values of the stimulus for each attribute (as mentioned at the beginning of this chapter).

Hue is the attribute of a visual sensation according to which a color stimulus appears to be similar to the perceived colors red, yellow, green, and blue, or a combination of two of them [11]. Brightness is the attribute of a color stimulus according to which it appears to emit more or less light [11]. Lightness is the brightness of a color stimulus judged relative to the brightness of a similarly illuminated reference white (appearing white or highly transmitting) [3].

Colorfulness is the attribute of a color stimulus according to which the stimulus appears to exhibit more or less chromatic color. For a given chromaticity, colorfulness generally increases with luminance [12]. In an indoor environment, observers tend to assess the *chroma* of surface colors. The perceived attribute chroma refers to the colorfulness of the color stimulus judged in proportion to the brightness of the reference white [3].

Saturation is the colorfulness of a stimulus judged in proportion to its own brightness [11]. A perceived color can be very saturated without exhibiting a high level of chroma. For example, a deep red sour cherry is quite saturated but it exhibits less chroma because the sour cherry is colorful compared to its (low) own brightness but it is not so colorful in comparison to the brightness of the reference white. Figure 1.10 illustrates the three perceived attributes, hue, chroma, and lightness.

The numerical scales modeling the above attributes of color perception (so-called numerical correlates) should be perceptually uniform. This means that equal differences of their scales should correspond to equal perceptual differences. Otherwise, they are not useful for practice. If the above-mentioned numerical correlates are computed, then the color stimuli can be arranged in a three-dimensional space, the so-called color space.

In a color space, the three perpendicular axes and certain angles and distances carry psychologically relevant meanings related to the perceived color attributes. Hence, these color spaces are very useful tools of color display design and evaluation, including all aspects of color perception, cognition, preference, and emotion. For

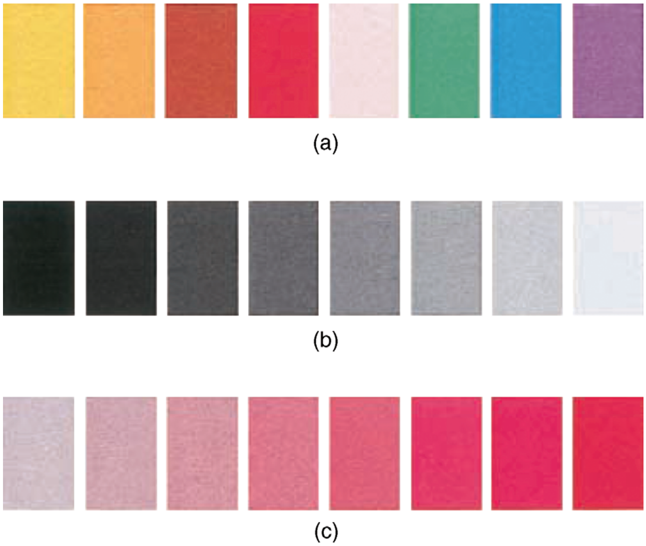

Figure 1.10 Illustration of three attributes of perceived color: (a) changing hue, (b) changing lightness, and (c) changing chroma. Reproduction of Figure 1 from Ref. [13] with permission from *Color Research and Application*.

example, preferred or ergonomic colors of a display user interface can be easily represented and understood if they are specified in such a color space. A schematic illustration of the structure of a color space can be seen in Figure 1.11.

As can be seen from Figure 1.11, lightness increases from black to white from the bottom to the top along the gray lightness scale in the middle of color space. At every

Figure 1.11 Schematic illustration of the general structure of color space. Lightness increases from black to white from the bottom to the top along the gray lightness scale in the middle. Chroma increases from the gray scale toward the outer colors of high chroma. The perceptual attribute of hue varies when rotating the image plane around the gray axis in space.

lightness level, chroma increases from the gray scale toward the most saturated outer colors. The perceptual attribute of hue varies when rotating the image plane around the gray axis in space.

CIE colorimetry recommends two such coordinate systems, CIELAB and CIELUV, the so-called CIE 1976 uniform color spaces [2]. Computations of the approximate numerical correlates of the perceived color attributes in these two uniform color spaces start from the XYZ values of the color stimulus and the XYZ values of a specified reference white color stimulus (X_n, Y_n, Z_n).

In many cases, the reference white is an object color, that is, the perfect reflecting diffuser illuminated by the same light source as the test object. The application of color spaces to self-luminous displays is described in Section 2.1.9. Although CIELAB and CIELUV represent standard practice today, their defining equations are repeated below. The CIELAB color space is defined by Equation 1.5.

$$\begin{aligned} L^* &= 116f(Y/Y_n) - 16 \\ a^* &= 500[f(X/X_n) - f(Y/Y_n)] \\ b^* &= 200[f(Y/Y_n) - f(Z/Z_n)] \end{aligned} \tag{1.5}$$

In Equation 1.5, the function f is defined by Equation 1.6.

$$\begin{aligned} f(u) &= u^{1/3} && \text{if} \quad u > (24/116)^3 \\ f(u) &= (841/108)u + (16/116) && \text{if} \quad u \leq (24/116)^3 \end{aligned} \tag{1.6}$$

In CIELAB, output quantities (approximate correlates of the perceived attributes of color) include L^* (CIE 1976 lightness of Equation 1.5), CIELAB chroma (C^*_{ab}), and CIELAB hue angle (h_{ab}). The quantities a^* and b^* in Equation 1.5 can be interpreted as rough correlates of perceived redness–greenness (red for positive values of a^*) and perceived yellowness—blueness (yellow for positive values of b^*). L^*, a^*, and b^* constitute the three orthogonal axes of CIELAB color space; compare with the illustration of color space shown in Figure 1.11. Equation 1.7 shows how to calculate C^*_{ab} and h_{ab} from a^* and b^*.

$$\begin{aligned} C^*_{ab} &= \sqrt{a^{*2} + b^{*2}} \\ h_{ab} &= \arctan(b^*/a^*) \end{aligned} \tag{1.7}$$

Similar quantities are defined in the other color space, CIELUV, as well. The value of L^* of the CIELUV color space is identical to the value of L^* of the CIELAB color space. The rectangular coordinates u^* and v^* are computed by Equation 1.8.

$$\begin{aligned} u^* &= 13L^*(u' - u'_n) \\ v^* &= 13L^*(v' - v'_n) \end{aligned} \tag{1.8}$$

In Equation 1.8, the u', v' values of the so-called CIE 1976 uniform chromaticity scale diagram (UCS diagram or u', v' diagram) are defined starting from the chromaticity coordinates x, y defined by Equation 1.4 (see Equation 1.9). The subscript n in Equation 1.8 refers to the reference white.

$$\begin{aligned} u' &= 4x/(-2x + 12y + 3) \\ v' &= 9y/(-2x + 12y + 3) \end{aligned} \tag{1.9}$$

In the CIELUV color space (L^*, u^*, v^*), CIELUV chroma (C^*_{uv}) and CIELUV hue angle (h_{uv}) are defined by substituting a^* and b^* by u^* and v^* in Equation 1.7, respectively. In addition to these, CIELUV also defines a numerical correlate of perceived *saturation*, s_{uv}, according to the underlying perceptually uniform UCS chromaticity diagram. This is shown in Equation 1.10.

$$s_{uv} = 13\sqrt{(u' - u'_n)^2 + (v' - v'_n)^2} \tag{1.10}$$

It is important to read the notes of the CIE publication [2] carefully stating (among others) that CIELUV and CIELAB are "intended to apply to comparisons of differences between object colors of the same size and shape, viewed in identical white to middle-gray surroundings by an observer photopically adapted to a field of chromaticity not too different from that of average daylight." To compare the color appearance of color stimuli viewed in different viewing conditions including tungsten light/daylight, average/dark/dim surround luminance levels, or different backgrounds, so-called color appearance models shall be used such as the CIECAM02 color appearance model [14] (see also Section 2.1.9). The CIECAM02 model computes numerical correlates for all perceived attributes of color. CIECAM02 correlates represent an improved model of color perception compared to CIELAB or CIELUV.

1.1.4
Color Difference Perception

A disadvantage of the CIE (x, y) chromaticity diagram [2] is that it is perceptually not uniform. In Figure 1.4, observe that a distance in the green region of the diagram represents a less change of perceived chromaticness than the same distance in the blue–purple region. The so-called MacAdam ellipses [15] quantify this effect (see Figure 1.12). Roughly speaking, perceived chromaticity differences are hardly noticeable inside the ellipse (for a more precise definition of the MacAdam ellipses, see Ref. [15]). Note that the ellipses of Figure 1.12 are magnified 10 times.

As can be seen from Figure 1.12, MacAdam ellipses are large in the green region of the CIE (x, y) chromaticity diagram while they are small in blue–purple region and the orientation of the ellipses also changes. To overcome these difficulties, the x and y axes were distorted so as to make identical circles from the MacAdam ellipses and this resulted in the u', v' diagram of Equation 1.9.

The u', v' diagram is perceptually uniform (at least approximately, in the sense that equal distances represent equal changes of perceived chromaticity in any part of the diagram) if the relative luminance difference of the two color stimuli is small, for example, $\Delta Y < 0.5$. This means that the u', v' diagram is useful to evaluate differences of perceived chromaticness without lightness differences.

Perceived total color differences between two color stimuli (ΔE^*_{ab} and ΔE^*_{uv}) are modeled by the Euclidean distances between them. Euclidean distances shall be computed in the rectangular CIELAB (L^*, a^*, b^*) and CIELUV (L^*, u^*, v^*) color spaces. Lightness, chroma, and hue angle differences of two color stimuli (ΔL^*, ΔC^*_{ab}, and Δh_{ab}) can be computed by subtracting the lightness, chroma, and hue angle values of the two color stimuli.

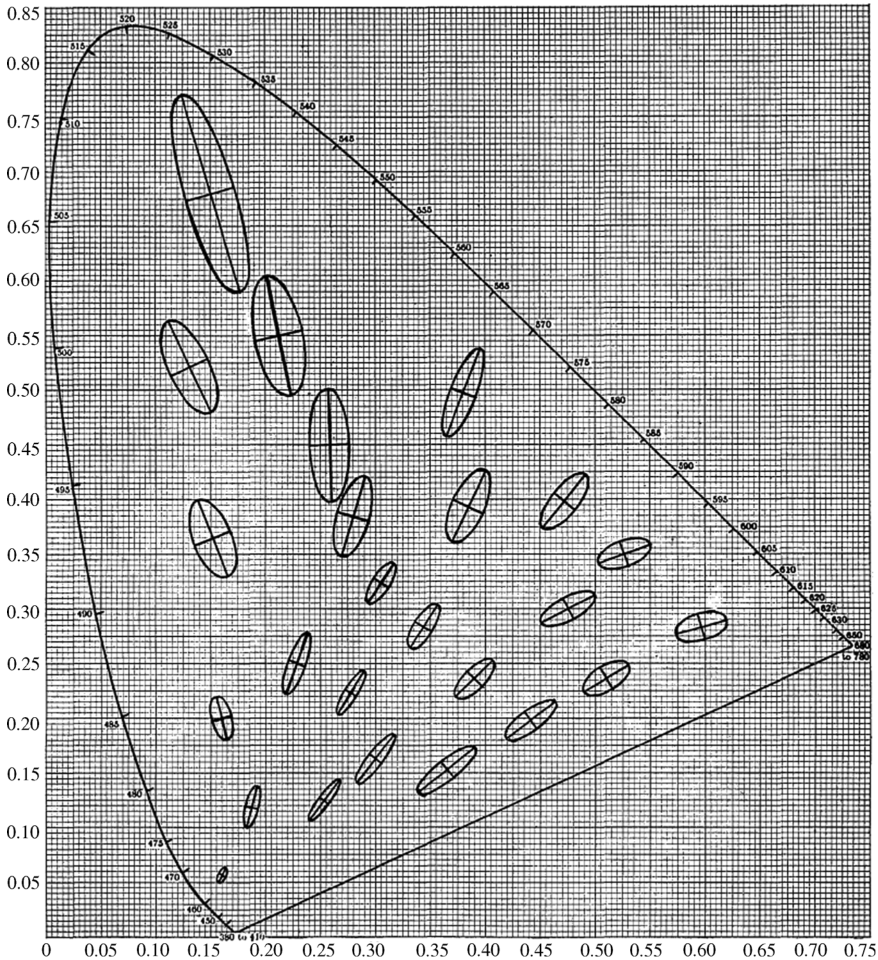

Figure 1.12 MacAdam ellipses [15] in the CIE (x, y) chromaticity diagram. Abscissa: chromaticity coordinate x; ordinate: chromaticity coordinate y. Roughly speaking, perceived chromaticity differences are not noticeable inside the ellipses. For a more precise definition of the MacAdam ellipses, see Ref. [15]. Ellipses are magnified 10 times. Reproduced from Ref. [15] with permission from the *Journal of the Optical Society of America*.

Hue differences (ΔH^*_{ab}) must not be confused with hue angle differences (Δh_{ab}). Hue differences include the fact that the same hue change results in a large color difference for large chroma and in a small color difference for small chroma (i.e., in the neighborhood of the CIELAB or CIELUV L^* axis). CIELAB hue difference is defined by Equation 1.11. In Equation 1.11, ΔH^*_{ab} has the same sign as Δh_{ab}.

$$\Delta H^*_{ab} = \sqrt{(\Delta E^*_{ab})^2 - (\Delta L^*)^2 - (\Delta C^*_{ab})^2} \tag{1.11}$$

However, CIELAB and CIELUV color differences exhibit perceptual nonuniformities depending on the region of color space (e.g., reddish or bluish colors), color difference magnitude (small, medium, or large color differences), and miscellaneous viewing parameters including sample separation, texture, and background color [16]. The CIEDE2000 total color difference formula corrects the nonuniformity of CIELAB for small color differences under a well-defined set of reference conditions [17]. The CIEDE2000 formula introduces weighting functions for the hue, chroma, and lightness components of CIELAB total color difference and a factor to account for hue–chroma interaction.

Recently, uniform color spaces based on the CIECAM02 color appearance model were introduced [18] to describe small (CIECAM02-SCD) and large color differences (CIECAM02-LCD). An intermediate space (CIECAM02-UCS) was also introduced. Recently, the superior performance of CIECAM02-UCS was corroborated in visual experiments on color rendering [19, 20] (see Section 6.2.1).

1.1.5
Cognitive, Preferred, Harmonic, and Emotional Color

Color perceptions undergo further processing in the visual brain, giving rise to cognitive, esthetic, emotional, and memory-related color phenomena. These effects can be exploited to enhance the usability and image quality of visual displays. Perceived color is classified into color categories described by color names such as yellow, orange, brown, red, pink, green, blue, purple, white, gray, or black. This categorization is the basic process of color cognition. The distinction between perception and cognition is that while perception refers to immediate mapping of objects or events of the real world into the brain, cognition refers to subsequent higher order processes of semantic and verbal classification of the perceptions or to the mental imagery of the same objects or events [21, 22].

Long-term memory colors of familiar objects (e.g., blue sky, green grass, skin, tan skin, or yellow banana) represent a further type of cognitive color [13]. The color quality of pictorial images on a display can be enhanced by shifting the actual image colors toward these long-term memory colors (Section 3.4). Cognitive color is also relevant in visual ergonomics (Sections 3.1–3.3) because it improves visual search performance due to the control of visual attention “filtering out” unattended visual objects or events [23]. Color is an effective code when used as a cue or alerting signal or a method of grouping similar items or separating items [24].

The esthetic aspect of color is related to the pleasing or preferred appearance of stand-alone color patches, pictorial color images, or combinations of color patches. The latter aspect (i.e., esthetic value or preference of color combinations) is called color harmony (Section 6.3). As an example, more or less harmonic combinations of watercolors can be seen in Figure 6.19. Color can also evoke very strong emotions often in combination with other visual and nonvisual factors of still or motion images and these emotions can be enhanced by dedicated video processing algorithms (Section 4.6).

1.1.6 Interindividual Variability of Color Vision

In the previous sections, interindividual differences of color perception were neglected and a hypothetic average observer, the CIE 1931 standard colorimetric observer [2], was considered. In reality, however, there are observers with anomalous or deficient color vision. According to the observer's genotype, spectral sensitivity maxima of the L-, M-, and S-cones can be shifted by up to 4 nm. Some observers have less L-, M-, or S-cones and exhibit protanomalous, deuteranomalous, or tritanomalous color vision, respectively. If one of the cone types is completely missing, then they are called protanope, deuteranope, or tritanope observers. The interesting domain of visual displays and deficient color vision is out of the scope of this book.

Even within the limits of normal trichromatic color vision, there is a large variability of retinal mosaics especially concerning the ratios of the L- and M-cones varying between 0.4 and 13 [25]. The postreceptoral mechanisms of color vision are very adaptable and – at least in principle – able to counterbalance this variability of photoreceptor mosaics. There are, however, in turn large variations among the subjects at the later stages of neural color signal processing including the perception of color differences (Section 6.6), color cognition, preference (Sections 3.5 and 3.6), harmony, long-term memory colors (Section 3.4.2), and visually evoked emotions.

1.2 Color Vision-Related Technological Features of Modern Self-Luminous (Nonprinting) Visual Technologies

In this section, specific features of the different display technologies (and cameras) are described related to specific color vision characteristics, for every relevant type of display technology separately. For digital film and high-resolution digital TV, image quality is a main issue, especially the accurate reproduction of color appearance. To do so, the set of displayable colors (the so-called color gamut) has to be optimized to cover the most important colors (see Sections 5.1 and 5.2). Color resolution should be high enough to be able to render continuous color shadings (see Section 2.2.2.5).

Image quality can be further improved if spatial resolution is increased by subpixel rendering and by reducing the extent of spatial color artifacts at the same time (see Sections 5.3 and 5.4). High dynamic range (HDR) imaging means the emergence of highlights (Section 2.3.3) on the display enhancing the emotional effect of the motion picture (Section 4.6). One important aim of color management (Section 4.1.3) is that the displayed colors have the same color appearance across different displays, for example, on a proof monitor, in an analog cinema, and in a digital cinema (see also Section 3.2). To do so, the colorimetric characterization of the display (Chapter 2) has to be carried out on one hand and a color appearance model accounting for the adaptation of the human visual system has to be applied on the other hand. These two components have to be built into the display's hardware and/or software (in the so-called color management system) converting digital electronic signals into visible radiation for the observer.

It is also important to evaluate the color differences between a proof monitor and the actual appearance in the cinema or on the TV (Section 4.2.3). To reduce the huge amount of data for digital TV and cinema, image compression without loss of visually perceptible spatial, color, and motion information is necessary. This can be done by exploiting the knowledge about achromatic and chromatic contrast sensitivity of the human visual system (Section 4.4). Note that, for digital cinema, often very specific viewing conditions apply, including dim viewing conditions and large viewing angles (Section 2.4) influencing color appearance.

Motion picture theaters evoke special emotions visually and this feature requires a specific film-like color appearance (Sections 4.2.4 and 4.6). Long-term human color memory and color image preference can also be considered to provide pleasing images, possibly also depending on the intended group of observers, for example, depending on the cultural background or on the age of the observers (Sections 3.4, 3.5, 3.6).

In a camera, the colorimetric, spatial, and temporal resolution of the sensor array and the lens determine the quality of the captured image (Section 4.4.2). The colorimetric characterization of the camera is equally important to be able to transform the raw image consisting of the sensor signals into a device-independent format, for example, XYZ values at each pixel. A color appearance model helps apply further corrections such as adjusting the white balance or the tone characteristics of the image. It is essential to apply visually error-free image compression to reduce the bandwidth of video data transmission.

Color monitors represent similar features to digital film and TV except that the viewing conditions and the aims of use are different. Color monitors are usually viewed in light office environments where ambient light cannot be neglected and this has to be taken into account when applying a color appearance model (Section 2.1.8). The size of monitors is usually less; hence, the color size effect (Section 2.4) can be neglected.

Instead of film-like color image appearance and visually evoked emotions, visual ergonomics plays a more important role (Sections 3.1 and 3.3) for color monitors because instead of entertainment purposes, color monitors are used as a component of a computer workplace or for infotainment. Thus, the basic concepts of visual ergonomics, visibility, legibility, readability, visual attention, and visual search features become the substantial factors of display hardware and software design.

Head-mounted displays (HMDs, Section 2.2.2.4) often provide an immersive visual environment that can be either a projection of the real world or an artificial visual world. As HMDs often visualize three dimensions, an important requirement is to reduce parallax artifacts arising from the imperfect representation of depth information. As immersion means very large viewing angles, the color size effect is also relevant (Section 2.4). In head-up displays, additional visual information is superimposed upon the directly viewed image of the real world; hence, it is essential to match the luminance of this superposition to the actual luminance level of the real-world image (Section 2.2.2.4).

Digital signage displays and large tiled displays cover large areas (Section 2.4) on indoor or outdoor walls of buildings and provide visual information for numerous users simultaneously. Results from visual ergonomics are necessary to ensure the legibility of displayed information. Removing flicker, jitter, and ambient light reflections is also substantial.

For projectors, the image is viewed in a dim or dark environment and this has to be considered in the color appearance model. The spectral power distributions of projector light sources have to be matched to the spectral transmission of the color filters of the projector to achieve a large color gamut (Section 2.3.3). Alternatively, for LED projectors, the peak wavelengths of the LEDs have to be chosen in a similar way.

Light sources of display backlighting (Section 2.3.2) should provide a spatially uniform illumination of the color filter mosaic of the display (Section 2.1.5). Again, to achieve a large color gamut, the spectral power distribution of the backlight should match the spectral transmission of the color filters (Section 2.3.3). Another criterion of co-optimizing backlight spectra and filter transmissions is that the primary colors of the display should be bright enough compared to the brightness of the white point (Section 5.1).

For the light sources of indoor illumination, specific visual requirements apply (see Chapter 6). The reason is that they illuminate a room with usually white walls and several reflecting colored objects inside the room. Figure 6.17 shows a so-called tabletop arrangement of colored objects intended to model this situation. First of all, the light source itself should provide an appropriate white tone (visible on the white standard in Figure 6.17), for example, warm white for home illumination in Western countries and cool or cold white for office environments.

In addition to this, the colors of the reflecting objects should be rendered by the light source in an appropriate way. Reflected colors should not be undersaturated or oversaturated and they should exhibit a natural hue similar to the usual color appearance of each object under daylight or tungsten light. Even if the white tone of the light source itself is acceptable, that is, it has no strange tints such as a greenish or reddish shade, the reflecting colors of the objects can be rendered poorly if certain spectral ranges are missing from the spectral power distribution of the light source (see Section 6.2).

Besides this so-called color rendering or color fidelity property of the light source, there exist several other aspects of color quality including the color harmony among the different colored objects (see Section 6.3). Other color quality aspects are dealt with in Section 6.4 including visual clarity, continuous color transitions, color preference, and the rendering of long-term memory colors by the light source (see also Section 3.4.1).

1.3
Perceptual, Cognitive, and Emotional Features of the Visual System and the Corresponding Technological Challenge

The starting point of the optimization of visual display technologies and indoor light sources is the analysis of the human user's characteristics, including the properties of the human visual system relevant for the most important visual task (e.g., work with a computer user interface or entertainment) on the display. In a second step, the technological challenge is that the visual display or the indoor light source should be designed to achieve the best perceptual, cognitive, emotional, or preference-based image appearance.

For self-luminous displays, the user's characteristics include the user's age, cultural background, and personality together with his or her spatial and color vision features as well as cognitive, emotional, and image preference characteristics. The task analysis should consider the mode of observation (e.g., still images or motion pictures), the surround luminance level (dark, dim, average, or bright), and the type of the user's task, for example, surveillance, monitoring, textual input on a user interface, programming, web browsing with extensive visual search, or watching still images or motion pictures for entertainment or infotainment purposes and appraising their spatiotemporal color appearance.

The next step in the optimization is considering the crucial visual mechanisms involved in the task, for example, the achromatic (luminance) channel of the visual system for the reading task. The final step is the optimization of the temporal, spatial, and colorimetric technological properties of the display in order to fulfill the requirements posed by the visual system for good image quality. For example, the design of new subpixel architectures (Section 5.3) can apply a set of design principles derived from the characteristics of the human visual system and novel types of subpixel architectures can be invented (Section 5.4).

Provided that the display is used for observers of normal color vision working in a well-lit office environment using predominantly still images, the color gamut of the new display can be co-optimized with its good spatial resolution in accordance with the properties of the retinal mosaic where the image of the display is projected by the user's eye lens. Thus, a huge amount of information stored in the computer memory can be mapped onto the user's brain very efficiently via the optical radiation emitted by the display and detected by the retina constituting an integral part of the visual brain.

For indoor light sources, the optimization workflow differs from the self-luminous display's workflow in the following aspects. In this case, human visual mechanisms should be considered from the point of view of indoor lighting, that is, the color appearance of the reflecting objects in the room, color discrimination among the different reflecting colors of the objects, the perceived color harmony of their combinations, and the fulfillment of the observer's color preference demands in the environment lit by the indoor light source. To optimize the light source, all available light source technologies should be kept in mind with the technological possibilities of tailoring their spatial and spectral power distributions by considering the spectral reflectance curves of the important objects that possibly appear in the indoor environment.

Since the beginning of the twenty-first century, lighting research has focused special attention on the spectral sensitivity of human circadian behavior, that is, the 24 h cycles of human activity synchronized by the "body clock." This circadian rhythm influences work concentration, sleep quality, and well-being of office and industrial workers. Today's technological challenge is to optimize the spectral and spatial power distributions of the light source to stimulate a special type of photoreceptors, the so-called intrinsically photosensitive retinal ganglion cells (ipRGCs, see Section 7.2.2).

Table 1.2 shows a selection of important perceptual, cognitive, and emotional features of the human visual system (examples) together with the challenges of display or light source technology. The corresponding sections of this book are also indicated in Table 1.2.

Table 1.2 Perceptual, cognitive, and emotional features of the human visual system and challenges of display or light source technology.

Feature	Technological challenge	
Trichromatic color vision, color matching	Accurate colorimetric characterization of color displays	Sections 2.1 and 2.2
Chromaticity contrast and visual search	Ergonomic color design of a user interface on a display	Sections 3.3.2 and 3.3.3
Spatial color vision	Ergonomic design of a color display with preferred color contrast for young and elderly users	Sections 3.3.4 and 4.4
Spatiochromatic properties of the retinal mosaic	Optimization of multicolor subpixel architectures on a color display, digital cameras, motion picture compression algorithms, and watermarking	Sections 4.4 and 5.3
Color appearance	Color gamut optimization of a modern multi-primary color display	Section 5.1
Color appearance of large color stimuli	Providing accurate color appearance on a large or immersive color display	Section 2.4
Color difference perception	Evaluation of color differences between soft-proof monitors and digital cinema	Section 4.2.3
Color appearance, color fidelity, chromatic adaptation, color preference, color harmony	Improving the color quality of the lit environment	Chapter 6
Cognitive color	Ergonomic presentation of information on a color display to enhance the user's recognition and visual search characteristics	Section 3.3.1
Long-term color memory	Enhancement of the color quality or perceived naturalness of pictorial color images	Section 3.4
Visually evoked emotions	Enhancement of the strength of the emotional effect in motion images	Section 4.6
Image color quality and preference	Enhancement of the color image quality of pictorial color images	Sections 3.5, 3.6, and 4.4.3
Circadian behavior	Optimize light source according to circadian behavior	Section 7.2.2

The corresponding sections/chapters of this book are indicated in the last column.

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