



# COLORIMETRY in textile industry

Michal Vik

# **COLORIMETRY**

# **IN TEXTILE INDUSTRY**

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# PREFACE

Color is a subject, which involves so many people with such different attitudes, and intentions that a book useful to all of them is quite difficult to write. Color is defined as the sensation experienced or caused by light reflected by or transmitted through objects. In the strict sense, we cannot directly measure perceived color, however we can measure and subsequently calculate certain factors, which are responsible for producing this sensation of color.

Color is an intrinsic form of visual attribute. Color has immediate perceptual and cognitive significance in human experience. It serves as an activating stimulus that intensifies visual consciousness and responsiveness. Since perception of color is the single strongest emotional part of the visual process, it has great force that can be utilized to express and reinforce visual information to a great advantage. A list of color topics includes the areas of philosophy, anthropology, psychology, aesthetics, chemistry, painting, photography, architecture, design, and communication. Nevertheless, color sprawls across the three enormous subjects of physics, physiology and psychology. In the past, it has been rare that any color has had the opportunity of understanding all the three phases. It is necessary to fill this gap, and in this regards book has been written. Each phase of the subject has been developed separately and it has been interwoven at the end. I hope that this approach, even though it makes some of it less interesting, will make it possible for student, engineers and others, regardless of their background, to learn the parts of the subject they do not know already.

Color is an integral component of a number of industries and is often considered to be a primary criterion in the selection of a product, thus significantly affecting sales volume. The main objective in color technology is to control and reproduce a target color on a specified material under a set of specified conditions and in the shortest possible period. In the textile industry, effective color control and communication between designer, dyer and retailer are critical. Color communication throughout the supply chain is a dynamic process. Attempts at optimizing color control must focus on the variability that arises due to the complex interaction between supplier and consumer. There are four questions in color science: how to describe color, how to measure color, how to measure color quality and how to produce correct color.

The subject of color appeals and affects everyone regardless of his or her particular attitude towards it. Unfortunately, the subject cannot be simplified without presenting it in biased, one-sided fashion. The present book attempts to treat the whole subject of color quality control without any simplified omissions. The individual concepts involved book is almost all simple and straightforward. It would be easy to decide on the topics to be included in a multivolume work covering all aspects of color. However, there might be a problem of how to limit the number of volumes. To make the same decision for a one-volume work of reasonable size presents a real challenge.

Colorimetry, the technique based on it, has become the norm in all fields of technology that deals with color in any way. The uses of colorimetry can be summed up under the following headings: color identification codes, systematic description of color phenomena, color quality control (color differences evaluation), color rendering and colorimetric color formulation.



The book has been a gradual growth over a period of years and the author would like to express his indebtedness to many people with whom he has had the opportunity of discussing different aspects of the subject. Such acknowledgement is impossible within the limitations of a preface; there are some, however, to whom the author feels particularly grateful. My thanks are due particularly to Prof. Manuel Melgosa Latorre (University of Granada, Spain) and Prof. Klaus Richter (TU and BAM Berlin, Germany).

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Liberec, CZ

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# INTRODUCTION

Color and shape are the major properties that give objects their own individual characters. Of these two, color is frequently the less important as far as recognition of the object is concerned. Color makes a unique contribution to the appearance of the object, imparting to it qualities that shape alone cannot give.

Since color is a sensation unrelated to anything else, it is essentially impossible to give a meaningful definition except indirectly and circularly; for example: Color is that aspect of perception, which distinguishes red from green, etc. A useful functional definition might be: Color is that part of perception that is carried to us from our surroundings by differences in the wavelengths of light, is perceived by the eye, and is interpreted by the brain. Again, we could say: Our brain perceives color when the eye receives a non-white distribution of light. Yet it is easy to find flaws in and exceptions to any such definition.

Communicating color has evolved from purely subjective descriptions of color by the viewer to mathematical theories used to create color matching and control functions that produce repeatable standards. The latter includes the classical equation by color measurement pioneers Kubelka and Munk as well as later theories which sought to perfect color matching through models based on tristimulus (three coordinate) or spectral (wavelength) data.

Color system suppliers have successfully translated these mathematical formulas into sophisticated systems to help textile manufacturers, colorant suppliers, and retailers standardize the basically non-standard art of coloration all the way through the supply chain: equations to deal with different substrates and dyes, instruments to handle varying materials and techniques to offset the variables of the dyeing process. Yet challenges in communicating color have remained, primarily because humans remain a necessary part of the equation. Regardless of how many numbers are assigned to a color, we don't see in numbers. We can't visualize precisely what another person means by fire engine red. Also, color is both a physical and psychological response to light. Each viewer brings a different response to the same stimulus. These differences can be due to age, fatigue, color vision defects, or experience.

The Commission International de l'Eclairage or CIE developed the most influential system for the description of color. The system is based on the using a standard source of illumination and a standard observer. The system is used to obtain CIE standard-observer curves for the visible spectrum of the tristimulus values, which are converted to the unreal primaries X, Y, and Z [1]. The CIE XYZ color space was deliberately designed so that the Y parameter was a measure of the brightness or luminance of a color. The chromaticity of a color was then specified by the two derived parameters x and y, two of the three normalized values which are functions of all three tristimulus values X, Y, and Z. The CIE chromaticity system is used primarily in the fields of color research, manufacturing, processing, and marketing. The CIE chromaticity system has the advantage of combining the effects of object color, source color, and the visual system to determine the actual perceived color under given conditions. True object color can be predetermined for a given light source color.

Color is used in many different industries, where the aesthetic value of the control of quality is of prime importance. The producer is both buyer and seller. He judges the worth and uniformity of his raw material by its color; and the product is judged in turn by its color. For example, the raw cotton, wool, silk and synthetic fibers are graded and priced according to its color.

The color of the finished product takes great importance only in a land whose business is organized on the principle that customer must be pleased. In a global competitive system such as ours, in which we usually have a wide choice, any producer can afford to overlook the fact that the act of purchasing is an emotional experience. Such fact is well described by example from food industry of trouble taken to color red of tomato products. The food value is not enhanced by addition of the red dye (obviously Cochenille red A, Acid Red 18, Ponceau 4R are names of the same chemical structure), but the consumer acceptance is to have expected color.

In the complicated network of processes that make up our economic life, we use our eyes time and again to choose among competing products. They carry out this inspection, color measurement, and selection, there have been developed various tools and technics. In the purpose of this book, first to describe basic terms and how the eye works, second to list the tools available to assist in color measurement, and third to select the best tool for a given color-measuring job, practice in colorimetry [2].

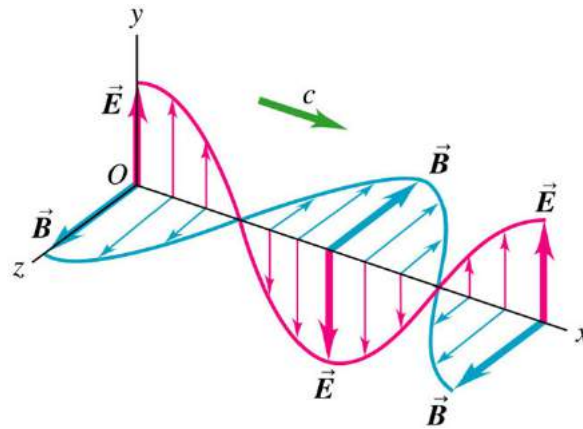
# 1 BASIC TERMS

In colorimetry are used terms from three different scientific fields such as Physics, Psychophysics and Psychosensorics. From physics, we need to understand such terms as light, spectral power distribution, etc. In point of view of psychophysics are important terms of chromaticity, color quality of light, object color. And from psychosensorial side, we will speak about color itself. All these terms are important for understanding of connections between each other's and structure of whole CIE colorimetry. Before we can define what is meant by color we need to discuss what is meant by light, because color cannot be seen in the dark.

## 1.1 Light

All electromagnetic radiation, including light, travels through a vacuum with a velocity  $c$  of  $2.997\,925 \times 10^8 \text{ m s}^{-1}$ . This value is constant for all types of radiation, and whatever its intensity [3].

Simple or monochromatic light (light of specific wavelength) we can imagine as propagation of electric and magnetic vector by mentioned speed. Both vectors are in rectangular position to each other and to the direction of motion as visible on Fig. 1.1.



**Figure 1.1** Representation of electric  $\vec{E}$  and magnetic  $\vec{H}$  vectors of light

Monochromatic light it is possible to describe by wavelength  $\lambda$ , frequency  $\nu$ , and wavenumber or by energy  $E$  [4]. Following relations connects such terms:

$$\lambda \cdot \nu = c \quad (1.1)$$

$$\tilde{\nu} = \nu / c = 1 / \lambda \quad (1.2)$$

$$E = h \cdot \nu \quad (1.3)$$

where  $c = 2.9979245 \times 10^8 \text{ m} \cdot \text{s}^{-1}$  is finite speed of light,

$h = 6.626176 \times 10^{-34} \text{ J Hz}^{-1}$  Planck's constant.

Many properties of light, particularly those relating to absorption and emission



cannot be fully explained by the wave theory and there is much commented the concept that light really exist as a series of energy packets commonly known as on photons. In modern physics are matter and energy two sides of description of the same reality [5].

Example is known Einstein equation:

$$E = mc^2 \quad (1.4)$$

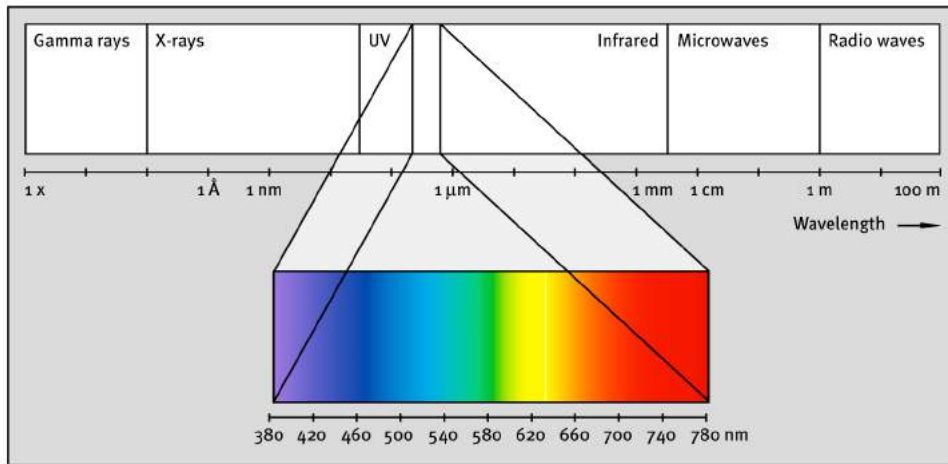
where  $m$  is photon gravity, which relates to a specific frequency.

Based on the appointing of the equation (1.4) into equation (1.3) we obtain following relation:

$$m = hv / c^2 = h / \lambda c \quad (1.5)$$

from which relates that light has higher energy, when has lower wavelength.

Similarly, in other cases, also in point of view of electromagnetic spectrum, it is impossible to define exact borders. Obviously whole range wavelength is divided in form as visible in scheme in Fig. 1.2.



**Figure 1.2** The electromagnetic spectrum

Visual part of spectrum, it is possible to divide into light of color red (720-627nm), orange (627-589nm), yellow (589-566nm), green (566-495nm), blue (495-436nm) and violet (436-380nm).

## 1.2 Blackbody radiation

The temperature of a black body radiator can be used as a means of quantifying the energy distribution of an illuminant. If a metallic object is heated, after a short time it becomes too hot to touch; this is because infrared radiation is being emitted. After more heating the object begins to glow, first a dull red followed by a bright red, yellow, white and even blue at higher temperatures. Blackbody radiation or cavity radiation refers to an object or system which absorbs all radiation incident upon it and re-radiates energy which is characteristic of this radiating system only, not dependent upon the type of radiation which is incident upon it. The radiated energy can be considered to be produced by standing wave or resonant modes of the cavity, which is radiating [4].

Classical description of blackbody radiation is based on Rayleigh-Jeans law:

$$E_v^0 = \frac{2\pi\nu^2}{c^2}kT \quad (1.6)$$

where  $k = 1,380662 \cdot 10^{-23} \text{ JK}^{-1}$  is Boltzmann constant.

Careful analysis by Rayleigh and Jeans showed that the number of modes was proportional to the frequency squared. The problem is that whole emitted energy is then infinitely high:

$$E^0 = \int_0^{\infty} E_v^0 d\nu \quad (1.7)$$

Although, the Rayleigh-Jeans law works for low frequencies, but the predicted continual increase in radiated energy with frequency (dubbed the "ultraviolet catastrophe") did not happen [6].

Max Planck who made a formula that agreed with experimental data made a major breakthrough. His idea was that the oscillating electrons of the surface atoms of the black body emitted radiation according to Maxwell's laws of electromagnetism. Before Planck it was assumed that these could have any value of energy, but Planck decided that the energy must go up in discrete amounts (quantized) because the frequencies of the oscillating electrons could only take certain values. As energy is proportional to the frequency – equation (1.3), if the frequency can only take discrete values, this means that energy is also quantized. The electrons have a fundamental frequency (like standing waves on a string) and the frequency can only go up in whole multiples of this frequency, called the quantum number. This assumption led Planck to correctly derive his formula [7]:

$$E_v^0 = \frac{2\pi\nu^2}{c^2} \frac{h\nu}{e^{h\nu/kT} - 1} \quad (1.8)$$

where  $T$  is thermodynamic temperature in kelvins (K).

It is visible, that Planck's law at low frequencies ( $h\nu \gg kT$ ) follows classical Raleigh-Jeans law. At high frequencies ( $h\nu \ll kT$ ) formula is changed in form:

$$E_v^0 = \frac{2\pi h\nu}{c^2} e^{-h\nu/kT} \quad (1.9)$$

Based on Planck's law, it is possible to derive empirical Stefan-Boltzmann law for whole emitted energy of blackbody radiator:

$$E^0 = \int_0^{\infty} E_v^0 d\nu = \sigma T^4 \quad (1.10)$$

where  $\sigma = 2\pi^5 k^4 / 15h^3 c^2 = 5.67 \times 10^{-8} \text{ W.m}^{-2}\text{K}^{-4}$

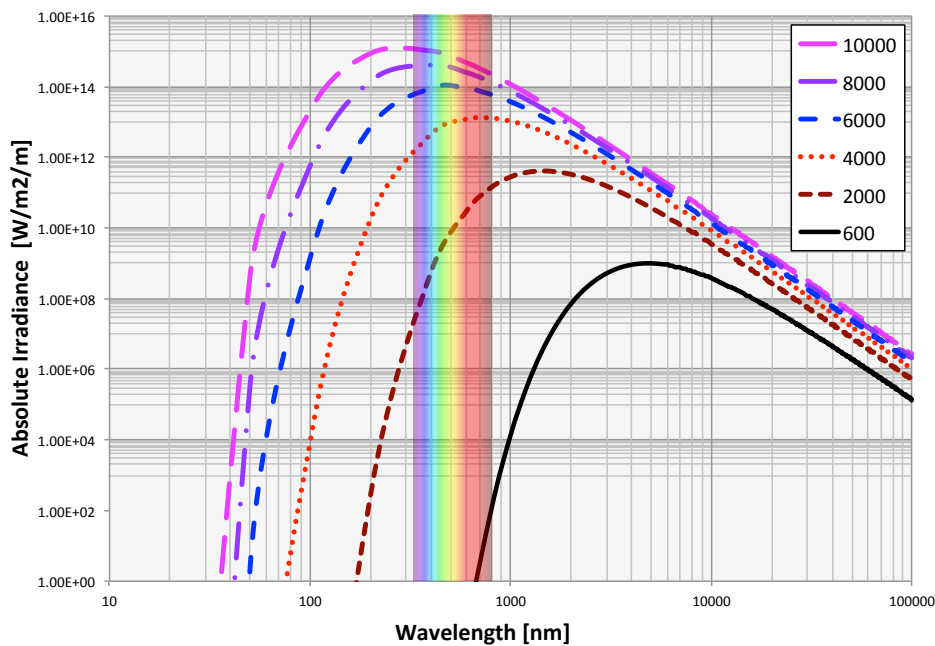
Consequently, it is possible to derive Wien's displacement law:

$$\lambda_m = \frac{b}{T} \quad (1.11)$$

where  $b = hc/4.965k = 2.896 \times 10^{-3}$  m.K and  $T$  is the absolute temperature in kelvin

This rearranged equation shows why the peak wavelength decreases as temperature increases. This decrease in wavelength explains why objects glow first red, then orange-red, then yellow, then even blue. These colors are successive decreases in wavelength.

The graph in Fig. 1.3 shows as the temperature increases, the peak wavelength emitted by the black body decreases (consequently below temperature of 600 K visible part of the spectrum is not connected and whole radiation is in the infrared part of the spectrum). This graph shows also as temperature increases, the total energy emitted increases, because the total area under the curve increases.



**Figure 1.3** Plot of absolute energy against wavelength for a black radiator over a range of temperatures

### 1.3 Color

The color is a term with a number of different meanings; due to insufficiently précised meaning and unclear interpretation will cause misunderstanding in communication. Most frequently, color is associated with a human eye perception. Color is of course related with light as its property and consequently with the objects. Color is the name we give it to visual sensations associated with the spectral content of the light entering our eyes.

When discussing about the color in general, we could be considering colored lights, colored solutions or colored surfaces such as textiles, plastics, paints. In almost all practical situations we are concerned with colored surfaces, although, as we shall see, the properties of colored lights are used in the specification of the surface colors. It is important to realize that the color of an object depends on the light source used to

illuminate its surface, the particular observer who views it and the properties of the surface itself. Obviously, the nature of the surface is most important factor. Term of color is frequently related with chromatic colors rather than achromatic such as white, grey and black [8][9][10].

It is commonly accepted that both specifications can be accurately defined in a three-dimensional space, that is, by specifying three attributes.

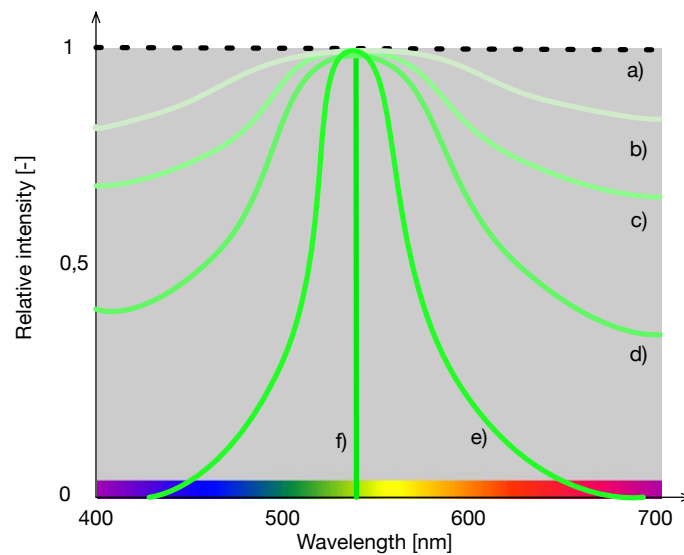
The three attributes that specify color in term of the observer are:

- Hue -  $\lambda$
- Chroma (purity) - P
- Brightness (lightness) – L

**Hue** is the name we associate with a particular color sensation, in our own language. Our parents teach us this at a very early age. The first of these attributes specifies one of the colors of the spectral sequence or one of the non-spectral colors such as purple, magenta, or pink. This attribute is variously designated in different descriptive systems as HUE, dominant wavelength  $\lambda_D$ , chromatic color, or simply but quite imprecise as color. It should be noted that these terms, do not have precisely the same meaning and therefore are not strictly interchangeable. The designation chromatic color is redundant in the strict sense, since chromatic already means colored, but it is validly used as a distinction from achromatic colors, which refers to the sequence white, gray, black. Verbal degrees of hue are *red, green, blue, yellow, purple, etc.*

**Saturation** is spectral purity degree of color, share of white addition, distance from the colorless point in the color chart, relative spectral color value. It is possible to say that saturation is the closeness of the color to a monochromatic spectral color of the same hue, or the difference from a grey of the same lightness. Other words, which are legitimately used for surface colors, are vividness and purity. This attribute gives a measure of the absence of white, gray, or black, which may also be present. Thus, the addition of white, gray, or black paint to a saturated red paint gives an unsaturated red or pink, which ultimately transforms into pure white, gray, or black as the pure additive is reached; with a beam of saturated colored light, white light may also be added but the equivalent of adding black is merely a reduction of the intensity, see Fig. 1.4. Important is that saturation is colorfulness relative to the color's lightness while chroma is colorfulness compared to white. When lightness changes, a change in saturation is perceived. Verbal degrees of saturation are *grayish, moderate, strong, and vivid.*

**Lightness/Brightness** specifies the achromatic (luminance) component, which is the amount of light emitted or reflected by the color. The term of *lightness refers to objects*, and is associated with reflected light. Verbal degrees of lightness are *very light, light, pale, medium, dark, very dark.* The term *brightness* is used in light sources, typically for photometric or physical-optical energy measure. This statement is necessary because the human eye assesses the hue of color slightly differently with varying brightness. For a color having a given hue and saturation, there can be different levels variously designated as brightness, value, lightness, or luminance (once again, these terms aren't strictly interchangeable), completing the three dimensions normally required to describe a specific color.



**Figure 1.4** Simplified representation of green colors with different spectral purity

- a) Spectral curve of ideal white
- b) – e) Decreasing of relative intensity of in other than the dominant wavelength caused increasing of green color purity from greenness tint to green color
- f) Spectral line of green color - purest color

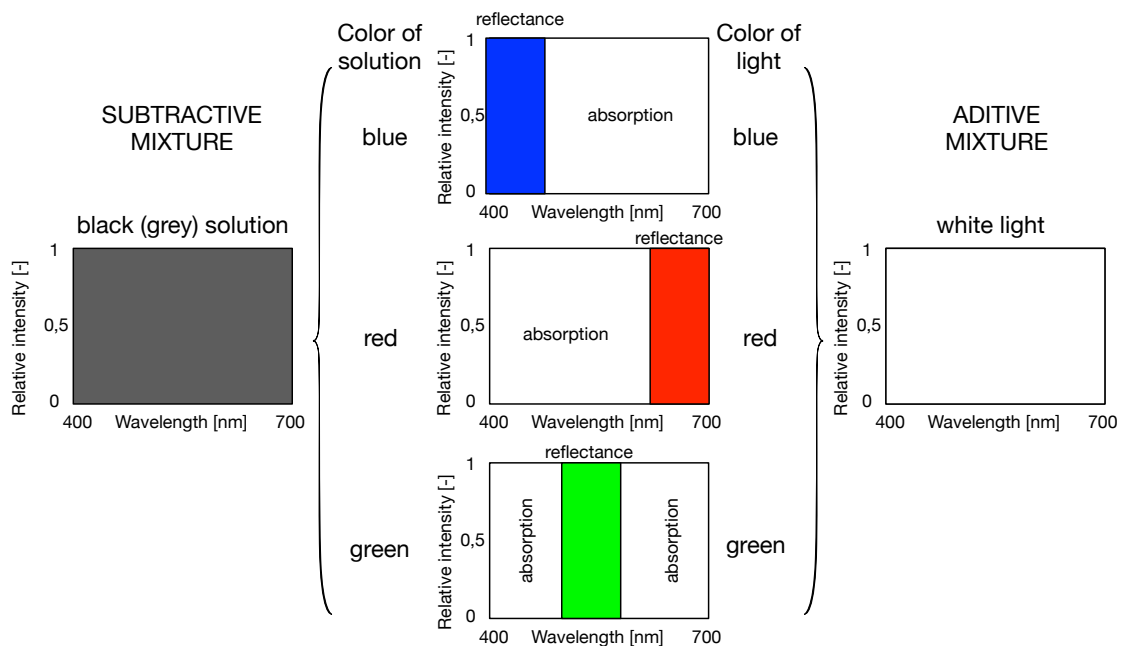
### 1.3.1 Additive and subtractive mixing

Most people's experience of color mixing is with paints. As children, we learned that the three primary colors are red, blue and yellow. Why is green absent? When using little pans of watercolor, we mixed yellow and blue and made green. However, we were not mixing color, but rather *colorants* (pigments or dyestuffs). This type of color mixture is called *subtractive colorant mixture* because the individual colorants absorb – that is, subtract – portion of the incident light in certain spectral region (see Fig. 1.5), leaving only the light from no absorbed spectral regions to be reflected or transmitted, and observed. Thus, in the case of the mixture of yellow and blue watercolors, the yellow absorbs the violet and blue regions of the visual spectrum, and the blue watercolor absorbs the orange and red regions of the spectrum. As a result, only green part of spectrum is left to be reflected. In this case we can say, that subtractive colorant mixture result is based on addition of absorption spectra [11]. Subtractive mixture is of major concern when identifying colorants.

Contrary to subtractive mixture, mixing of additive primaries (red, green and blue) produces white. Yet how can be red and blue common to both mixing, additive and subtractive? How can nearly the same colors produce either black and white? The problem is that in *additive color mixture* we are mixing light together. Thus, if we will have three surfaces reflecting red, green and blue part of visual spectrum as a result of these three lights combination is white light as visible on Fig. 1.5.

Back to our question: *How can nearly the same colors produce either black and white?* We must separate the perception of color from the production of color. We

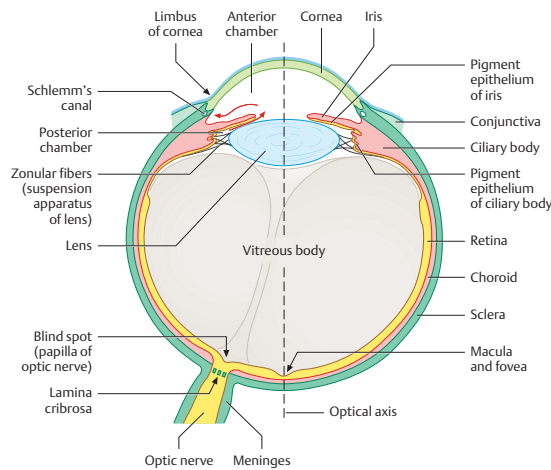
recognize that color names such as red, green, yellow and blue are vague. In fact, primaries in both mixing are not the same. The standard choice for additive primaries is red, green and blue light, as this provides the maximum *gamut* (range of colors). A mixture of two color lights is additive in term of the colors produced, but the intensity of mixture color is not the sum of separate colors, but rather the average of them. A balanced mixture of these 3 primaries produces white, when mixed in pairs; the secondary colors are cyan, magenta and yellow. It was mentioned that, the standard choice of subtractive (colorants) primaries is cyan (turquoise blue), magenta and yellow, these being the colors that absorb red, green and blue light respectively. When these are mixed in pairs the secondary colors are red, green and darkish blue/violet. The secondary additive colors are therefore the same as the subtractive primaries, and vice versa.



**Figure 1.5** The theoretical additive and subtractive primaries

## 1.4 Color sensation

The front-end interface of our visual system is the eyes see Figure 1.6. The eye consists of several components. The pupil controls the amount of light admitted to the eye (a camera's aperture is modeled after the pupil). Two lenses, the cornea, which is fixed, and a variable-focus lens, provide distance adaptation. *The retina*, located at the back of the eye, provides the first layer of "image processing" of our visual system. The quality of the retinal image depends on the absorption; scatterings, and focusing properties of the cornea, lens and fluids filling the eyeball (vitreous humor), see Fig. 1.6. These optical elements influence the spectral and spatial properties of the light receptors. The retina contains five layers of cells, in charge of several early image-processing tasks.

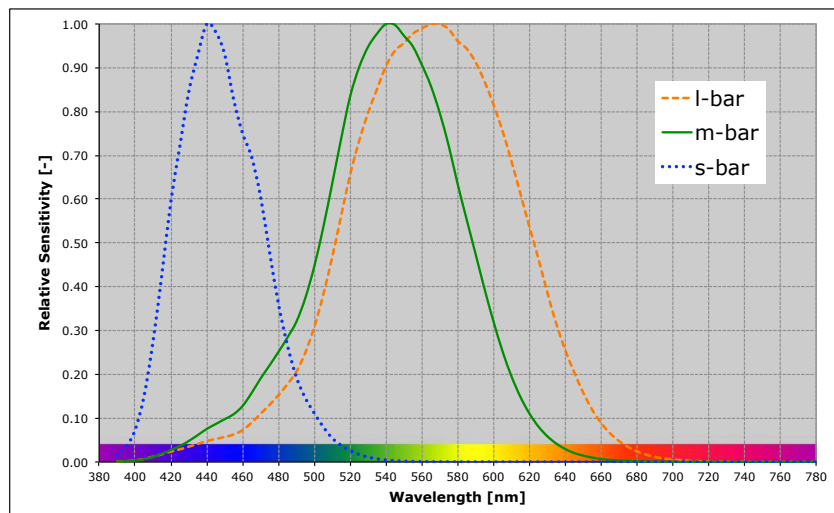


**Figure 1.6** Human eye

The first layer contains four types of photoreceptors. These are light sensitive cells, grouped to filter different light phenomena. Approximately 120 million rods, which are achromatic light sensitive cells (i.e., they only see black and white), are responsible for night and other low light level vision. Daytime color vision is provided by approximately 8 million cones of three types, which operate like filters for different ranges of wavelength (see Fig. 1.7):

- S-type cones: short wavelength, with peak sensitivity at 440 nm (violet, but often referred to, erroneously, as blue “B”)
- M-type cones: medium wavelength, with peak sensitivity at 550 nm (often referred to as green “G” but perceived as yellowish-green)
- L-type cones: long wavelength, with peak sensitivity at 570 nm (yellow, often referred to as red “R”)

Thomas Young suggested that three different types of receptors underlie the human color vision. Cones are mainly concentrated in the central vision center of the retina, in particular in the *fovea* (pit – the central one degree of vision as visible on Fig. 1.6); rods are mainly concentrated in the periphery of the retina.



**Figure 1.7** Spectral sensitivity of LMS cones

There are no photoreceptors (causing a blind spot) in the optic disk, where the optical nerve connects photoreceptors in the retina to ganglion cells in the brain, transferring image signals to the brain for further processing.

As I have already mentioned previously, it is accepted among color scientists as well as psychologists and others who have studied human color vision, that color is a tri-stimulus phenomenon, i.e., human color perception is a three-dimensional space. Color scientists often refer to this as *trichromacy*. Trichromacy starts in the retina, where the cones provide three broadband filters, tuned to three overlapping ranges of wavelength, often referred to as the blue, green, and red filters, though these are misnomers, as will be demonstrated shortly.

First, the color names do not represent the precise colors where these filters peak, respectively. The so called blue mechanism peaks at a wavelength we would call blue, but the green and red mechanisms are largely overlapping, and peak at two close wavelengths we would probably call yellow or greenish yellow.

More important, each cone filter mechanism by itself is “colorblind”. For example, the signal out of a particular cone filter would be identical whether it is the result of the component on the left of the peak of the filter, or the one on the right.

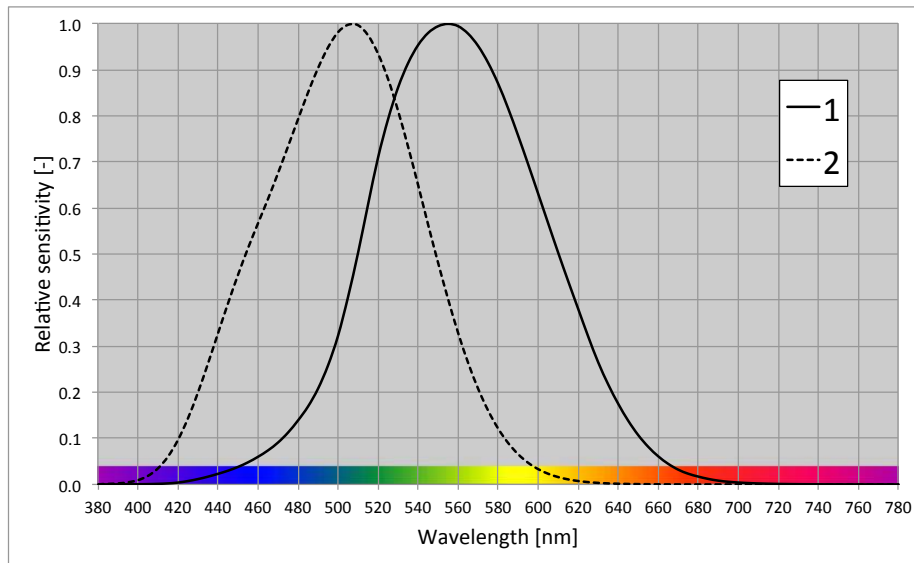
The nature of trichromacy is that the perceived hue depends on the three-dimensional vector of signals detected by three cone mechanisms in combination. Due to the many-to-one mapping from the infinite-dimensional light vector to the three-dimensional vector at the retina, the sensation of any color can be created by exposing the three cones to many different three-dimensional vectors (metamerism). This means that even with trichromacy, there are ambiguities, but with fewer cone mechanisms, color perception becomes deficient or disappears altogether (that is the problem of color deficiencies).

In summary, the visual system images the world onto the retina, which is composed of rods and cones, arranged in a mosaic. In the very low light, the rods send signals to the brain, resulting in monochrome perception and adaptation luminance intensities are in *scotopic* area. With an increase of light the cones start responding. Range of luminance levels, where rods and cones works together is called *mesopic*. When luminance level reach  $10 \text{ cd.m}^{-2}$  rods are overexposed and works only cones. Luminance levels starting from  $10 \text{ cd.m}^{-2}$  till  $10^8 \text{ cd.m}^{-2}$  we understand as *photopic* levels. The standard luminosity function is normalized to a peak value of unity at 555 nm. The value of the constant in front of the integral is usually rounded off to 683 lm/W. For very low levels of intensity (*scotopic* vision), rods, not cones, and shifts toward the violet, peaking around 507 nm for young eyes, mediate the sensitivity of the eye; the sensitivity is equivalent to 1700 lm/W at this peak (see Fig. 1.8).

The International Commission on Illumination (CIE) formally adopted these curves as standards in 1924 (photopic) and 1951 (scotopic), respectively. Tabulated values can be found in Appendix A1.

The relation between the maximum of scotopic and photopic sensitivity is called as the Purkinje effect. This effect (sometimes called the Purkinje shift, or dark adaptation and named after the Czech anatomist Jan Evangelista Purkyně) is the tendency for the peak luminance sensitivity of the human eye to shift toward the blue end of the color spectrum at low illumination levels.





**Figure 1.8** Human eye luminous sensitivity:  
 1 – photopic curve (spectral luminous efficiency function  $V_{\lambda}$ ),  
 2 – scotopic curve (standard scotopic luminosity function  $V'_{\lambda}$ )

Color deficiency is defined in terms of color discrimination tasks. A color-deficient person will perceive certain colors as being identical, which a color-normal person will be able to distinguish as different. With decreased red-green sensitivity (the most common), colors that are primarily defined by their red or green components, such as rose, beige, and moss green, may appear identical, since the color-deficient observer is less sensitive to the red and green that distinguish to them. And many color deficient people aren't even aware of their deficiency.

Approximately 8% of the male population (less for non-Caucasians than for Caucasians), and slightly less than 1% of the female population suffer from some genetic color deficiency. The most common deficiency (5% of males, 0.5% of females) is *deuteranomaly*. Deuteranomaly is an anomalous trichromacy, caused by an abnormal M-type cone, resulting in abnormal matches and poor discrimination between colors in the medium (M) and long (L) range of wavelengths. The typical result of deuteranomaly is what is referred to as a red-green deficiency: the inability, or at least a great difficulty, to discriminate reds and greens. The abnormal M-type cone has its peak sensitivity much closer to the peak of the L-type cone, thus the two overlap more than in normal population, causing significantly reduced discrimination [13].

A similar deficiency can be caused by an abnormal L-type cone. In this case, the peak of the L-type cone is shifted closer to the M-type cone, causing again reduced red-green discrimination.

A more severe case that causes red-green deficiency is *deuteranopia* (deutan defect), or a complete lack of the M-type cone. Similar deficiency can be caused by a complete lack of the L-type cone and we called it as *protanopia* (protan defect).

These, as well as other deficiencies, which are caused by a missing or an abnormal cone type S are much less common. Such defects are called as *tritanopia* (tritan defect) or *tritanomaly*.

However, color naming may not be impaired in color-deficient observers since it depends on learning. Also, luminance, and other cues can contribute to the ability of color-deficient observer to call colors by their correct names (for example, red is dark, yellow is bright). It is well known that red-green deficient drivers use the physical position of the red light at the top and the green light at the bottom of traffic lights to distinguish them. The (rare) practice of placing traffic lights horizontally removes this additional physical clue (for example, in Japan are traffic lights placed horizontally and nevertheless green is replaced by blue signal light).

Beside such congenital color deficiencies, which have been found in people without previous history, we can meet with acquired color blindness. A defect in color perception in the center or the periphery of the visual field may occur in any disease affecting the retina, the optic nerve, or the optic cortex in the occipital lobe of the brain. The most common disease of the central nervous system that causes central color defects is multiple sclerosis. The most common occurrences of a defect of color perception in the center of retina are connection with toxic amblyopia, and the poisons that commonly depress the color sensitivity such as carbon disulfide, lead and thallium poisoning, narcotics, tobacco and alcohol.

The clinical assessment of color vision is not difficult and it may be worth giving thought to why it isn't always done in routine clinical practice. There are a number of possible reasons. The first is that there is no single test of color vision that provides the clinician with all the information needed to advise tested persons. Many practitioners use only the *Ishihara test*<sup>1</sup> to assess color vision. That is insufficient for industry in many reasons, while the Ishihara test is very good at detecting red-green abnormal color vision, it provides no useful information about its severity, a classification into protan/deutan is not always possible and it does not include a test for the tritan color vision deficiencies.

The Ishihara test has to be included in the basic battery of tests for the assessment of color vision in clinical practice because it is widely accepted, readily available and not unduly expensive. It is a splendid test for the detection of red-green color vision deficiency: it has high sensitivity and specificity and can perform acceptably even when it is given under the wrong illumination (test is designed for daylight). Its only problem is that it is so readily available that those who wish to pass, so they can pass the color vision standard for an occupation, can obtain a copy and learn the correct answers. Generally, we put the Ishihara test, which is famous, into pseudo-isochromatic plates. These plates were designed based on the results of the color matching experiment and can be used to identify different types of dichromats based on a few simple judgments.

Each plate consists of a colored test pattern drawn against a colored background. The test and background are both made up of circles of random sizes; the test and

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<sup>1</sup> *The Ishihara test was designed by Shinobu Ishihara (1879–1963) who was a surgeon in the Japanese army before specializing in ophthalmology. He took an appointment at Tokyo University in 1908 but remained an instructor at the Army Medical College. Studying in Germany from 1912 to 1915 may have helped his insights into color vision. On his return he resumed his work with the Army Medical College before becoming Professor of Ophthalmology at Tokyo University in 1922. Some of his research was on the selection of soldiers and he was asked to devise a test to screen military recruits for color vision deficiency.*

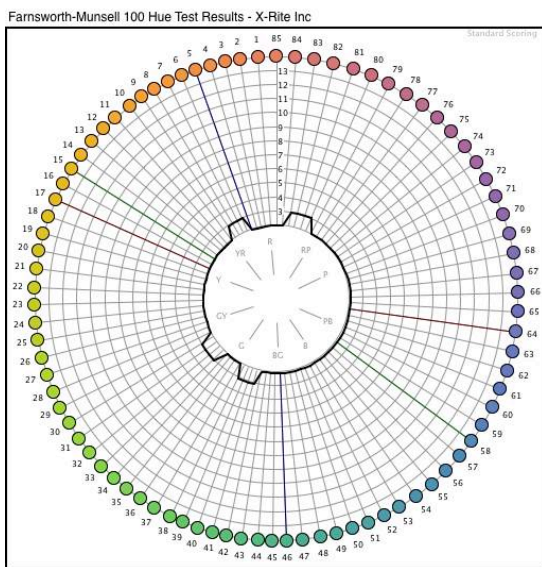
background are distinguished only by their colors. The color difference on each plate is invisible to one of the three classes of dichromats. Hence, when a subject fails to see the test pattern, we conclude that the subject is missing which is cone class.

The *Farnsworth-Munsell 100 Hue test* is also commonly used to test for dichromacy. In this test, which is much more challenging than the Ishihara plates, the observer is presented with a collection of cylindrical objects, roughly the size of bottle caps and often called *caps*. The colors of the caps can be organized into a hue circle, from red, to orange, yellow, green, blue-green, blue, purple and back to red. Despite the name of the test, there are a total of 85 caps, each numbered according to its position around the hue circle. The color of the caps differs by roughly equal perceptual steps.

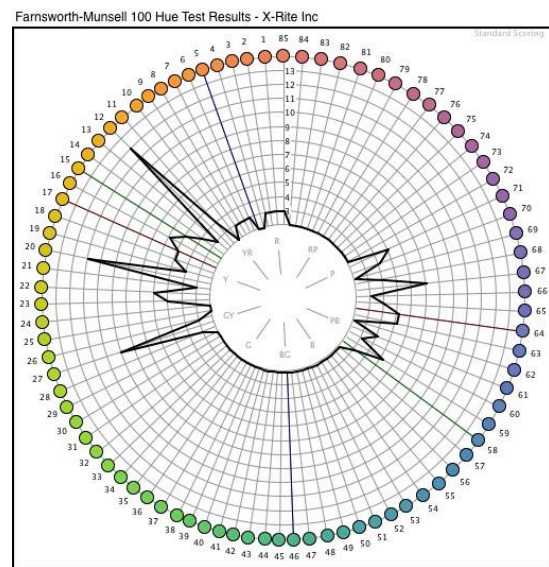
The observer's task is to take a random arrangement of the caps and to place them in order around the color circle. At the beginning of the task, four of the caps (1,23,43, and 64) are used to establish anchor points for the color circle. The subject is asked to arrange the remaining color caps to form a continuous series of colors.

The hue steps separating the colors of the caps are fairly small; subjects with normal color vision often make mistakes. After the subject finishes sorting the caps, the experimenter computes an error for each of the 85 positions along the hue circle. The error is equal to the sum of the differences between the number on the cap and its neighbors. For example, in a correctly ordered series the caps are ordered continuously, say 1-2-3. In that case, the difference between the cap in the middle and the one on the left is -1, and the one on the right is +1. The error score is 0 in this case. If the caps are ordered 1-3-2, the two differences are +2 and +1 and the error is 3. Normal observers do not produce an error greater than 2 or 3 at any location.

The subject's error scores are plotted at 85 positions on a circular chart as in Figure 1.9. An error score of zero plots at the innermost circle and increasing error scores plot further away from the center. Subjects missing the L cones (protanopy), M cones (deutanopy), and S cones (tritanopy) show characteristically different error patterns that cluster along different portions of the hue circle, see Fig. 1.10.



**Figure 1.9** FM 100 Hue test – color superior discrimination



**Figure 1.10** FM 100 Hue test – protan color deficiency

## 2 VISUAL EVALUATION OF COLORS

Visual evaluation of color is focused on two directions. First is color naming, color ordering respectively. Second one is focused on color difference evaluation, where is batch compared to target of specific products. Since color is a sensation in the mind of an individual observer, it follows that the most straightforward method of assessing the quality of one color versus another is simply to look at it. While one cannot ignore the validity of color measurement instruments, one must also be reminded that instruments do not measure the color but factors, which directly relating to the color. In cases where visual and instrumental results are in disagreement, the visual assessment is the final arbiter of acceptability of a sample.

### 2.1 Color order systems

A variety of color scales or schemes are used to describe the color. Color spaces and solids are always expressed in terms of differences of any kind between color perceptions. There are various kinds of differences that have been proposed for color spaces. A kind of color space of particular interest is one in which distances in the solid in all directions are proportional to the magnitude of perceived differences between the related color experiences. Those most often used in the industry include temporal targets, standard scales, the Munsell color solid, NCS and Pantone system.

Some typical applications for the color order systems include:

- A means of specifying color without the use of instrument. For example, a manufacturer might specify the color of fabric to his supplier or vendor using color order system coding terms (alphanumeric combination obviously). If the supplier or vendor has a chip with these particular color order system specifications, he can attempt to match with his fabric.
- Samples that are too small to be measured on an instrument can be visually compared to nearest sample of used color order system, which is large enough to be measured and specified instrumentally<sup>2</sup>.
- Designers, project managers, and sales personnel can use the color order system when working with customers. When using this system for color matching and control, the user should bear in mind that it is still necessary to visually judge when his product color is a match to the specified sample of color order system. This function involves a subjective decision on the part of both the buyer and the seller and can often result in a dispute if their visual sensitivities differ. Since metamerism can frequently be involved, due to the fact that the product being produced may contain different colorants than those used to produce the sample of color order system, it is necessary

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<sup>2</sup> *Worldwide used color systems are also available in form of appropriate guaranteed dataset that means it is not necessary to measure it directly on own version of color order system.*

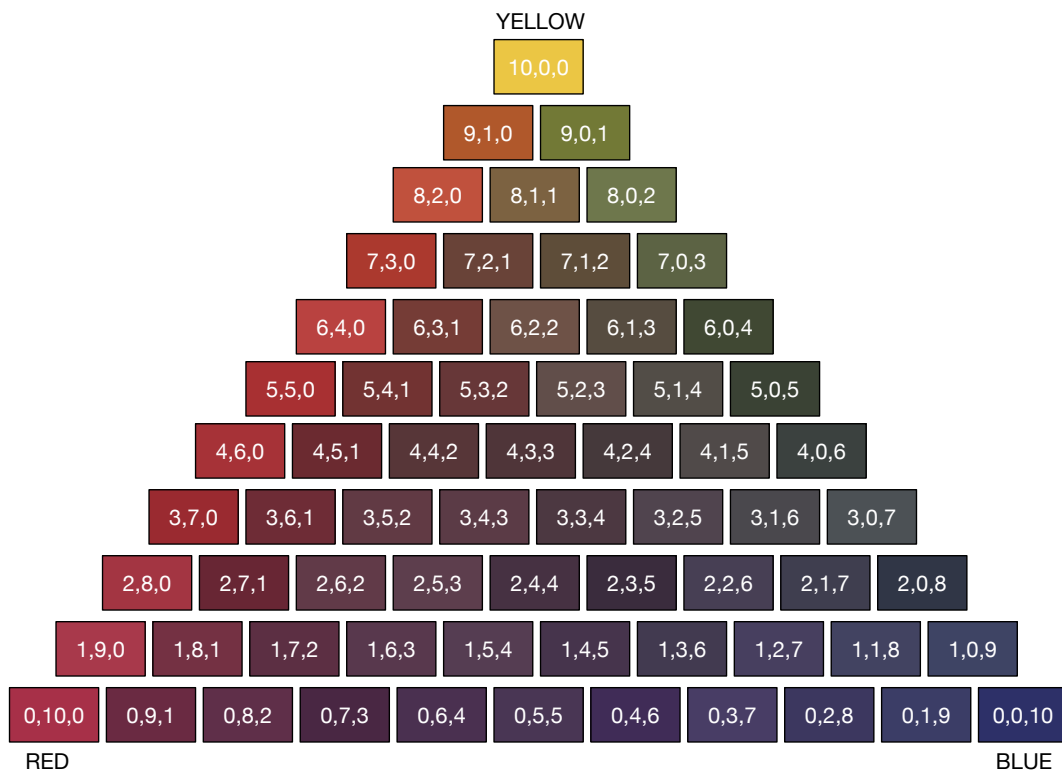
to judge the match under several light sources. Because of this fact, it is highly desirable that both buyer and seller use the same type of color matching lamp, viewing cabinets respectively<sup>3</sup>.

**Temporal target** is obviously textile fabric sample given by the customer. Present day such targets are gradually replaced by soft samples (controlled image of original sample) eventually by a set of tristimulus or reflectance data.

**Standard scale.** The simplest kind of scale applicable to the universe of color experiences is the ordinal scale. It describes the order of entities that form the scale. As ordinal scales are used sets of dyestuff's concentrations.

**Color order system** is a systematic and rational method of arranging all possible colors or subsets by means of material samples. Once the colors are arranged systematically they are named in some descriptive terms and/or are numbered.

- *Colorants (color) triangle*
- *Munsell Book of Color*
- *Natural Color System (NCS)*
- *Pantone*



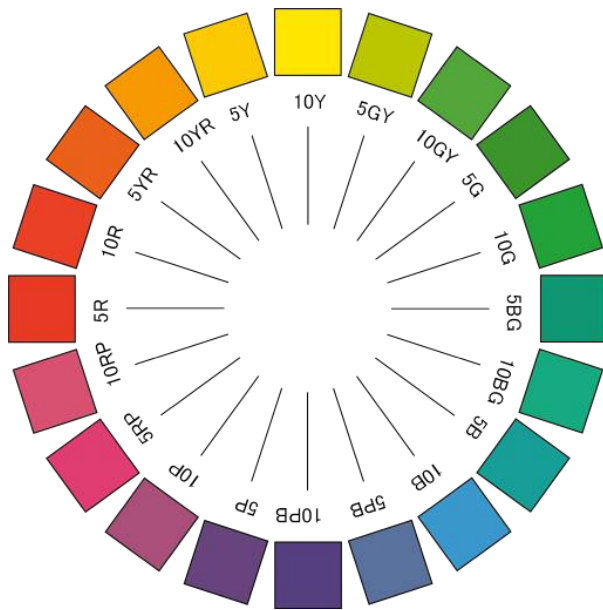
**Figure 2.1** Colorants triangle

<sup>3</sup> Due to ageing effect of lamp sources used in viewing cabinet it is important to check its spectral power distribution. For this task are on the market for disposal portable spectroradiometer or light source matching strips – typically for D65 and D50 such as PANTONE Lighting Indicator Stickers.

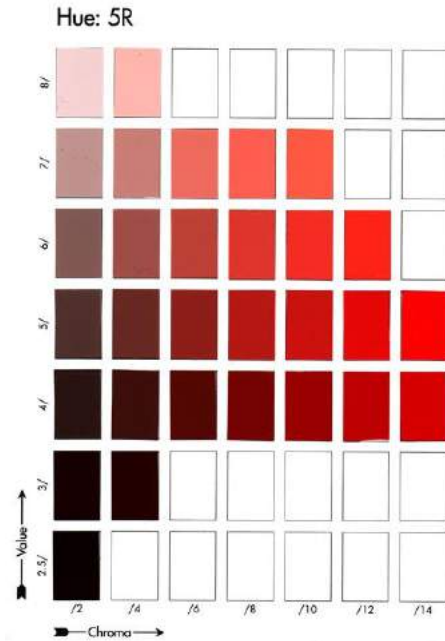
**Colorants triangle** it is a triangular classification of color patterns, in which the standard dyeing of selected dyes occupies the corner points of a color triangle. In the color triangle illustrated (trichromatic dyeing) these are e.g.: yellow, red, blue (Fig.2.1). The numerical values relate to the percentage applied for each dye in the combinations and each color pattern consists of the 3 values, which is % yellow dyestuff + % red dyestuff + % blue dyestuff. In the example of all dyeing's are set up with total of 1% dyestuff. The proportion of relevant dyestuff decreases as the distance from the corner point in question increases, which greatly simplifies the patterning.

**The Munsell Book of Color** is widely used in industry and while its use does not upon the use of instruments, many companies use it in conjunction with their instrumental color-matching program [14]. Because color is essentially a perception, the best way to characterize or measure it is through a psychophysical experiment. The Munsell color-order system is a way of specifying colors and showing the relationships among colors. Every color has three qualities or attributes: hue, value, and chroma. Munsell established numeric scales with visually uniform steps for each of these attributes. The Munsell Book of Color (MBC) displays a collection of colored chips arranged according to these scales. Each chip is identified numerically using these scales. Comparing it to the chips, under proper illumination and viewing conditions, can identify the color of any surface. The color is then identified by its hue, value, and chroma. These attributes are given the symbols H, V, and C and are written in a form H V/C, which is called the Munsell notation. The spacing between the samples is visually equal.

- **Hue:** Describes general areas of color such as Red, Yellow, Green, Blue, Purple, etc. The five basic hues in the Munsell system are arranged around a circular axis from red (R), through yellow (Y), green (G) and blue (B), to purple (P). With hues on the middle between each basic hue we obtain 10 hues, which were published firstly in 1915. They are designated R, YR, Y, GY, G, BG, B, PB, P and RP. Each of the ten hues has ten subdivisions for a total of 100 hues. For example, the series of hues around yellow are designated ... 8YR, 9YR, 10YR, 1Y, 2Y, 3Y, ... 8Y, 9Y, 10Y, 1GY, 2GY, ... and so on. However, each of these ten steps may also be broken into further ten sub-steps, so that 100 hues are obtained with integer values (though Munsell originally sampled only 20 hues, later 40), see Fig. 2.2.
- **Value:** That dimension of color space from white through grey to black, expressed in term of a 0 to 10 units' scale. The Value of 10 is defined as an ideal white (100% reflectance). The value of 0 is defined as an ideal black having 0% reflectance.
- **Chroma:** The quality of color relating to the distance from the neutral point of color space (grey scale as visible on Fig. 2.3). Differences in Chroma can be visualized as the change in color that would occur when a colorant (dye or pigment) such as green is added in increasing quantities to a container of grey colorant having the same value as the colorant. As the amount of green colorant is increased, the intensity of the green or its Chroma would increase. The Chroma scale starts at 0 at the neutral point and increases, as the color becomes more saturated or higher in Purity. The highest Chroma now used in the Munsell system, is 16 (Glossy collection, 14 Matte collection).



**Figure 2.2** Munsell Hue circle



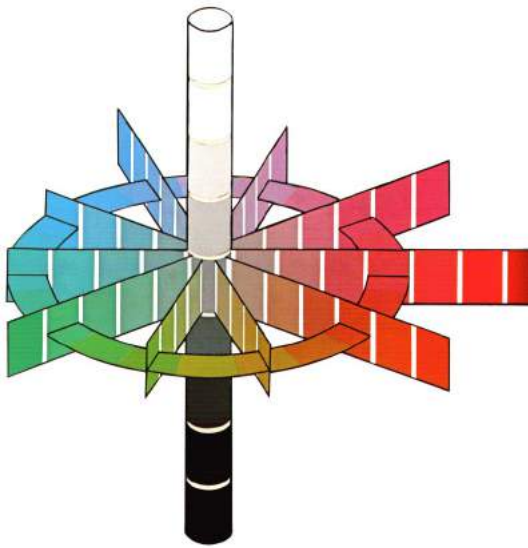
**Figure 2.3** Munsell Hue sheet

All colors lie within a specific region of Munsell color space (see Fig. 2.4) called the Munsell color solid (Fig. 2.5). Prior to 1943, the Munsell system was defined by the physical samples composing the 1929 MBC color chips and thus the basic specification of the Munsell system was the spectral reflectance function of each color chip. The Colorimetry Committee of the Optical Society of America intensively studied the spacing of the chips and in 1943 the CIE tristimulus values of ideally spaced chips were published as the Munsell Renotations [15].

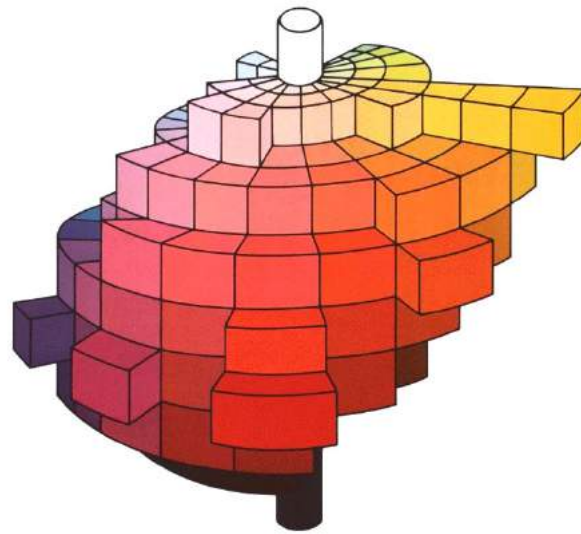
The Munsell atlas is usually available on painted paper in glossy (1488 chips) and matt forms (1277 chips). As subsidiary of these two collections was in 1990 published the Munsell Nearly Neutrals Collection, with 1100 samples [16]. The colored paint chips in the book are prepared to high tolerances and are available in a glossy or matte finish. The chips are selected and arranged in such a way that the perceived color difference between any pair of neighboring samples along the radial chroma axis is always the same independent of the hue or value. This is also true of neighboring samples that lie along the vertical value scale, or around the circular hue axis. Unfortunately, samples differing by one value step have about the same degree of color difference as neighboring samples differing by two chroma steps, or three hue steps (at chroma = 5). In addition, the color notation in the Munsell system is not limited by the samples in the Munsell Book of Color. Thus, each area of application can add more samples, and necessarily, additions must be very closely related with the samples to be evaluated. These characteristics have contributed to the wide applications of the Munsell system. Nevertheless, the Munsell system represents a well-organized, three-dimensional color space. Each standard in this book is associated with an alphanumeric notation as follows:

$$\left. \begin{array}{c} \text{HUE} \\ 3\text{Y} \end{array} \right\} \left. \begin{array}{c} \text{VALUE} \\ 4 \end{array} \right\} \left. \begin{array}{c} \text{CHROMA} \\ 10 \end{array} \right\}$$





**Figure 2.4** Munsell color space

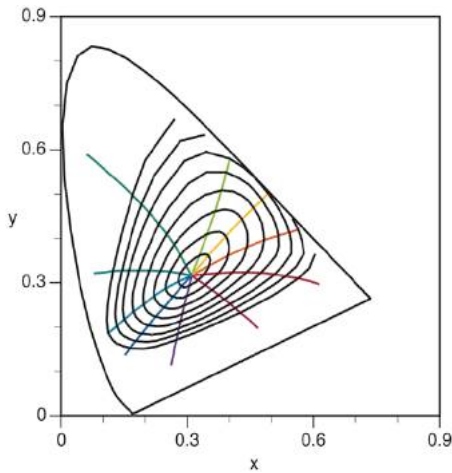


**Figure 2.5** Munsell color body

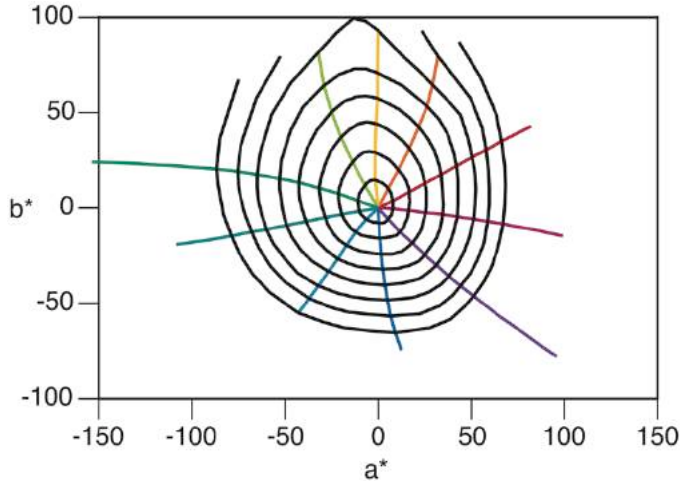
Its major disadvantage is that the color differences between adjacent pairs of samples are quite large, greatly exceeding typical commercial color tolerances [17].

Measurements of the CIE tristimulus values of the colors of Munsell samples have been carried out and recommendations made to ensure the equality of the color differences between neighboring chips in any given direction, despite of the differences in the visual steps of the hue, value and chroma directions. These improvements are called the Munsell Renotations, as was mentioned before. They are important because they directly relate visual color differences to colorimetric measurements. Via CIE tristimulus values it is possible to demonstrate a major problem with the CIE XYZ colorimetric system is its non-uniformity in terms of visual assessment. This means simply that equal differences in perceived color between pairs of samples do not correspond to equal differences in the tristimulus values. The ideal color space is one for which identical spacing between the points corresponding to the coordinates of similar colors would always correspond exactly to the same observed color differences, independent of the actual colors of the samples. The CIELAB color space is much more uniform in terms of numerical versus visual color differences than the XYZ system. When the coordinates of a number of Munsell colors of constant hue and value, but varying chroma, are plotted on the CIE  $x$ - $y$  chromaticity diagram, a series of smooth curves is obtained. If the XYZ color space were visually uniform, this series of Munsell colors of increasing chroma or purity would give a series of straight lines with equally spaced points which is not the case in the left-hand Fig. 2.6. Similar  $x$ - $y$  plots for Munsell colors of constant value and chroma, but varying hue, do not give circles, as would be required for a uniform XYZ color space, but deformed ellipses. Along any axis of the Munsell system, the samples have constant differences of hue, chroma or value. Similar plots of the  $L^*$ ,  $a^*$  and  $b^*$  values of Munsell samples demonstrate the improved uniformity of the CIELAB color space (Fig. 2.7).





**Figure 2.6** CIE chromaticity diagram showing Munsell paint chips of constant Value 5/

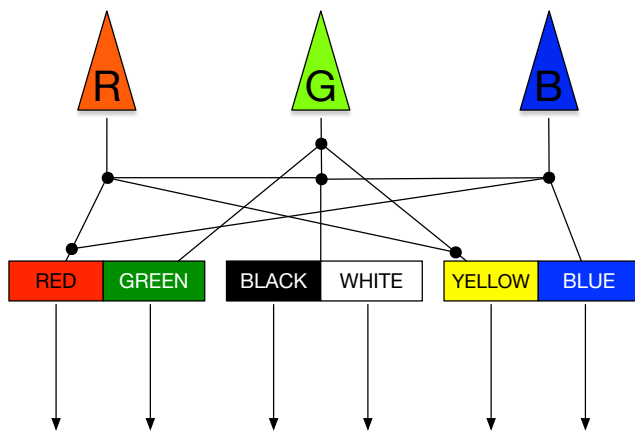


**Figure 2.7** CIELAB a\*b\* plane showing Munsell paint chips of constant Value 5/

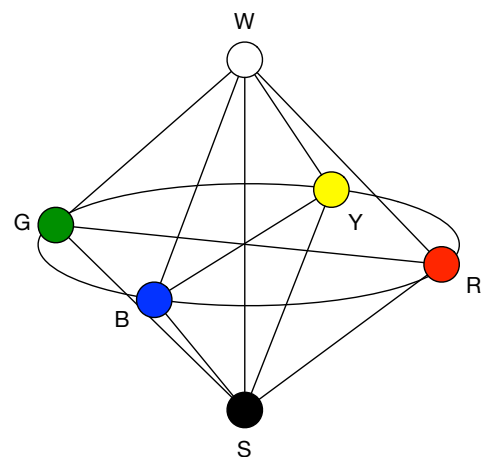
**NCS.** The acronym NCS corresponds to the initials of the English expression “Natural Color System”. This system is based on Ewald Hering’s ideas, more specifically, on his opponent-processes theory; see Fig. 2.8 [18]. According to this theory, any visual stimuli can be described in terms of its similarity to the six basic sensations: black, white, red, yellow, green, and blue. The two first sensations are achromatic, and the rest of them, chromatic (Fig. 2.9).

The nomenclature used in the NCS assumes that any visual stimulus can be partly described by three parameters, the values, which must add up to 100. The first parameter indicates tile similarity with perfect black (blackness level). The second one indicates similarity with perfect white (whiteness level). The third parameter indicates the stimulus chromatism (chroma). The second parameter value is usually not provided because, if the others are known, it can be deduced using the following equation:

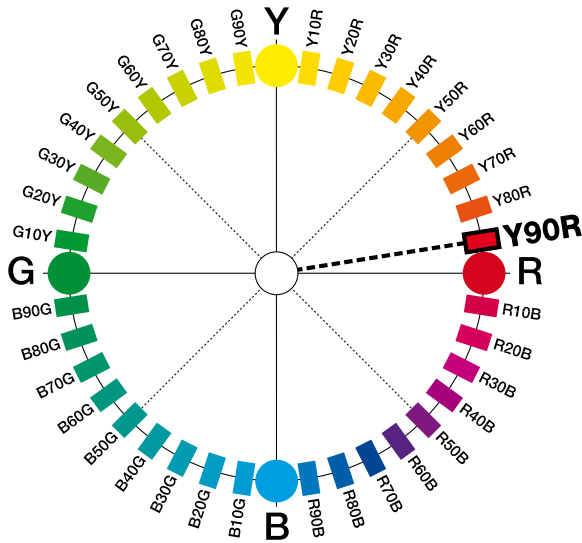
$$\text{Whiteness} = 100 - (\text{blackness} + \text{chroma})$$



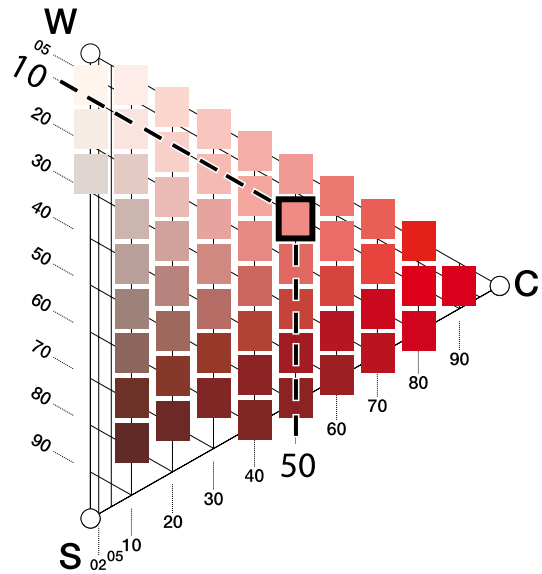
**Figure 2.8** Hering’s theory of color vision



**Figure 2.9** NCS color body



**Figure 2.10** NCS Hue circle - Y90R Hue card is marked



**Figure 2.11** Y90R Hue card of NCS with marked sample 1050

NCS assumes that any hue can be described in terms of its similarity to the four basic chromatic sensations (red, green, blue, and yellow), and postulates the existence of four hue scales: the Y-R scale (from yellow to red), the R-B scale (from red to blue), the B-G scale (from blue to green), and the G-Y scale (from green to yellow). One, and only one, of these scales must be used, in combination with a value ranging from zero to one hundred, to specify the hue of a specific stimulus. The lower the number, the higher the similarity between the hue of the color and the one indicated by the capital letter to the left of the denomination (for example, B10G, corresponds to a slightly greenish blue), whereas high values mean the opposite (for example, B90G corresponds to a slightly bluish green). The NCS color notation appears as follows:

### S 1050–Y90R

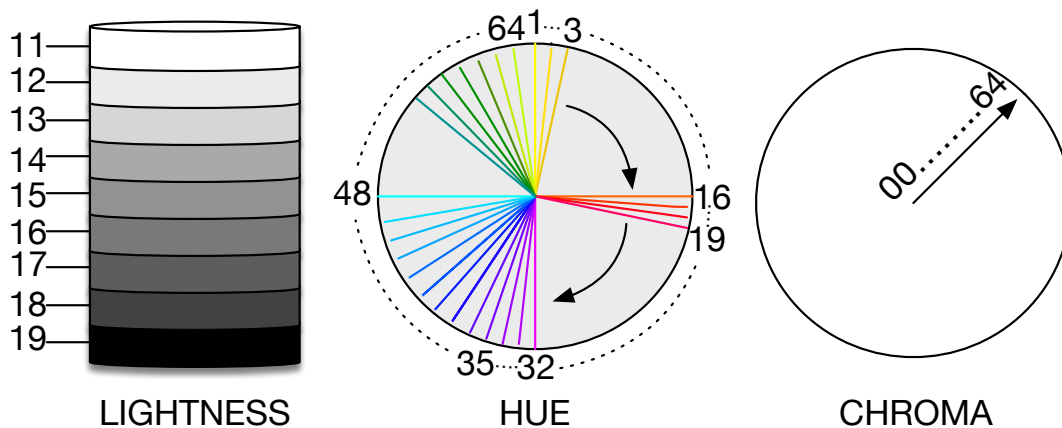
NCS Notation S 1050–Y90R describes a color that is included in the standard collection (S) and lies in between the yellow (Y) and red (R) color span with:

- 90% perceived red (the remaining 10% going towards yellow)
- 10% perceived Blackness
- 50% perceived Chromaticness

This means the color looks like week pale cyan.

Since the second edition of the Natural Color System (NCS) atlas had recently become available in 1990 and is widely used by designers in some European countries, it is important to understand some of the disadvantages of this system such as that color proportional expression results in color saturation costs and NCS color circle corresponds partially to theory of color vision, not to subtractive mixture of color paints.

**The Pantone color system** is basically a color mixture system. The Pantone system began life in 1963 in the USA for defining colors for printers with 504 colors, but expanded into other fields later, e.g. textiles in 1984, plastics in 1993, and architecture and interiors (1925 colors) in 2002, each of which has a six-digit numerical notation (e.g. # 19-1764) and an ‘inspirational’ color name. This is widely used in graphic art and also in the textile and fashion industry, mainly because of its low cost, though the colors are not equally spaced and the shades are prepared on paper using printing inks. It is not a color order system since it does not include a continuous scale. It is more appropriately considered a color naming system. The Pantone system is loosely based on a three-dimensional scale using a six-digit reference number, two each of which indicate lightness, hue and chroma successively (Fig. 2.12), but CIE specifications are not available. Recently, the PANTONE Fashion, Home + Interiors Color System features up to 2 310 shades, has been introduced in the market.



**Figure 2.12** PANTONE FASHION + HOME coding system

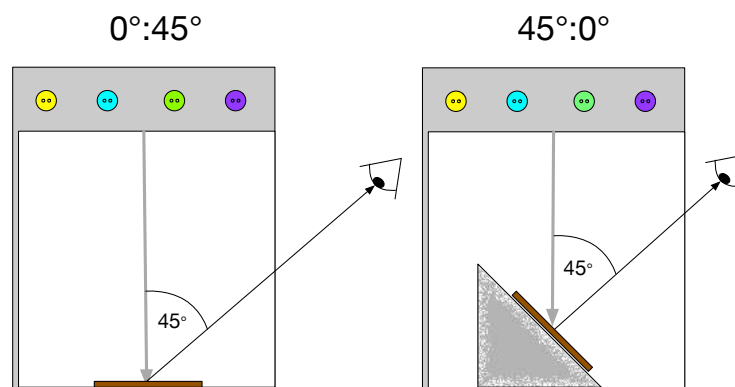
The greatest advantage of the PANTONE system is its ubiquity – it is without doubt the best-known set of color collection across a wide range of applications. As disadvantage, we can understand frequent actualization and huge number of different versions.

## 2.2 Visual color measurements

When an observer looks at two pieces of fabric for visual comparison, the observer’s eyes and brain work together to produce the assessment of appearance. There are many factors, both physical and psychophysical, which affect an observer’s visual perception of the optical properties of textile fabric. Several of these factors will be discussed, as follows:

- *Illumination* – the amount and spectral power distribution of the light, which illuminates the samples being viewed has a direct bearing on the color, which is observed. Obvious conditions are written in a number of standards: Illuminance in interval of 900-1700 lx and CIE D65 daylight simulator. Important is to **turn off the overhead lights**. A frequent mistake is done in laboratories, if assessment is arranged under a light mixture of cabinet and overhead light sources.

- *Observer* – there are two most important factors connected with the observer. Color deficiencies, which should be eliminated from the evaluation process, because in industrial applications only color normal vision observers are accepted. Second factor is age of observer. Due to aging process, the human lens actually yellows which causes a filtering out of blue light. As a result, older persons and younger persons will view color quite differently. Both factors we can measure by color vision tests such as the Farnsworth-Munsell 100 Hue test, Cambridge test and others [19 - 23].
- *Surround conditions* – The appearance of some colors will depend upon the lightness and color of the surrounding area. For example, the same piece of grey fabric will appear lighter if a black mask in comparison to white surrounding surrounds it. Similarly, a sample, which is surrounded by a colored mask, will appear to take on a complimentary shade. Based on that, a grey sample, which is surrounded by a blue mask, will appear to take on a yellow shade and vice versa, if a yellow mask surrounds the grey color, it will appear to take on a blue shade. Because of these effects, it is recommended that background for visual color assessment should be a neutral pale grey, typically N7 from Munsell book of colors. The only specimens that are in the viewing cabinet should be those undergoing visual measurements. Having the cabinet littered with specimens can cause the spectral properties of lighting to change appreciably.
- *Proximity and Size of Samples* – When two samples of nearly the same color are being viewed, it is recommended that the samples be cut to approximately the same size and that they be placed side by side with no space between them. Differences in size or spacing between the samples can adversely affect visual determinations. Based on that, it is recommended in case, when it is impossible to have equal size or spacing of samples to use covering mask allowing to prepare a visual assessment of color surfaces near to aperture colors (color lights).
- *Observation angle* – The specimens should be placed on the floor of the viewing cabinet so that the illumination is centered perpendicular to the plane of the specimens. The observer is about 10 to 30 centimeters from the opening of the viewing cabinet and at a height such that the observation angle is  $45^\circ$  from the normal to the specimen as visible on the left part of Fig. 2.13. Opposite conditions are shown on the right part of Fig. 2.13.



**Figure 2.13** Visual evaluation using viewing box

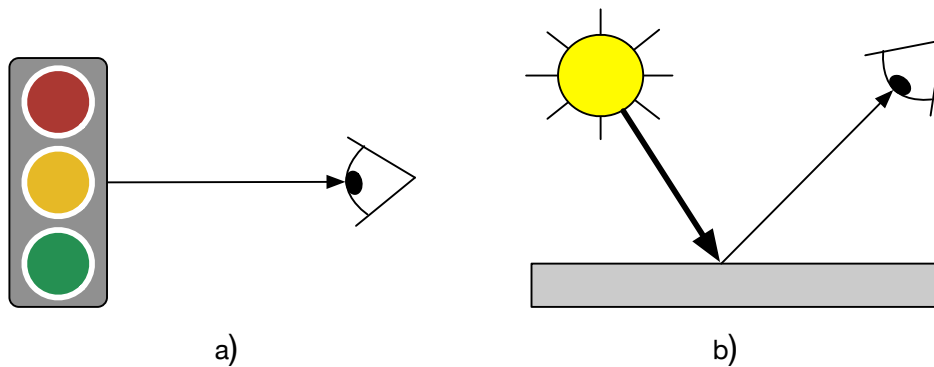
- *Time of observation* – If an observer stares at sample of colored material for 30 to 60 seconds, *retinal fatigue* occurs which, in effect, desensitizes the eye's ability to perceive that color. If the eye is then allowed to view something else, retinal fatigue will diminish and the eye will return to its normal sensitivity for all colors. Because of this effect, the recommended procedure for assessing a visual color match between 2 samples is to view the sample pair for only a few seconds at a time rather than staring at the samples for extended periods.

When the control of appearance properties is left to subjective human judgment, problems likely arise. In addition to the physical factors, which affect visual assessment, there are often psychological factors, which also have an important influence. For example, some people prefer, as a matter of taste, certain shades such as pink. If a sheet of paper, which is supposed to be white, has pinkish tint, the person who likes pink would not be offended, however, the customer who ordered white paper and got pink paper might have a vastly different opinion. Similarly, visual assessment tends to vary greatly from day to day. Based on that, a quality worker might happily accept a product, which is lightly out of tolerance on a Monday morning when he or she is in a good mood, however, on Friday afternoon when the worker is tired and irritated, the same product would probably be rejected. Based on that it is possible to be summarized: people have physical differences that make them see things differently. A psychology of individuals changes from time to time causing them to view the same thing differently.

There is, therefore, a definite need for instrumentation, which will make consistent objective judgments day in day out, year in and year out without human physical or psychological influences.

### 3 CIE COLORIMETRY

Since the beginning of twenty century, several organizations have been working hard to define and propose the adoption of standard light sources, to be used in color measurement. At the 1900 meeting of the International Gas Congress several participants agreed that one of the main problems facing the industry was the photometry of incandescent gas mantles and Commission Internationale de Photometrie (CIP) was founded. The First World War forced a break in the activities of the Commission Internationale de L'Eclairage, designated as CIE, which had been formed in 1913, by a proposal presented in the CIP Congress in Berlin, Germany. In 1924, in Geneva the first standard of light was adopted, based on a full radiator at the melting point of platinum and working group of colorimetry was established [24, 25]. To quantify and to model the human color perception, colorimetry has been introduced, which is the science of measuring color. This takes into account the physical characteristics of the light source, the object's spectral properties and the physiological aspects of human vision [26].



**Figure 3.1** Schematic representation of the principles of viewing color  
a) color lights  
b) color surfaces

In order to have the color we normally require an object to reflect or transmit the light from light from the source (see Fig. 3.1b). Besides that, we can see also colors, which are directly emitted from light source (see Fig. 3.1a). Nevertheless, color quality control in textile industry is focused on color of object – textile fabric.

The color of a physical sample depends primarily on the composition of the light reflected from it, which enters the observer's eyes. Those governed by two factors, the reflectance characteristics of the sample and the composition of the light falling on it. In the textile industry, for instance, a dyer determines the reflectance characteristics by his choice of dyes but he has no control over the composition of lights under which the textile will be viewed. Natural daylight itself varies in spectral power distribution, from the reddish light of sunrise and sunset in the bluish light cloudless northern sky. Furthermore, natural daylight is not available either at night or in many interior rooms. These limitations have motivated a long search for ways to simulate natural daylight, usually by choosing the lamps and developing filters to modify their spectral power distributions (frequently blue glass filters). Before daylight could be simulated, it was necessary to characterize it by measurement, to decide which phase to use, and to standardize it.

### 3.1 Standard light sources

The perceived color of an illuminated object depends not only on its intrinsic color or spectral reflectivity, but also on the power spectrum of the light source. In this chapter, we will study some of the most important light sources used in colorimetric studies. Most sources of light emit a range of wavelengths. A standard light source is best described in a number of ways. The indication of its chromaticity coordinates is not enough, as they don't give any indication of the color rendering properties, which are extremely important to define a light source quality. The definition of color rendering indexes became very usual, especially after the introduction of discharge and solid-state light sources, which are different in spectral power distribution (SPD) to thermal radiators.

To describe the light that is emitted from a source, it is necessary to express the radiance of the source at each wavelength, yielding the spectral radiance distribution or, more succinctly, the spectrum of the source. More specifically, we are concerned with the spectral radiant flux incident per unit area of our object that is we are concerned with the spectral irradiance provided by our illuminant or source.

It was written, that in case of visual triplet are three subjects necessary: light, object (sample) and observer. If we assume that the light source emits approximately equal amounts of all wavelengths, the light striking the sample will appear white. If the sample reflects equal amounts of all wavelengths, the color seen by the observer will be either white or some shade of gray. If, on the other hand, the sample absorbs some wavelengths of light and reflects others, the observer will see a colored sample. For example, if the sample absorbs blue part of the visual spectrum and reflects other wavelengths, the sample will appear to be yellow to the observer. When on the same sample will turn out blue light, the sample will appear green, because sample will absorb a huge part of short wavelength blue light and due to absence of long wavelength in spectrum of blue light no red light is reflected. Therefore, the only wavelengths, which are both available from the light source and reflected by the sample, are mid-range green wavelengths. Since the color content of the light source has such a pronounced effect upon the colors being observed, it is necessary to define and specify a standard light source to be used visual assessment and in instruments for the determination of optical properties. The current recommendation of the CIE is that the visible spectrum be sampled at 1-nm increments between 380 and 780 nm. Illuminants are normally specified in terms of the relative energy tabulated for each wavelength or wavelength band. Another possibility is based on color temperature. The color temperature of a light source is the temperature of an ideal blackbody radiator that radiates light of comparable hue to that of the light source.

**Color temperature  $T_C$**  is used for a light source with the spectral distribution of energy identical with that given by the blackbody radiator (Planck's law).

**Equivalent color temperature  $T_{CE}$**  is used for a light source with the spectral distribution of energy not identical with that given by the Planck's law, but still is of such a form that the quality of the color evoked is the same as would be evoked by the energy from a blackbody radiator at the given color temperature.

**Correlated color temperature  $T_{CP}$**  is used for a light source with the spectral distribution of energy such that the color can be matched *only approximately* by a stimulus of the blackbody radiator of spectral distribution.

Color temperature has been described most simply as a method of describing the color characteristics of light, usually either warm (yellowish) or cool (bluish), and measuring it in degrees of Kelvin (°K).

In the above variants of Planck's law, the *Wavelength* and *Wavenumber* variants use the terms  $2hc^2$  and  $hc/k_B$ , which comprise physical constants only. Consequently, these terms can be considered as physical constants themselves, and are therefore referred to as the **first radiation constant**  $C_{1L}$  and the **second radiation constant**  $C_2$  with

$$C_{1E} = 2hc^2 \text{ and } C_2 = hc/k_B.$$

$E(L)$  is used here instead of  $B$  because it is the SI symbol for spectral radiance. The  $E$  in  $C_{1E}$  refers to that. This reference is necessary because Planck's law can be reformulated to give spectral radiant exitance  $M(\lambda, T)$  rather than spectral radiance  $E(\lambda, T)$ , in which case  $c_1$  replaces  $C_{1E}$ , with  $C_1 = 2\pi hc^2$ , so that Planck's law for *spectral radiant exitance* can be written as

$$M_\lambda = C_1 \lambda^{-5} \left( e^{(C_2/T\lambda)} - 1 \right)^{-1} \quad (3.1)$$

where  $C_1 = 3.74183 \times 10^{-16} \text{ W.m}^2$ ,  $C_2$  are mentioned constants<sup>4</sup>.

It was written, that the CIE system considers three essential components, light sources, objects and observers, which determine the color perception. It is a well-known phenomenon that different light sources may affect the color appearance of an object quite significantly. To standardize the light sources in practice, the CIE defined standard illuminants and artificial light sources representative of these illuminants.

### **What is the difference between a light source and an illuminant?**

The terms light source and illuminant have precise and different meanings. A light source is a physical emitter of radiation such as a candle, a tungsten bulb, and natural daylight. An illuminant is the specification for a potential light source. All light sources can be specified as an illuminant, but not all illuminants can be physically realized as a light source.

In 1931, CIE recommended three standard illuminants, A, B and C. Later were added D, F and in some cases, is used illuminant E [27].

- Illuminant **A** is intended to represent typical, domestic, tungsten-filament lighting. Its relative spectral power distribution is that of a blackbody radiator at a temperature of approximately 2856 K. CIE standard illuminant A is used in many calibration procedures, and it is the only illuminant for which the corresponding source can also be realized with reasonable accuracy, its central position is kept also after the ban of incandescent lamps for general use. The relative spectral power distribution  $S_A(\lambda)$  is defined by the equation (3.2):

---

<sup>4</sup> In 1968, the *Comité International des Poids et Mesures* modified the "International Practical Temperature Scale, 1948 (amended 1960)" and the value of the radiation constant  $c_2$  was set equal to  $1.4388 \times 10^{-2} \text{ m.K}$ . This modification has affected the color temperature or correlated color temperature of the CIE illuminants and sources.

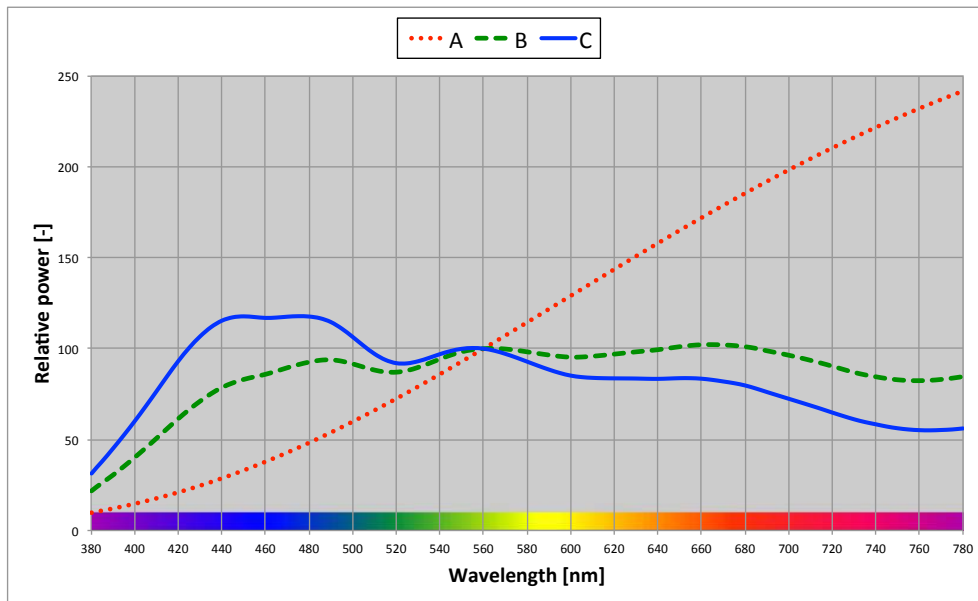


$$S_A(\lambda) = 100 \left( \frac{560}{\lambda} \right) \times \frac{\exp \frac{1.435 \times 10^7}{2848 \times 560} - 1}{\exp \frac{1.435 \times 10^7}{2848 \times \lambda} - 1} \quad (3.2)$$

where  $\lambda$  is the wavelength in nanometers and the numerical values in the two exponential terms are, definitive constants originating from the first definition of Illuminant A in 1931. This spectral power distribution is normalized to the value 100 at the wavelength 560 nm.

*Remark: Equivalent color temperature of 100 W incandescent lamp is approx. 2870 K, 40 W incandescent lamp  $\approx$  2500 K and 100 W tungsten-halogen lamp  $\approx$  3000 K*

- Standard illuminant **B** has a correlated color temperature of about 4874 K ( $205,17 \text{ MK}^{-1}$ ) and was intended to represent sunlight. Standard illuminant B is now obsolete.
- Standard illuminant **C** old standard for average daylight from the northern sky, defined in 1931 by the CIE with a  $T_{CE} = 6\,774 \text{ K}$  ( $147.62 \text{ MK}^{-1}$ ); has a significant lower UV content than the D-types; does not have CIE status of “standard illuminant” anymore.
- CIE Illuminant Series **D**. These series of illuminants that has been statistically defined in 1964 upon numerous measurements of real daylight. Although mathematically described, they can hardly be realized artificially. The correlated color temperatures (CCT) of the commonly used illuminants D50, D55 and D65 are slightly different to the values suggested by their names. Due to the revision of an estimate of one of the constant factors in Planck’s law after the standards were defined, the correlated color temperature was shifted a little. For example, the CCT of D50 is 5003K and that of D65 is 6504 K. A whole range of series D is starting from 4000 K till 25000 K ( $250 - 40 \text{ MK}^{-1}$ ) [10,27].



**Figure 3.2** Spectral power distribution (SPD) of CIE light sources from 1931

Daylight illuminant D at a nominal correlated color temperature ( $T_{cp}$ ) can be calculated using the following equations. These equations will give an illuminant whose correlated color temperature is approximately equal to the nominal value.

a) Chromaticity

The 1931 ( $x$ ,  $y$ ) chromaticity coordinates of the daylight (D) to be defined must satisfy the following relation:

$$y_D = -3.000x_D^2 + 2.870x_D - 0.275y_D \quad (3.3)$$

with  $x_D$  being within the range of 0.250 to 0.380.

The correlated color temperature  $T_{cp}$  of daylight D is related to  $x_D$  by the following formulae based on normal (rectangular line) to the Planckian locus (or blackbody locus is the path or locus that the color of a blackbody would take in a particular chromaticity space as the blackbody temperature changes) on the  $u$ ,  $v$  uniform chromaticity diagram

(I) for correlated color temperatures from approximately 4000 K to 7000 K:

$$x_D = \frac{-4.6070 \times 10^9}{(T_{cp})^3} + \frac{2.9678 \times 10^6}{(T_{cp})^2} + \frac{0.09911 \times 10^3}{(T_{cp})} + 0.244063 \quad (3.4)$$

(II) for correlated color temperatures from greater than 7000 K to approximately 25 000 K:

$$x_D = \frac{-2.0064 \times 10^9}{(T_{cp})^3} + \frac{1.9018 \times 10^6}{(T_{cp})^2} + \frac{0.24748 \times 10^3}{(T_{cp})} + 0.237040 \quad (3.5)$$

b) Relative spectral power distribution

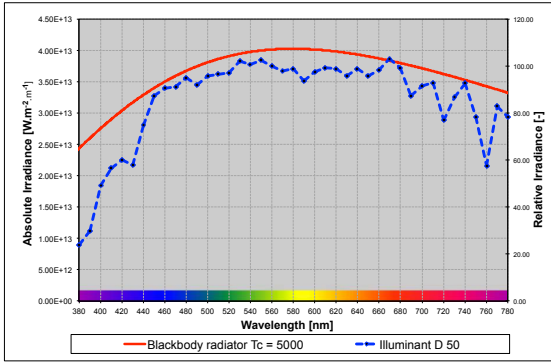
$$S(\lambda) = S_0(\lambda) + M_1 S_1(\lambda) + M_2 S_2(\lambda) \quad (3.6)$$

where  $S_0(\lambda)$ ,  $S_1(\lambda)$ ,  $S_2(\lambda)$  are functions of wavelength  $\lambda$ , given in Appendix B2, and  $M_1$ ,  $M_2$  are factors whose values are related to the chromaticity coordinates  $x_D$ ,  $y_D$  as follows:

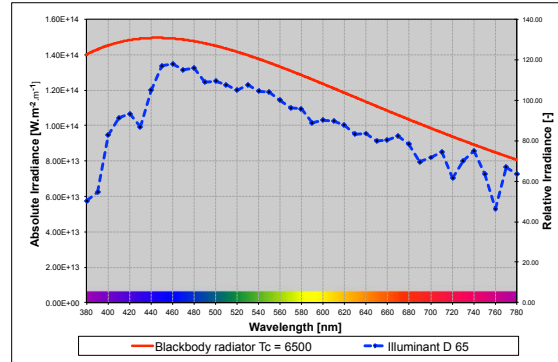
$$M_1 = \frac{-1.3515 - 1.7703x_D + 5.9114y_D}{0.0241 + 0.2562x_D - 0.7341y_D} \quad (3.7)$$

$$M_2 = \frac{0.0300 - 31.4424x_D + 30.0717y_D}{0.0241 + 0.2562x_D - 0.7341y_D}$$

The relative spectral power distribution representing a phase of daylight with a correlated color temperature of approximately 6500 K (called also nominal correlated color temperature of the daylight illuminant), symbol:  $S_{D65}(\lambda)$ . CIE standard illuminant D65 contains power in the UV range as well, as does natural outdoor daylight. It is recommended that, in the interest of standardization, D65 was used whenever possible. When D65 cannot be used, it is recommended that one of the daylight illuminants D50, D55, or D75 defined in Appendix B1 be used.



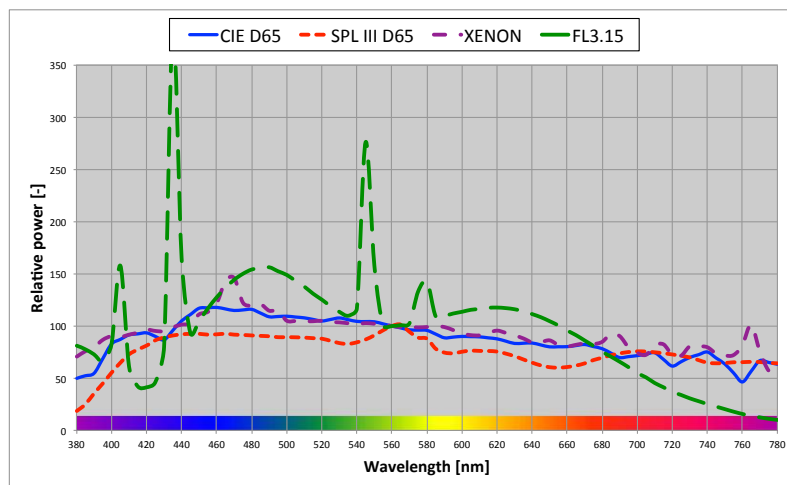
**Figure 3.3** Spectral power distribution (SPD) of CIE illuminant D50 and Planckian radiator at 5000K



**Figure 3.4** Spectral power distribution (SPD) of CIE standard illuminant D65 and Planckian radiator at 6500K

Differences between spectral power distribution of CIE illuminant D calculated following equations (3.3) till (3.7) and Planckian radiator based on equation (1.8), (3.1) respectively, are shown in the graph in Fig. 3.3 and Fig. 3.4.

Present day is used three major categories of daylight simulators: Xe-sources, T-sources and F-sources. The Xe-sources are high-pressure short-arc xenon lamps. The agreement between the SPDs of the Xe-sources and that of the CIE D65 illuminant appears quite good throughout the spectral range from 300 to 800 nm, except for a considerable excess of irradiance around 470 nm and above 700 nm as visible in graph on Figure 3.5. The T-sources are either tungsten halogen lamps combined with one or more colored glass filters used as spectrum modulators. The agreement between the SPDs of the T-sources and D65 is quite good in the visible region of the spectrum. However, in the ultraviolet region ( $\lambda < 380$  nm), the T-sources exhibit serious deficiencies and the use of the spectrum modulators consist of conventional absorption filters, is insufficient (see SPL III D65 in Fig. 3.5). The F-sources are fluorescent lamps. The discrepancies between SPDs of the F-sources and CIE D65 illuminant are generally quite severe at the wavelength of the emission lines as visible in graph of FL3.15 in Fig. 3.5. Another discrepancy that is characteristic of F-sources occurs in the wavelength region above 650 nm, where these sources show a rapid decrease of spectral irradiance to the corresponding CIE daylight illuminant.

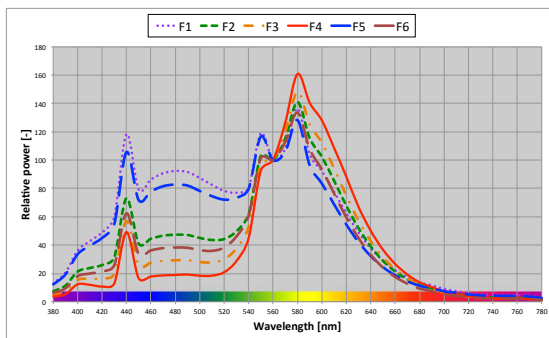


**Figure 3.5** Spectral power distribution of D65 and its simulators

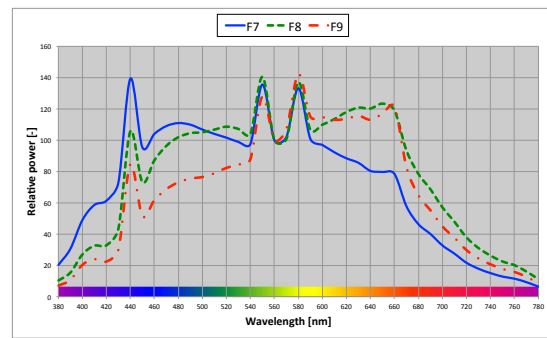
- Illuminant **E**. This is a hypothetical reference radiator. All wavelengths in CIE illuminant E are weighted equally with a relative spectral power of 100.0. Since it is not a Planckian radiator, no color temperature is given, however, it can be approximated by a CIE D illuminant with a correlated color temperature of 5455 K. The CIE standard illuminant D55 is the closest to match its color temperature.

Fluorescent lamps are widely used for store, office and works lighting. There is a wide range of fluorescent lamps due to the use of different phosphor types and formulations. Ultraviolet light, mainly at 253.7 nm, emitted by mercury vapor excites the fluorescent coating on the inside of the glass tube. The phosphors are inorganic compounds of high chemical purity and sometimes some metals are added as activators to increase their efficiency. Following illuminants are not included in CIE standard illuminant category; nevertheless, are frequently used in many standards [28].

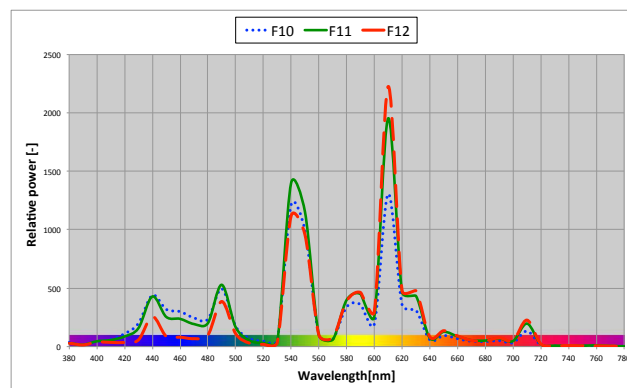
- Illuminant F1 to F12 (in CIE Colorimetry standard 15, 2004 [28] are signed as FL1 to FL12, and a new set of fluorescent illuminants is included with marking FL3.1 to FL3.15) are representative of fluorescent lamps of different types differ widely in spectral power distribution. Common used illuminants are only F2, F7 and F11. F2 represents a cool white fluorescent lamp (4230 K), F7 represents a broadband daylight fluorescent lamp (6500 K), and F11 represents a narrowband white fluorescent lamp (4000 K). Former code of narrowband fluorescent lamp, which was replaced by F11, is Philips TL84. Relative SPDs of twelve CIE fluorescent illuminants are shown on Fig. 3.6 till Fig. 3.8.



**Figure 3.6** Spectral power distribution of CIE illuminants FL1 - FL6



**Figure 3.7** Spectral power distribution of CIE illuminants FL7 - FL9



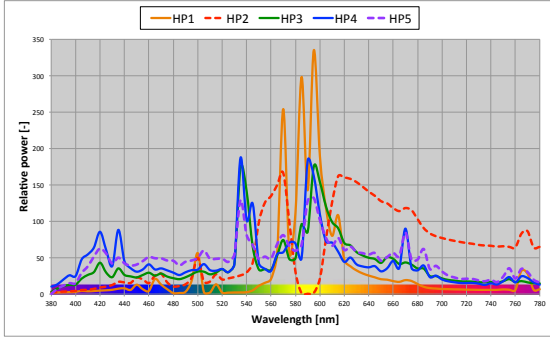
**Figure 3.8** Spectral power distribution of CIE illuminants FL10 - FL12

- The HP-illuminants are typical high-pressure lamp spectra used at the time of publishing this book. The operation principle of high-pressure discharge lamps differs considerably from that of standard incandescent lamps. Light is produced by gas discharge that occurs in an arc tube between two electrodes after ignition. Electrical conductivity is established by ionized filler components. The electrodes are fed into a completely sealed discharge vessel. During gas discharge, the additives (metal halides) and the mercury are excited by the current flow and emit the excitation energy in the form of their characteristic radiation. The mixture of different radiation components produces the desired color temperature and color reproduction properties. HP1 is standard high-pressure sodium lamp; HP2 is color enhanced high-pressure sodium lamp; and HP3 to HP5 are three types of high-pressure metal halide lamps, which SPDs are shown in the graph on Fig. 3.9.

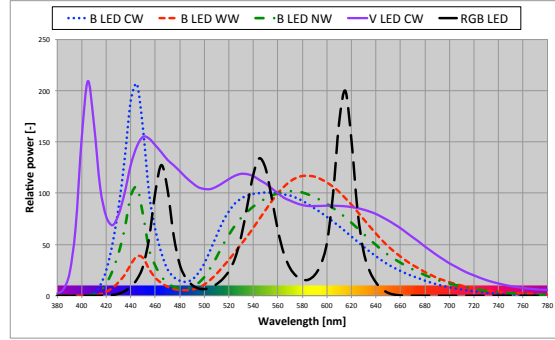
Light sources of principle importance in the near future are expected to be light emitting diodes (LEDs) and lasers. The central component part of an LED consists of a p–n semiconductor junction. So-called white LED is possible to prepare by two ways:

- Combining multiple differently colored LEDs in a single package, but this is complicated, inefficient, and the color consistency is not good. The simplest multiple differently colored LEDs are based on combination of Red, Green and Blue LED. The RGB mixing ratio required to reproduce a target white point varies according to the chromaticity coordinates of the primary color emitters being used. For example, the two sets of RGB LEDs have identical red and green emitter characteristics, but their blue emitters have different dominant wavelengths (465 nm and 476 nm, respectively). It becomes evident that changing even one LED's dominant wavelength results in dramatic changes in the value of the RGB mixing ratio required to match the D65 target white point. The LED set with the 476-nm blue emitter will require a 2.1:4.3:1.0 RGB mixing ratio but simply changing to a 465-nm emitter shifts it to 4.1:10.6:1. SPD of typical RGB white LED is shown in graph on Fig. 3.10.
- A single monochrome LED emitter, usually an InGaN blue LED, and phosphors. The technique involves coating a blue LED (commonly called the pump, as it pumps light into the phosphor) with a phosphor, or mix of phosphors. The phosphor produces a broadband yellow light that combines with the blue to create a spectrum we perceive as white light. Based on ratio between intensities of these two lights it is possible to prepare different appearance of white light from warm white, through neutral to cool white, see graphs in Fig. 3.10, where are examples of three different blue LED based white light sources (B-LED). As alternative are now available „full“ spectrum white LEDs, which utilizing a violet LED (V-LED on Fig. 3.10) element achieves full-spectrum real white color thanks to the use of R/G/B phosphors.

Correlated Color Temperature (CCT) and Spectral Power Distribution (SPD) are two common characteristics. Beside these two, we can characterize light sources by its CIE special metameric index, which are used daylight simulators mainly. Light sources that have different SPDs but produce identical relative absorptions by the three cone types will have the same chromaticity. At the same luminance, these lights will also appear to be identical under the same viewing conditions. Light sources of this type are known as **metamers**. More information is written in chapter 7.4 Metamerism.



**Figure 3.9** Spectral power distribution of CIE illuminants HP1 till HP5



**Figure 3.10** Spectral power distribution of white B-LED, V-LED and white RGB LED

Last parameter, which is commonly used for rating the color property, is Color Rendering Index (CRI).  $R_a$ , is the ability of a light source to properly reproduce the colors of the illuminated objects, is derived from CIE 1960 (u, v) chromaticity coordinate and correlated color temperature by using the procedure CIE 13.3-1994.  $R_a$  is the average values of the eight special indices  $R_{is}$ . They are obtained by estimating the shift of coordinate (u, v) with respect to the reference light source for the specified reflectivity spectra of the test samples. Unless otherwise specified, the reference illuminant for light sources with correlated color temperature below 5000K should be a Planckian radiator and from 5000K one of a series of spectral power distributions of phases of daylight [29].

Different light sources have different color rendering properties. For instance, low-pressure sodium lamps, which emit light at virtually only one wavelength, result in the appearance of color being very different from that in daylight. With the advent of fluorescent lamps, whose spectral power distribution could be varied at will over quite a wide range, it became desirable to have some means of expressing the degree to which any illuminant gave satisfactory color rendering. The CIE method to calculate CRI is based on resultant color shifts for 14 test-color samples (the reflectance values of these samples are supplied in the CIE publication [29]). Eight of the fourteen test-color samples were chosen from the Munsell color order system, covering the hue circle with moderate chroma and approximately equal lightness. The other six test-color samples, representing four highly saturated primary colors (R, B, G, Y) as well as complexion and foliage colors, were added in this method to indicate the color rendering property of a tested light source under extreme conditions. The CIE Color Rendering Index is given by:

$$R_a = 100 - 4.6\Delta E_i \quad (3.8)$$

where  $\Delta E_1$  to  $\Delta E_{14}$  are the values of  $\Delta E_i$  for each number of CIE test color samples specified by the spectral radiance factors in CIE 1960 color space (CIE U\*V\*W\*).

A reference source, such as blackbody radiator, is defined as having a CRI of 100. This is why incandescent lamps have that rating, as they are, in effect, almost near to blackbody radiators. The best possible faithfulness to a reference is specified by a CRI of one hundred, while the very poorest is specified by a CRI below zero. A high CRI by itself does not imply a good rendition of color, because the reference itself may have an imbalanced SPD if it has an extreme color temperature.

### 3.2 Interaction of materials with radiation

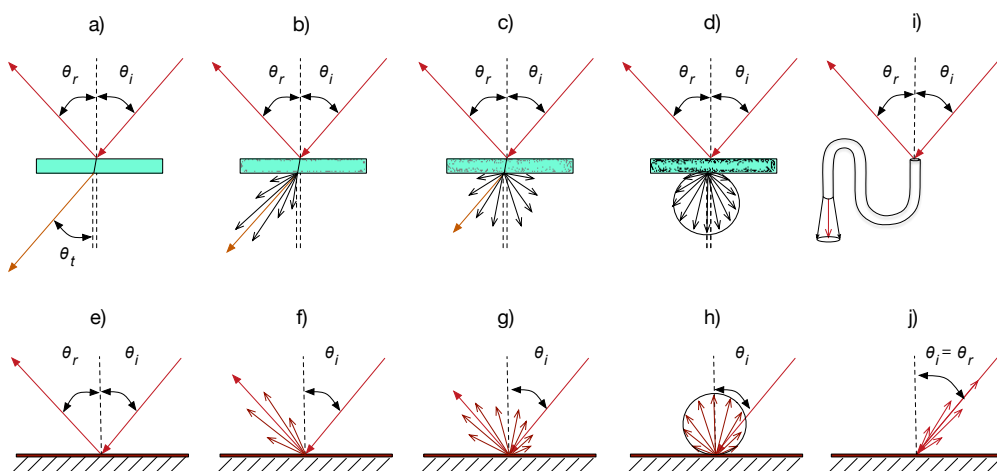
Since visual color judgments can be affected by a wide variety of factors, from plant lighting conditions and angle of observation to individual differences in color perception, instrumentation to measure color provides a subjective and consistent method of color quality control.

Visible light is found between 380 and 780 nm in the electromagnetic spectrum. It is bordered by ultraviolet light on the low end and infrared light to the upper end. When light strikes an object, it is reflected, absorbed, or transmitted. Because reflected light determines the color of a material, the appearance can change depending on amount of light, the light source, the observer's angle of view, size, and background differences. Depending on how light acts, products can be classified as opaque, translucent, or transparent.

It is important to understand that the entire color impression is certainly composed of at least two components: the light interactions in the volume and at the boundary surface of a colored sample (see Fig. 3.11). In other words, the reflection or transmission from the volume is superimposed on the boundary surface reflection. This reflection is caused by different refractive indices at the boundary surface. Such kinds of boundary surfaces are present in paints, coatings, plastic materials, emulsion paints, or ceramics. This distinction cannot be made for undefined surfaces such as of textiles, uncoated papers, plasters, or suede leather.

**Transparent materials** (Fig. 3.11a): In the field of optics, transparency is the physical property of allowing light to pass through the material without being scattered. On a macroscopic scale (one where the dimensions investigated are much, much larger than the wavelength of the photons in question), the photons can be said to follow Snell's Law. Examples of transparent materials are glass, transparent solutions of dyestuffs, etc.

**Semi-transparent materials** (Fig. 3.11b) and **Semi-translucent materials** (Fig. 3.11c) are characterized by the mixed transfer of light – regular and diffuse. In this category are included materials such as plastic foils with milk shade, colloidal solutions with low concentration, etc.



**Figure 3.11** Scheme of interaction radiation with materials

**Translucent materials** (Fig. 3.11d): Translucent materials allow light to pass through them, but they diffuse the light in a way that makes objects on the opposite side appear blurred. Examples of translucent materials are frosted glass, oilpaper, some plastics, ice and tissue paper.

**Glossy surfaces**, Fig. 3.11e): At smooth interfaces between two materials with different dielectric properties specular reflection occurs. The direction of incident ray, reflected ray, and the surface normal vector span the plane of incidence perpendicular to the surface of reflection. The angles of incidence and reflection are equal.

**Semi-gloss**, Fig. 3.11f) and **Semi-matte surfaces**, Fig. 3.11g): Very few materials have pure specular surface reflectivity. Most surfaces show a mixture of matte and specular reflection. As soon as surface micro roughness has the same scale as the wavelength of radiation, diffraction at the microstructures occurs. At larger scales, micro facets with randomly distributed slopes relative to the surface normal are reflecting incident light in various directions. Depending on the size and slope distribution of the micro roughness, these surfaces have a great variety of reflectivity distributions ranging from isotropic (Lambertian) to strong forward reflection, where the main direction is still the angle of specular reflection. A typical example of such materials is alumina, satin, etc.

**Matte surfaces**, Fig. 3.11h): cause a strong diffuse reflection of light and weak specular reflection of light, resulting in a less saturated, duller color. A surface of perfectly matte properties is a **Lambertian surface**, which means that it adheres to *Lamberts cosine law*. Lambert's cosine law states that the reflected or transmitted luminous intensity in any direction from an element of a perfectly diffusing surface varies as the cosine of the angle between that direction and the normal vector of the surface. An example of matte surface is Barium sulfate pellet, chalk, etc.

**Optical waveguide**, Fig. 3.11i) is a physical structure that guides electromagnetic waves in the optical spectrum. Common types of optical waveguides include optical fiber and rectangular waveguides. Optical fibers consist of a light-carrying core and a cladding surrounding the core. There are generally three types of construction: glass core/cladding, glass core with plastic cladding, or all-plastic fiber. Optical fibers typically have an additional outside coating, which surrounds and protects the fiber

**Retro reflective surfaces** are typically used on warning clothing, traffic signs, etc. Retro reflection is defined as reflection in which radiation is returned in directions close to the direction of the incident radiation as visible on Fig. 3.11j. Such materials are based on corner reflectors or glass spheres.

When one observes a colored paper or other object that has some gloss, the color of the object changes, depending on the viewing angle. This indicates that the reflection from a glossy object depends greatly on the angles at which the light is incident and viewed. Although usually less dramatic, the transmission of an object can also vary with incident and viewed angles.

The degree of correlation between measured values and visual appraisals depends on the degree to which the geometric conditions of measurement simulate the geometric conditions of viewing. This is very important to describe fully condition used during measurement especially in case, when data are transferred to customer and opposite.



### 3.2.1 Geometric conditions for colorimetry

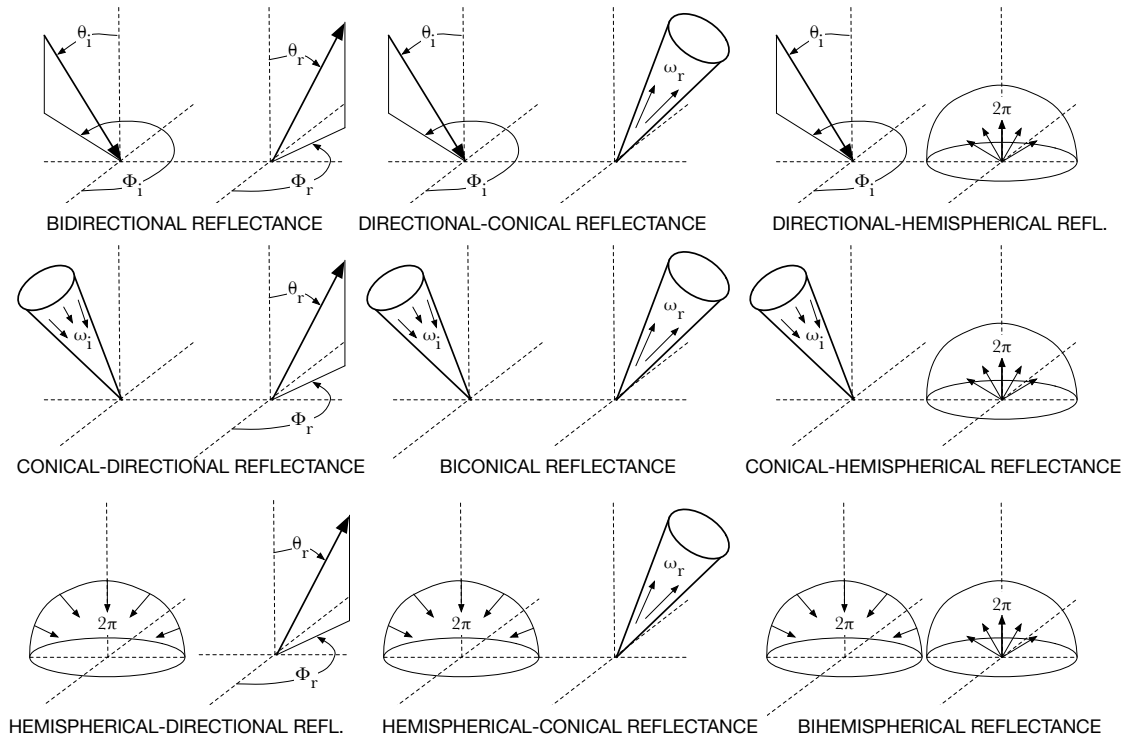
There are many different types of devices. Colorimetric specifications are derived from spectral or tristimulus measurements. The measured values depend on the geometric relationships between the measuring instrument and the sample. Reflection and transmission are purely physical phenomena, which mean the related measurable quantities describe properties of how materials interact with radiation, as was mentioned before. The reflection or transmission spectrum gives the fraction of the incident light that an object reflects or transmits as a function of wavelength. Of the many factors that influence them, the ones of interest here are those to radiation: the direction of incidence, the direction of observation, and the aperture angles of the incident and observed beams [30]. We can speak about three configurations of the observed radiation are consistent with the good technical realization:

- Directional (the beam consists of quasi-parallel rays)
- Conical (the beam has the shape of a narrow cone)
- Hemispherical (the beam is uniformly distributed over the half-space)

Based on that we can speak about:

- Radiance factor  $\beta$  (directional observation)
- Reflection factor  $R$  (conical observation)
- Reflectance factor  $\rho$  (hemispherical observation)

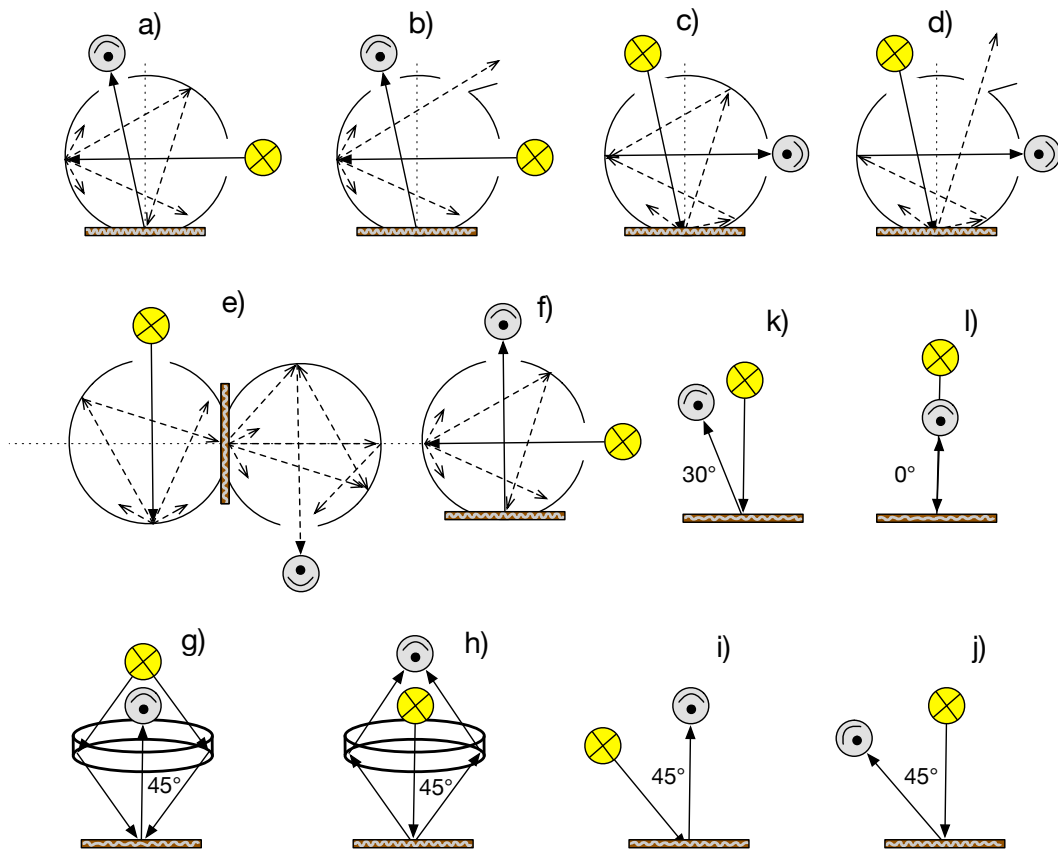
If the illumination condition is included in the classification, nine geometries must be listed since there are three possibilities for illumination and three for viewing (see Fig. 3.12).



**Figure 3.12** Nine geometrical definitions of reflectance.

To ease comparisons when reflection or transmission is measured, the CIE defined some standard terms and geometrical conditions [28]. The geometrical conditions denoted by symbols, such as  $d:8^\circ$  or  $45^\circ:0^\circ$ . The symbol ‘d’ indicates the use of an integrating sphere, and the numbers before and after the colon indicates the angles of incidence and viewing, respectively. For instruments using an integrating sphere a glossy sample can be measured in two conditions either with the specular component included or excluded. Hence, the geometry is distinguished by adding the letter ‘e’ for excluded or ‘i’ for included. The current CIE recommendations for reflection measurements with diffuse geometries are visible on Fig. 3.13.

Beside these recommendations are in different standards other conditions typically for transmission measurements  $\tau$  [31, 32, 33].



**Figure 3.13** Measuring conditions for CIE colorimetry:

- a) Diffuse : eight-degree geometry, specular component included ( $di:8^\circ$ )
- b) Diffuse : eight-degree geometry, specular component excluded ( $de:8^\circ$ )
- c) Eight degree : diffuse geometry, specular component included ( $8^\circ:di$ )
- d) Eight degree : diffuse geometry, specular component included ( $8^\circ:de$ )
- e) Diffuse : diffuse geometry ( $d:d$ )
- f) Alternative diffuse geometry ( $d:0^\circ$ )
- g) Forty-five degree annular geometry ( $45^\circ a:0^\circ$ )
- h) Zero degree directional geometry and annular reading ( $0^\circ:45^\circ a$ )
- i) Forty-five degree directional geometry ( $45^\circ x:0^\circ$ )
- j) Zero degree directional geometry and directional reading ( $0^\circ:45^\circ x$ )
- k) Thirty-degree directional geometry ( $30^\circ x:0^\circ$ )
- l) Zero degree directional geometry ( $0^\circ:0^\circ$ )

### 3.2.2 Measuring devices in colorimetry

The human eye is the oldest means of measuring color, but it has certain drawbacks in connection with the analytic specification of color. These include individuality of spectral response and poor color memory. Instrumental methods of measuring color are therefore required and such instruments must evaluate the color by illuminating the material with light of a standard spectral composition and have sensors with standard spectral responses, corresponding to those of a human observer with normal color vision. This underlines the importance of the CIE's definition of both illuminants and the "standard observer", to which reference has already been made (section 3.3).

While radiometry deals with electromagnetic radiation of all wavelengths, photometry deals only with the visible portion of the electromagnetic spectrum. The human eye is sensitive to radiation between 380 and 780 nm and only radiation within this visible portion of the spectrum is called light.

The accurate measurement of color is a difficult task. While cameras and image scanners record color information, they are not suitable for the most accurate color measurements. For the accurate measurement of color, the instrument must have carefully controlled sensors (filters and detectors) and optical geometry. If the color of reflective material is to be measured, the illumination must be precisely known and matched with the sensors. There are physical problems with the color media that further complicate the task. Properties such as specular reflectance and translucence should be taken into account. These properties will be discussed in the follow sections.

If only the tristimulus values or some derivative of them, such as  $L^*a^*b^*$  values, are desired, a *colorimeter* can be used. This device uses filters to match the vector space defined by the eye. Thus, a measurement is limited to one set of viewing conditions. The colorimeter need measure only the quantities that can be transformed into tristimulus values. The minimal system consists of three filters and three detectors or changeable filters and a single detector. These devices are much less expensive than the devices designed to measure the entire spectrum.

The most complete information is obtained by measuring the entire visible spectrum. A *spectroradiometer* measures radiant spectra; a *spectrophotometer* measures reflective spectra. Having the spectrum allows the user to compute tristimulus values under any viewing condition. To measure the spectrum requires that the spectrum of the light be spread physically. This can be done with a prism, following Newton's famous early experiments. However, to make accurate measurements, the exact spreading of the spectrum must be known and controlled. This is done with optical gratings, which can be made more precisely and are much less bulky than prisms. A system of lenses is used to focus the spectrum onto the detector. The high-quality optics required for this task greatly increases the cost of these color measurement instruments. After the spectrum is spread, the intensity of the light at each wavelength must be measured. This can be achieved in several ways. The most common method currently is to use a linear CCD array. A movable slit can also be used to limit the wavelength band being measured. The exact spread of the spectrum on the array is determined by measuring a known source. Interpolation methods are used to generate the data at the specified wavelengths. The range of wavelengths and their sampling interval varies among the instruments. Higher precision instruments, record data over a larger range and at finer sample spacing. The CIE recommends a range of 360–830 nm with a sample spacing of 1 nm

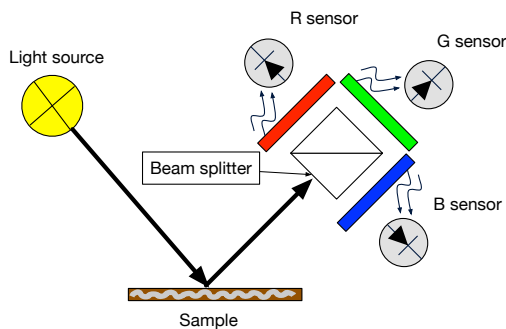
for computation of color. However, there are few instruments that actually take data at this specification. High-end instruments sample at 1 nm over a typical range of about 360 nm to 780 nm. The most popular instruments sample at 10 nm over 400 to 700 nm.

### *Tristimulus colorimeter*

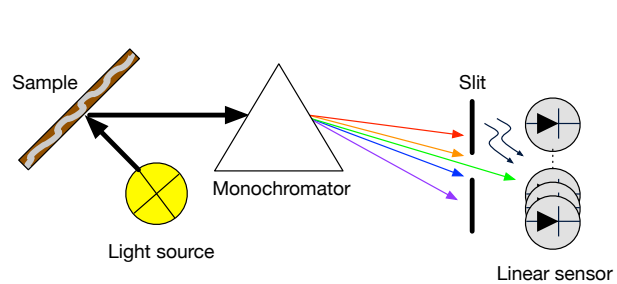
The simplest device to measure colors is a tristimulus colorimeter whose spectral responsivity mimics the color matching functions of the CIE standard observer. It measures, as suggested by its name, color tristimulus values and reports these as color values in CIEXYZ, and CIELAB. The key elements include a light source (for measuring materials) usually illuminant C or D65, a set of color filters and commonly a silicon photodiode as a photo-detector. The spectral separation is obtained by either using color filters placed in front of the photodiode or by using spectrally different light sources to illuminate the sample, often using 45°:0° geometry, i.e. circumferential 45° illumination and normal viewing. To be able to report CIE colorimetry the sensitivities of the color filters are intended to have a close match to a set of color matching function. For filter based colorimeters, four independent filters are usually used, two approximate the  $y(\lambda)$  and  $z(\lambda)$  color matching functions and two approximate the two humps of the  $x(\lambda)$  color matching functions. Alternatively, are used three filters as seen in Figure 3.14a. Then first hump of  $x(\lambda)$  color matching function is measured as 20% of signal from blue filter, which is corresponding with  $z(\lambda)$  color matching function.

### *Spectrophotometer*

Nowadays, the most common color measurement instrument in the industry is the spectrophotometer, which measures the ratio of reflected to incident light (the reflectance) from a sample at many points across the visible spectrum. The main components of all spectrophotometers for color measurement include a light source, a wavelength selection device (monochromator), and a photo detector as shown in Fig. 3.14b. The reflected or transmitted light is passed on to the wavelength selection device or spectral analyzer, where the light is split into its spectral components to be measured. In a spectrophotometer, prisms, gratings, and interference filters are the technologies used to separate light into narrow bands. Prisms and gratings both separate the wavelength spatially. Although both methods of dispersing light can still be found, today most spectrophotometers use diffraction gratings. Light passing through the grating will be diffracted at a fixed angle, which is dependent on its wavelength and the dispersed light is focused directly onto the photo detector array.



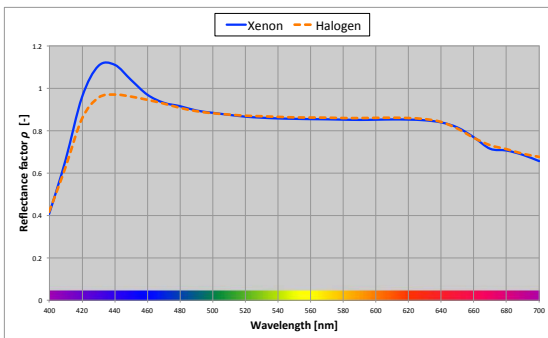
**Figure 3.14a** Basic features of a tristimulus colorimeter



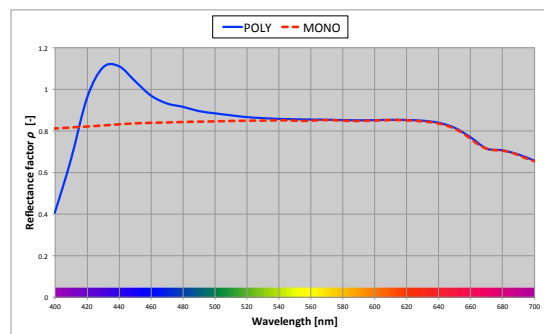
**Figure 3.14b** Basic features of a spectrophotometer

Most spectrophotometers work in the range 400 nm - 700 nm with sampling intervals reporting reflectance at 5-, 10-, or 20-nm intervals. Typically, data are measured for 31 wavelength intervals centered at 400 nm, 410 nm, 420 nm, ..., 700 nm. If it has been checked that measurement data obtained only at 10 nm or 20 nm intervals satisfy the need of the observer, computation methods as described e.g. in ASTM E308 tables [27] might be used. This publication contains weighting factors for both the CIE 1931 standard colorimetric observer and the CIE 1964 standard colorimetric observer and a number of illuminants and practical light sources used in colorimetry. Table 5 of the ASTM publication has been developed for the case when the instrument manufacturer has built in a correction to zero bandwidth. Table 6 of the ASTM publication provides weighting factors for the case when a correction to a zero bandwidth is required (see Appendix E).

Because we are measuring the ratio of incident to reflected light with a spectrophotometer, the type of light source illuminating the sample should not matter. However, as certain textile materials contain a fluorescent whitening agent (FWA), they absorb energy at one part of the spectrum and re-emit at another. Thus, the spectral power distribution (SPD) of the light source can have a dramatic effect on the measured color. It is necessary to point out how important the UV-content of the illuminant can be when carrying out color measurements on materials containing FWA; even small changes in UV-content can affect the measured reflectance spectra. Pulsed xenon, quartz halogen and tungsten gas filled, type A lamps are common light sources for spectrophotometers. Due to SPDs differences between these two lamps can be measured two different reflectance spectra on FWA contains sample as visible on Fig. 3.15. In most recording spectrophotometers is used arrangement of monochromator into incident beam. This type of optical system which illuminates the sample with *monochromatic light* and measures all the reflected or transmitted light will give an incorrect measurement on samples containing fluorescent colorants, see Fig. 3.16. The Fig. 3.14 shows an optical system that illuminates the sample with the entire spectrum of light and the reflected light is passed through a monochromator. This system will properly measure both fluorescent and non-fluorescent samples, but usually suffers from lack of light energy. In order to get sufficient energy, it is necessary to use a high level of illumination in integrating sphere, which can result in heating of the sample or it's overexposure. The spectral content of the light source used in this *polychromatic light* instrument is very important when measuring fluorescent samples and simulator D65 is recommended for this purpose.



**Figure 3.15** Reflectance curves of FWA containing sample measured under Xenon and Halogen lamp



**Figure 3.16** Reflectance curves of FWA containing sample measured by poly- and mono-chromatic arrangement

### Image systems

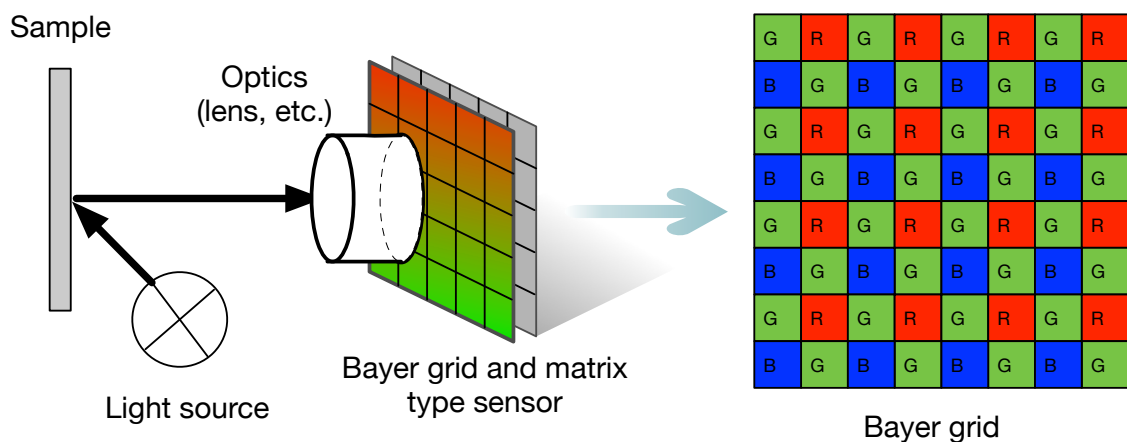
The main purpose of the sensors in a camera is to convert the incoming light into electrical or electronic signals that represent the color image at each spatial position within the field of view (FOV). All practical systems use either charge-coupled devices (CCDs) or complementary metal-oxide semiconductor (CMOS) sensors in 2D arrays. Because all of the sensors in a CCD or CMOS array have the same spectral response to the incident light, images detected by a sensor array are, in principle, gray scale images. To provide a color image, each cell of the sensor array is covered with an optical filter with a particular absorption spectrum.

Color images can be produced with a single image sensor in combination with a color filter array (CFA - Bayer grid, etc.) or color filter mosaic. A color filter array is a mosaic of color filters placed over the sensors of an imaging device. In such a mosaic, at least three different color filters must be arranged with a particular spatial disposition so that each photo detector is sensitive to only one spectral band or color, Fig. 3.17.

The Bayer grid arranges the G filter on a diagonal grid, and the R and B filter on a rectangular grid, as shown in Figure 3.17. Thus, the G image is measured at a higher sampling rate; this is based on the fact that the peak sensitivity lies in the medium wavelengths of light, corresponding to the G portion of the spectrum. Furthermore, the curve of absorption of green is similar to the luminosity function  $V_\lambda$ , and the luminance component has a higher bandwidth than the chrominance components.

It is important to understand that each pixel receives only a specific range of wavelengths according to the spectral transmittance of the filter that is superposed to that specific pixel. Indeed, one pixel “sees” only one color channel. The color information is obtained by directly combining the responses of different channels, and then it is essential that the convergence properties of light be perfectly controlled.

All measurement of surface colors in reflected light are referred to the ideal matte surface (ideal white diffusor), which reflects the incident radiation with a reflectance factor  $\rho = 1$  independent of the angle. Following equation (3.9) incident beam intensity ( $I_{0\lambda}$ ) is equal to reflected light intensity ( $I_\lambda$ ).



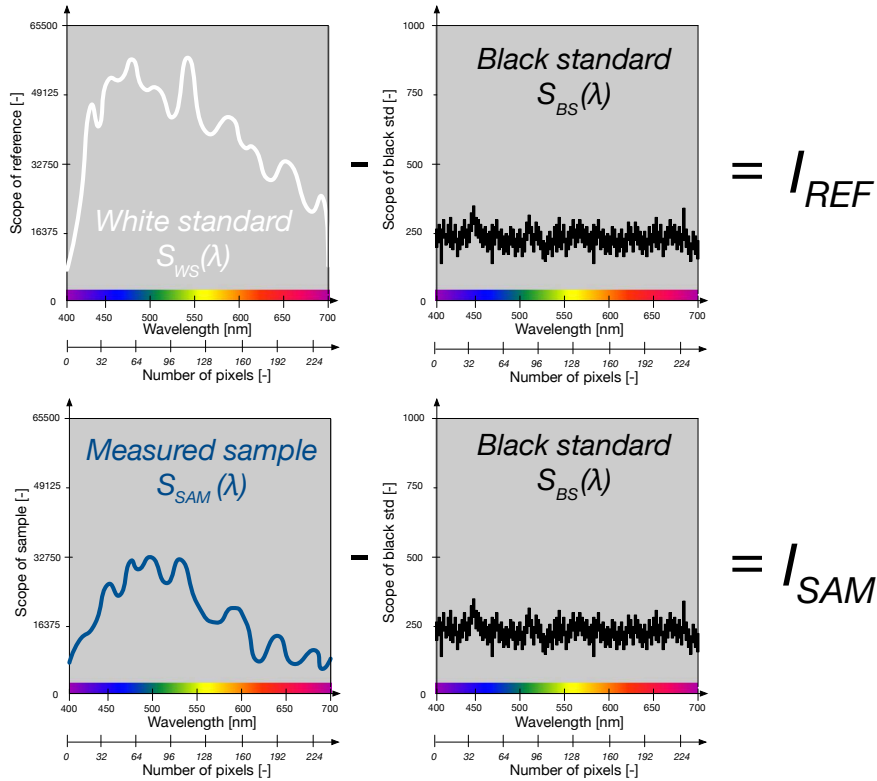
**Figure 3.17** Optical analysis system and color filter array – Bayer grid

$$\rho_{\lambda} = R_{\lambda} = \frac{I_{\lambda}}{I_{0\lambda}} = \frac{I_{SAM}(\lambda)}{I_{REF}(\lambda)} = \frac{S_{SAM}(\lambda) - S_{BS}(\lambda)}{S_{WS}(\lambda) - S_{BS}(\lambda)} \quad (3.9)$$

In most reflection spectrophotometers, the reflection of light by the sample is measured at each wavelength relative to that of a white standard such as a plate coated with MgO or BaSO<sub>4</sub>. These standards give almost 100% diffuse reflection (light rays reflected in all directions) between 380 and 750 nm (BaSO<sub>4</sub> ≈ 0.992; MgO ≈ 0.980 [35]). They are, however, rather fragile and often a working standard such as a ceramic tile of known reflectance is used. Calibration of the instrument with a white standard tile allows calculation of the reflectance of the sample relative to that of a perfect diffuse reflector having 100% reflection of the incident light at all wavelengths if is Eq. (3.9) corrected by reflectance factor of white standard:

$$\rho(\lambda) = \frac{S_{SAM}(\lambda) - S_{BS}(\lambda)}{S_{WS}(\lambda) - S_{BS}(\lambda)} \cdot \rho_{WS}(\lambda) \quad (3.10)$$

The principle of measurement of the spectral reflectance  $R$  is sketched below in Fig. 3.18. The first step is to measure the dark counts or the background intensity. In the next step the reference intensity is measured. This corresponds to the reflection of a perfect matte white sample. Numerical subtraction of the dark counts from the reference signal yields the intensity  $I_{REF}$ . In the third step the intensity reflected from the sample is measured, and the dark counts get subtracted. This difference defines the intensity  $I_{SAM}$ . Finally, the ratio of  $I_{SAM}$  and  $I_{REF}$  defines the spectral reflectance  $R_{\lambda}$  as written in equation (3.9).



**Figure 3.18** Scheme of the measurement of the spectral reflectance



### 3.3 CIE standard observer

To be able to describe colors, we need to know how people respond to them. Human perception of color is a complex function of context; illumination, memory, object identity and emotion can all play a part. The simplest question is to understand which spectral radiances produce the same response from people under simple viewing conditions. This yields a simple, linear theory of color matching which is accurate and extremely useful for describing colors.

As color sensations cannot be measured (not yet), for the measurement of color one only asks whether two stimuli can be discriminated or not and does not consider the sensations at all. To eliminate any influence of the object's shape and surroundings, and to make comparison easy, the colors to be compared are presented as structure less colors (aperture colors), each filling half of the viewing field, which appears like a shining opening.

Particularly useful for the investigation of surface colors is the *Maxwellian mode of observation*: looking at something with a magnifying glass, the distances can be chosen such that the whole aperture of the glass shows the same color. For a color, which does not appear to belong to a specific object, the separation of object and illuminant color, which in most cases is performed inadvertently and with remarkable precision, is not possible any more. Comparing colors presented in that way, the experiment is reduced to the comparison of fluxes of light, of color stimuli.

If two stimuli agree on their spectral composition,  $\varphi_{1, \lambda} = \varphi_{2, \lambda}$ , they will appear equal to all observers under any conditions; this is called an **isomeric** match. Color stimuli may look equal also if their spectral functions are different from each other; such a match is called **metameric**. Different observers may disagree in their determination of metameric matches.

To account for metamerism, i.e. the fact that different stimuli can produce the same color sensation, one introduces the **valence**  $\mathbf{V}$  of the stimulus with respect to the specific observer. If an observer perceives two stimuli as a match, we write

$$\mathbf{V}_1 = \mathbf{V}_2,$$

meaning that the two valences are equal, and nothing is implied for the stimuli [36].

While normal color vision observers agree fairly well in their judgment of metameric equality, the equation above strictly holds only for the specific observer [37].

Obviously, in a useful color space, lights that appear the same (visually match) must occupy essentially the same point in the color space, i.e., the values of R, G, and B computed via the color-matching functions for the two visually matching lights must be essentially the same:  $R_1 = R_2$ ,  $G_1 = G_2$ , and  $B_1 = B_2$  [38].

#### 3.3.1 Color matching functions

In a typical experiment a subject sees a colored light — the test light — in one half of a split field. The subject can then adjust a mixture of lights in the other half to get it to match. The adjustments involve changing the intensity of some fixed number of primaries in the mixture. In this form, a large number of lights may be required to obtain a match, but many different adjustments may yield a match.

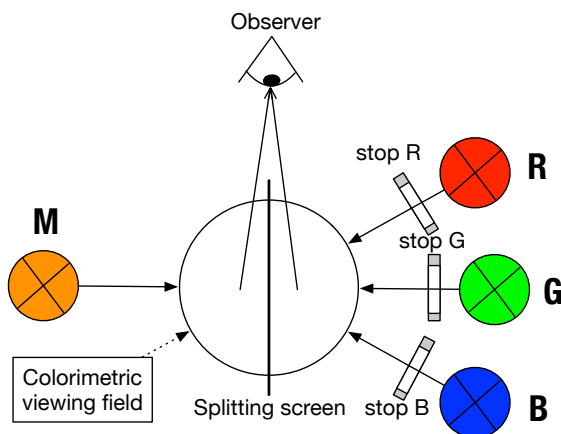


The drawing on Fig. 3.19 shows the outline of such an experiment. The observer sees a test light  $\mathbf{M}$ , and can adjust the amount of each of three primaries in a mixture that is displayed next to the test light. The observer is asked to adjust the amounts so that the mixture looks the same as the test light. The mixture of primaries can be written as  $R_i(\mathbf{R}) + G_i(\mathbf{G}) + B_i(\mathbf{B})$ ; if the mixture matches the test light, then we write:

$$\mathbf{M} = R_M(\mathbf{R}) + G_M(\mathbf{G}) + B_M(\mathbf{B}) \quad (3.11)$$

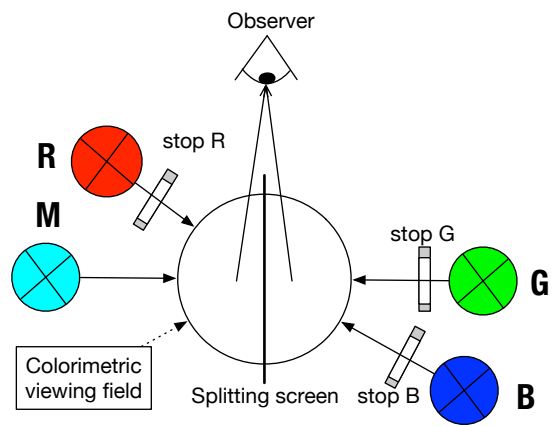
It is a remarkable fact that for most people three primaries are sufficient to achieve a match for many colors, and for all colors if we allow subtractive matching (i.e. Some amount of some of the primaries is mixed with the test light to achieve a match).

Some people will require fewer primaries. Furthermore, most people will choose the same mixture weights to match a given test light. Wright and Guild have determinate them accurately for a number of normal observers using specified experiment [39]. These determinations have been collated and the mean results, transformed to a system having monochromatic stimuli of wavelengths 435.8, 546.1 and 700 nm as reference stimuli and an equal-energy stimulus as basic stimulus, adopted as standard by the CIE. The relative amounts of the three reference stimuli required to match every wavelength of an equal-energy spectrum are known as distribution coefficients and are given the symbols  $\bar{r}$ ,  $\bar{g}$ ,  $\bar{b}$  for the red, green and blue reference stimuli respectively. It was noted in many cases, one of the tristimulus values  $\bar{r}(\lambda)$ ,  $\bar{g}(\lambda)$ ,  $\bar{b}(\lambda)$  is negative, indicating that the color match was actually obtained by using one or two primaries to desaturate the test stimulus. In point of view of simplified scheme of visual colorimeter on Fig. 3.20, one or two primaries were moved on the left side, where is placed test light  $\mathbf{M}$ . In other cases, one or two tristimulus values are zero, indicating that color match was obtained, respectively, by the use of two primaries or one primary only. The spectral stimulus values  $\bar{r}(\lambda)$ ,  $\bar{g}(\lambda)$ ,  $\bar{b}(\lambda)$  of the monochromatic stimuli of different wavelength, but constant radiance are appropriately called color-matching functions with respect to the given primaries  $\mathbf{R}$ ,  $\mathbf{G}$ ,  $\mathbf{B}$ . Fig. 3.21 illustrates these functions.



$$\mathbf{M} = R_M(\mathbf{R}) + G_M(\mathbf{G}) + B_M(\mathbf{B})$$

Figure 3.19 Visual colorimeter – setup a)



$$\mathbf{M} + R_M(\mathbf{R}) = G_M(\mathbf{G}) + B_M(\mathbf{B})$$

Figure 3.20 Visual colorimeter - setup b)

The simple possibility to transform tristimulus values induced the CIE in 1931 to introduce special virtual primaries  $X$ ,  $Y$ , and  $Z$  and to define the tables of the corresponding color matching functions as standard for colorimetry.

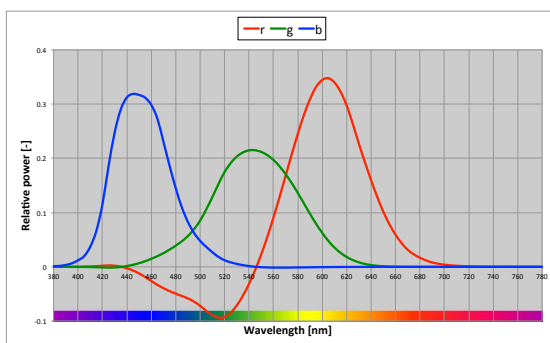
The new primaries  $X$ ,  $Y$ ,  $Z$  has been chosen such that no negative tristimulus values  $X$ ,  $Y$ ,  $Z$  occur in any color. In the unit plane, the spectral locus is then entirely within the triangle ( $XYZ$ ) which naturally implies that the valences  $X$ ,  $Y$ ,  $Z$  cannot be realized, they only supply a convenient coordinate system for measurements and graphical representation. The primaries  $X$  and  $Z$  have been assumed to lie in that plane (alychne), thus  $L_X = L_Z = 0$ , and the color matching function of the valence  $Y$  then must be proportional to the photopic luminous efficiency function  $V(\lambda)$ , thus the coordinate  $Y$  proportional to the luminosity.

The requirements that illuminant  $E = 1/3(X + Y + Z)$  and that the  $XYZ$ -color space encompasses the gamut of real colors as closely as possible have been used to fix the valences  $X$  and  $Z$  and thus to get the color matching functions  $\bar{x}(\lambda)$ ,  $\bar{y}(\lambda)$  and  $\bar{z}(\lambda)$  as transforming of  $\bar{r}(\lambda)$ ,  $\bar{g}(\lambda)$  and  $\bar{b}(\lambda)$ .

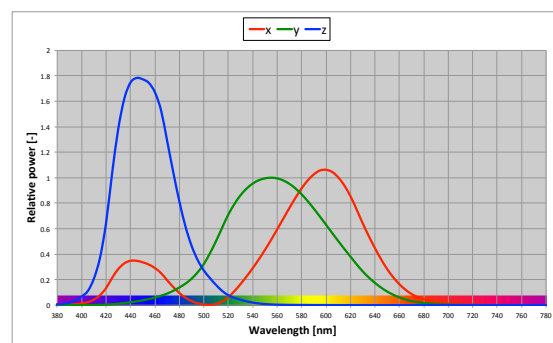
As the functions  $\bar{x}(\lambda)$ ,  $\bar{y}(\lambda)$ ,  $\bar{z}(\lambda)$  are arbitrarily normalized (such that the maximum of  $\bar{y}(\lambda)$  is equal to 1, as visible on Fig. 3.22), we have written a proportionality factor before the summation sign. The hypothetical observer whom the CIE 1931 color-matching functions describe is often referred to as the CIE 1931 standard observer.

In 1964, the CIE standardized a second set of color-matching functions appropriate for larger field sizes. These color-matching functions take into account the fact that human color matches depend on the size of the matching fields. The CIE 1964  $10^\circ$  color-matching functions are an attempt to provide a standard observer for these larger fields. The use of  $10^\circ$  color-matching functions is recommended by the CIE when the sizes of the regions under consideration are larger than  $4^\circ$  [36].

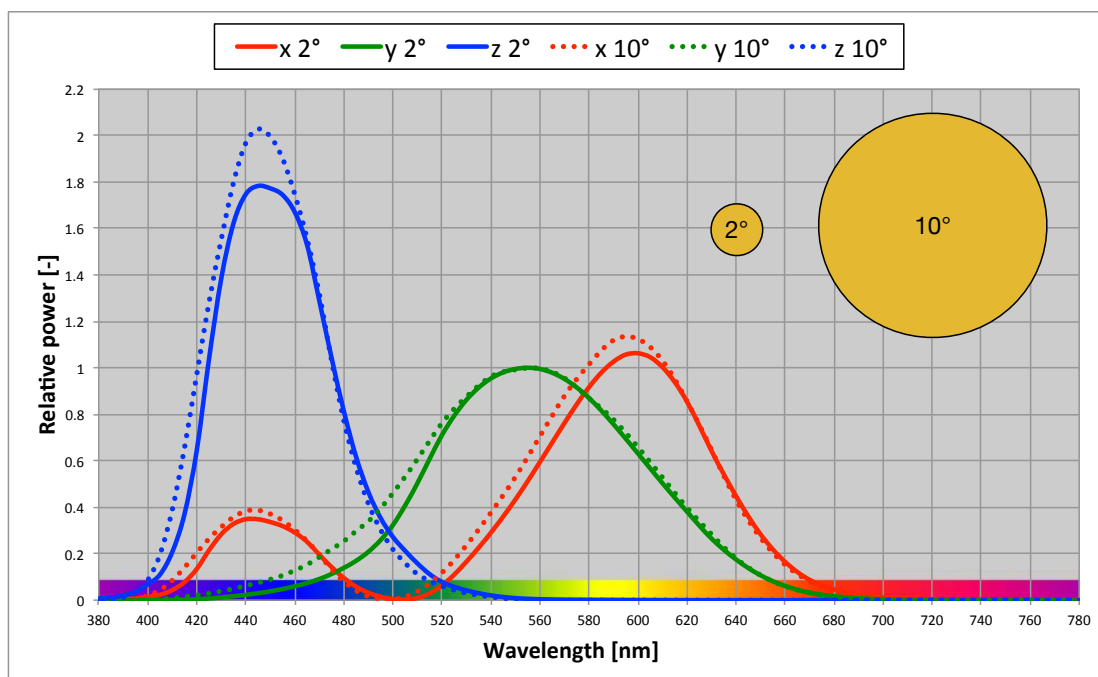
The difference between a large and a small field can be clearly observed in a very large uniform field, where the appearance to the observer clearly shows a central spot with a slightly different color. This central zone is known as the Maxwell spot, which has a diameter of about four degrees; when the eye looks for a different point, the Maxwell spot moves with the eye. This spot is most clearly seen with a moderate luminance in the field. This is due to the presence of the macular pigment in the central portion of the retina.



**Figure 3.21** The  $\bar{r}$ ,  $\bar{g}$ ,  $\bar{b}$  color-matching functions



**Figure 3.22** The  $\bar{x}$ ,  $\bar{y}$ ,  $\bar{z}$  color-matching functions



**Figure 3.23** Color-matching functions

The plot shows a set of color-matching functions for normal human vision standardized by the CIE in 1931 - 2° and CIE in 1964 – 10°.

It is interesting to notice that the spectral relative luminous efficiency of the eye  $V(\lambda)$  is not defined for large fields, but only for a 2° field. Then,  $y_{10}(\lambda)$  is slightly different from  $V(\lambda)$ , with the most noticeable difference being in the blue region, as visible in the graph on Fig. 3.23.

### 3.4 CIE XYZ

The CIE  $XYZ$  color space encompasses all color sensations that an average person can experience. That is why CIE  $XYZ$  (Tristimulus values) is a device invariant color representation. It was written, that metameric lights are lights that though of dissimilar spectral radiation are seen as the same by the observer. In a prototypical color-matching experiment using additive lights, the metamers are presented in a bipartite field. For 2° foveal fields, metamers have three important properties that allow treatment of color mixture as a linear system (Grassmann, 1853) [24, 40]:

I. The additive property. When a radiation is identically added to both sides of a color mixture field, the metamerism is unchanged.

II. The scalar property. When both sides of the color mixture field are changed in radiance by the same proportion, the metamerism is unchanged.

III. The associative property. A metameric mixture may be substituted for a light without changing the metameric property of the color fields.

The Grassmann's assumption of additivity and its quantitative formulation, Trichromatic Generalization, allow handling quantities of color stimuli as ordinary algebraic values, and are the basis of colorimetry. According to Grassmann's laws, a color match is invariant under a variety of experimental conditions that may alter the appearance of the matching fields. Metameric matches will hold with the addition of a chromatic surround or following pre-exposure to a moderately bright chromatic field. This implies that the background light differentially adapted some sites controlling the appearance of lights. A pair of metameric lights placed on an adapting field of moderate luminance (insufficient to bleach a significant proportion of the cone photo pigments) continues to be metameric even though the appearance of the lights may change. This phenomenon is referred to as the *persistence of color matches*.

The CIE Standard Colorimetric Observer CMF data are used to calculate the CIE tristimulus values of a stimulus with known spectral power distribution. It is important that the CIE system of color measurement is an internationally adopted method to specify the characteristics of a light source or an object color in terms of its tristimulus values. For a desired light source specified by its spectral power distribution  $S_\lambda$  in the visible range the tristimulus values  $XYZ$  are given by [41]:

$$X = k \int_{\lambda} S_{\lambda} \rho_{\lambda} \bar{x}_{\lambda} d\lambda \quad (3.12)$$

$$Y = k \int_{\lambda} S_{\lambda} \rho_{\lambda} \bar{y}_{\lambda} d\lambda \quad (3.13)$$

$$Z = k \int_{\lambda} S_{\lambda} \rho_{\lambda} \bar{z}_{\lambda} d\lambda \quad (3.14)$$

where  $S_{\lambda}$  is spectral power distribution of used light source

$\rho_{\lambda}$  is spectral reflectance factor,

$\bar{x}_{\lambda}$ ,  $\bar{y}_{\lambda}$ ,  $\bar{z}_{\lambda}$  are CIE standard observer functions,

The normalizing constant  $k$  usually is chosen such that for an ideal white surface one would obtain the luminance  $Y$  of 100:

$$k = 100 / \int_{\lambda} S_{\lambda} \bar{y}_{\lambda} d\lambda \quad (3.15)$$

The integration is approximated by summation, thus [27]:

$$X = \sum E_{\lambda} R_{\lambda} \bar{x}_{\lambda} \Delta\lambda \quad (3.16)$$

$$Y = \sum E_{\lambda} R_{\lambda} \bar{y}_{\lambda} \Delta\lambda \quad (3.17)$$

$$Z = \sum E_{\lambda} R_{\lambda} \bar{z}_{\lambda} \Delta\lambda \quad (3.18)$$

One particular feature of the  $XYZ$  system is that the  $\bar{y}_{\lambda}$  function was chosen to be equal to the photopic luminosity curve,  $V_{\lambda}$ , defined by the CIE in 1924. This choice leads to the  $Y$  tristimulus value being proportional to luminance. It is common practice

to specify a light in terms of its chromaticity coordinates and luminance,  $(x, y, Y)$ , from which the three tristimulus values are easily recalculated.

Tristimulus values **XYZ** are defined in **RGB**<sup>5</sup> color space by following coordinates:

$$\begin{aligned} r_X &= 1.2750 & g_X &= 0.2778 & b_X &= 0.0028 \\ r_Y &= -1.7394 & g_Y &= 2.7674 & b_Y &= -0.0280 \\ r_Z &= -0.7429 & g_Z &= 0.1409 & b_Z &= 1.6020 \end{aligned}$$

According to vector theory the correlation between primary color valence systems can be obtained simply from a linear transformation with 3 x 3 matrices. Then for conversion of **RGB** to **XYZ** we have:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 2.770 & 1.750 & 1.130 \\ 1.000 & 4.590 & 0.006 \\ 0.000 & 0.056 & 5.590 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (3.19)$$

Above mentioned transformation was used during re-computing of standard observer functions  $\bar{x}$ ,  $\bar{y}$ ,  $\bar{z}$  from measured matching functions of average Wright-Guild observer  $\bar{r}$ ,  $\bar{g}$ ,  $\bar{b}$ .

The fact that new color spaces can be constructed by applying linear transformations has an important implication for the study of color. If we restrict attention to what we may conclude from the color-matching experiment, we can determine the psychological representation of color only up to a free linear transformation. There are two attitudes one can take toward this fact. The conservative attitude is to refrain from making any statements about the nature of color vision that depend on a particular choice of color space. The other is to appeal to experiments other than the color-matching experiment to choose a privileged representation. At present, there is not universal agreement about how to choose such a representation and we therefore advocate the conservative approach.

Because the visual representation of light is three-dimensional (see Fig. 3.24), it is difficult to plot this representation on a two-dimensional page. Even more difficult is to represent a dependent measure of visual performance as a function of color coordinates. A strategy for plotting color data is to reduce the dimensionality of the data representation. One common approach is through the use of chromaticity coordinates.

Although the *XYZ* tristimulus values do not correlate to color attributes, important color attributes are related to the relative magnitudes of the tristimulus values, called the chromaticity coordinates. The chromaticity coordinates are derived from the *XYZ* tristimulus values via a projective transformation and defined as:

---

<sup>5</sup> *CIE RGB color space is based three monochromatic light stimuli at 700 nm (red), 546.1 nm (green), and 435.8 nm (blue) as the primaries to represent colors. In case of other light stimuli, it is necessary to calculate new transformation matrix to XYZ system. Thus sRGB color space is defined with different transformation matrix as matrix in equation (3.19).*

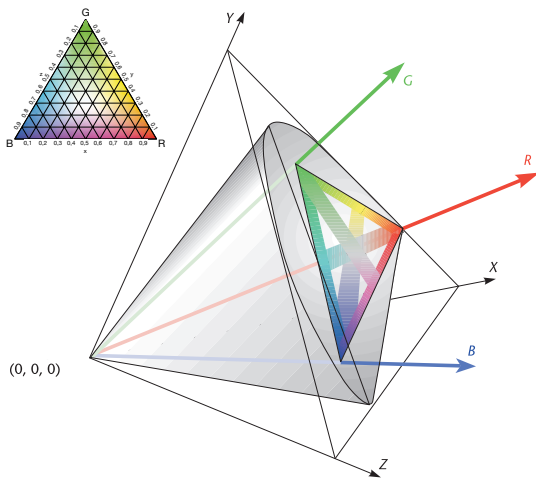
$$x = \frac{X}{X+Y+Z} \quad (3.20)$$

$$y = \frac{Y}{X+Y+Z} \quad (3.21)$$

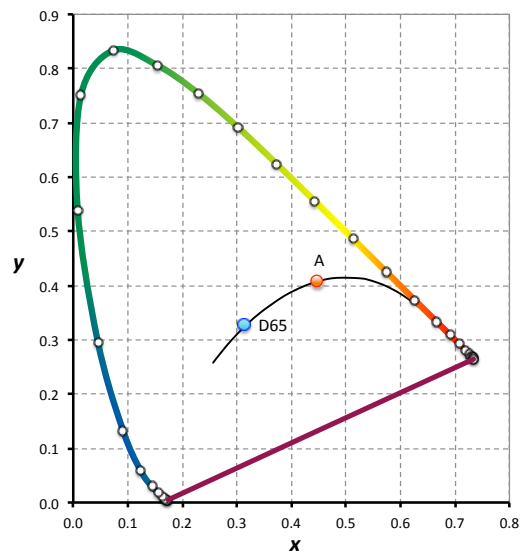
This color representation system is referred to as  $xyY$ . A third coordinate,  $z$ , can also be defined in a manner similar to the definition of  $y$  in Equation 3.21, but is redundant, because:

$$x + y + z = 1 \quad (3.22)$$

With the two variables  $x$  and  $y$ , it is possible to represent colors in a 2D color diagram; this diagram is known as the *CIE chromaticity diagram* in the sense that the third variable,  $Y$ , has only the brightness content. Note that the  $Y$  component in the  $XYZ$  space represents luminance; brightness is a perceptual attribute associated with luminance. The CIE  $x, y$  chromaticity diagram is shown in Fig. 3.25. The horseshoe-shaped curve is sometimes called the *locus of spectral colors*, or *locus of monochromatic colors*. Any point on the locus corresponds to the chromaticity of monochromatic light of a particular wavelength. A scale of wavelength in that connection is shown on the curve. Chromaticities which lie along the straight line joining the open ends of the locus of spectral chromaticities (they are various purple hues) do not appear in the light spectrum, and accordingly are not monochromatic. They are called *the non-spectral purples*, and are arbitrarily considered to have 100% saturation. Remember that in any color space, if we start with a particular color, with certain values of three primaries, and increase its luminance (without changing its chromaticity), the proportions of its three primary components remain unchanged. Thus, in the CIE system, for an unchanging chromaticity,  $X$  and  $Y$  increase by the same ratio that  $(X+Y+Z)$  does, and so  $x$  and  $y$  remain unchanged. Therefore, the point  $x, y$  in fact represents the chromaticity of a color. Keeping in mind that the variable  $Y$  indicates the luminance of the color of interest, the entire 1931 color space is often designated the  $xyY$  (or sometimes  $Yxy$ ) space.



**Figure 3.24** CIE XYZ color space together with triangle of tristimulus values sRGB



**Figure 3.25** The CIE 1931 chromaticity diagram

Beside the color coordinates  $x$ ,  $y$  it is possible to calculate two other coordinates, which are called excitation purity and dominant wavelength, or Helmholtz numbers [31]. The wavelength associated with the point on the horseshoe-shaped curve at which the extrapolated line intersects is the dominant wavelength. When the line is extrapolated in the other direction (from the end that terminates at the reference white point), the wavelength associated with the point on the horseshoe-shaped curve at which this line intersects is called the “complementary wavelength”. When the line used to locate, the dominant wavelength does not intersect the horseshoe-shaped curve at all (i.e., it intersects the straight line that contains the purples near the bottom of the diagram), then the complementary wavelength instead of the dominant wavelength is used to describe the color most accurately, and in this case, it is called the “complimentary dominant wavelength”. The excitation purity is defined to be the ratio of the length of the line segment that connects the chromaticity coordinates of the reference white point and the color of interest to the length of the line segment that connects the reference white point to the dominant wavelength. The larger the excitation purity, the more saturated the color appears, or the more similar the color is to its spectrally pure color at the dominant wavelength. The smaller the excitation purity, the less saturated the color appears, or the whiter it is. Pastel colors are very poorly saturated, for example.

The chromaticity coordinates  $x$ ,  $y$  depends on the primaries  $\mathbf{X}$ ,  $\mathbf{Y}$ ,  $\mathbf{Z}$  which have been chosen more or less arbitrarily. The chromaticity diagram depends on this choice; however, another choice will only lead to a *perspectival* distortion of the diagram, accompanied by a redefinition of units such that the simple rules for computing additive mixing remain valid. With respect to color differences, the chromaticity chart is not quite satisfactory: the distances on the chart are not nearly proportional to perceived differences. No wonder, any perceptions beyond color matching have until now been deliberately excluded. If now color differences are compared, this is beyond the initial restriction. A measure for the perceived distance may be obtained from the scattering of data points when color matching is repeated many times.

## 4 COLOR DIFFERENCE MEASUREMENT

Our treatment so far has not included any discussion of the precision to which observers can judge identity of color appearance. To specify tolerances for color reproduction, it would be helpful to know how different the color coordinates of two lights must be for an observer to reliably distinguish between them. A number of techniques are available for measuring the human ability to discriminate between colored lights.

One method, employed in work by MacAdam is to examine the variability in individual color matches. That is, if we have observers set matches to the same test stimulus, we will discover that they do not always set exactly the same values. Rather, there will be some trial-to-trial variability in the settings. MacAdam and others used the sample covariance of the individual match tristimulus coordinates as a measure of observers' color discrimination.

A second approach is to use psychophysical methods to measure observers' thresholds for discriminating between pairs of colored lights. Examples include increment threshold measurements for monochromatic lights and thresholds measured systematically in a three-dimensional color space. Measurements of small color differences are often summarized with iso-discrimination contours. An iso-discrimination contour specifies the color coordinates of lights that are equally discriminable from a common standard light. Iso-discrimination contours are often modeled as ellipsoids and the figure is drawn to the typical ellipsoidal shape. The well-known MacAdam ellipses are an example of representing discrimination data using the chromaticity coordinates of a cross section of a full three-dimensional iso-discrimination contour. In ideal color space, such iso-discrimination contours should have the character of circles. That was idea of Judd [39], who was first described CIE  $XYZ$  color spaces non-uniformity. The resulting solution is frequently called as Uniform Color Scale (UCS).

Beside measurement of iso-discrimination contours, were developed transformations of CIE  $XYZ$  into new more color uniform color space, with the help of the Munsell color system. It is known that Munsell system is uniform, but not based on CIE colorimetry. Such color spaces are obviously called as  $LAB$  for differentiating from UCS. Last way is based on computing color differences with equations developed under the umbrella of accepted color space, typically CIELAB.

### 4.1 UCS

A uniform color space is one in which the distance in coordinate space is a fair guide to the significance of the difference between two colors — in such a space, if the distance in coordinate space was below some threshold, then a human observer would not be able to tell the colors apart. The term “Uniform Color Scale” is actually a misnomer in that none of the scales achieved the goal of being a perfect visually uniform system. Some are better than others in this aspect; however, for the sake of simplicity, it will be continuing to refer to them as UCS.



In 1935 Judd described a transformation that he called Maxwell triangle since it proposed three equally important visual responses as suggested by Maxwell in 1860 [39]. To demonstrate how the Maxwell triangle predicted color spacing in the CIE  $xy$  diagram, Judd transformed circles of equal size in the Maxwell triangle back into CIE  $xy$  diagram. These are shown in Fig. 4.1 as distorted ellipses, each representing equal visual distances from their center points as predicted by the transformation. Based on that Judd derived a projective transformation of the type:

$$u = \frac{c_{11}x + c_{12}y + c_{13}}{c_{31}x + c_{32}y + c_{33}}, \quad (4.1)$$

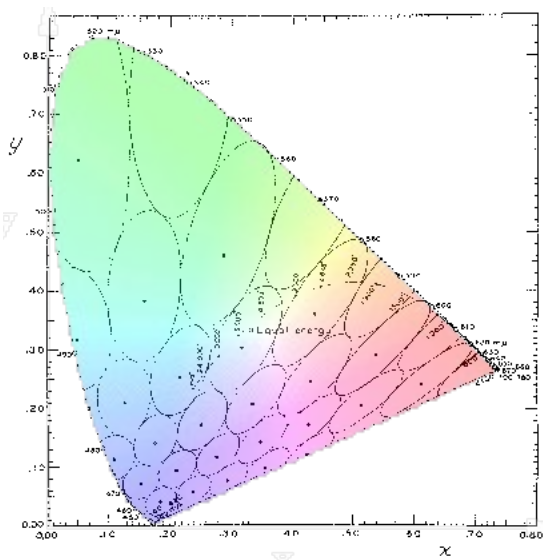
$$v = \frac{c_{21}x + c_{22}y + c_{23}}{c_{31}x + c_{32}y + c_{33}}$$

which converts the CIE  $xy$  diagram into a new  $uv$  chromaticity diagram. The new chromaticity diagram is called a uniform-chromaticity-scale (UCS) diagram because it yields, according to the spacing data on which it is based, approximately constant distance between pairs of points corresponding to chromaticities found experimentally to differ by perceptually equal amounts as mentioned before. Judd's solution of equation (4.1) was following:

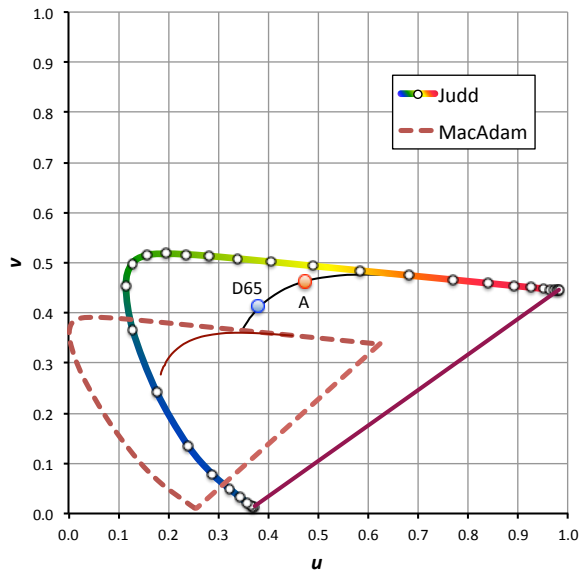
$$r = \frac{2.7760x + 2.1543y - 0.1192}{-x + 6.3553y + 1.5405}, \quad g = \frac{-2.9446x + 5.0323y - 0.8283}{-x + 6.3553y + 1.5405},$$

$$u = \frac{0.4661x + 0.1593y}{y - 0.1574x + 0.2424}, \quad v = \frac{0.6581y}{y - 0.1574x + 0.2424} \quad (4.2)$$

Resulting uniform chromaticity diagram  $u, v$  is shown on Fig. 4.2.



**Figure 4.1** Judd uniform ellipses inside CIE  $xy$  diagram



**Figure 4.2** MacAdam  $uv$  triangle (dashed line) and Judd transformation

### 4.1.1 MacAdam $u, v$ diagram

In 1937 MacAdam [40] modified the Judd triangle into a more usable form. Keeping its essential shape (as can be seen in Figure 4.2), he moved away from an implied Young-Helmholtz theory of vision and used rectangular rather than triangular coordinates. His  $u, v$  chromaticity diagram was the first to be oriented in red-to-green and yellow-to-blue dimensions. MacAdam's equations are shown below:

$$u = \frac{2x}{6y - x + 1,5} = \frac{4x}{-2x + 12y + 3}, \quad v = \frac{3y}{6y - x + 1,5} = \frac{6y}{-2x + 12y + 3} \quad (4.3)$$

$Y = Y \text{ CIE } 1931$

### 4.1.2 Breckenridge - Schaub: RUCS

In 1939 Breckenridge and Schaub [41] developed a variation of the UCS diagram in which the equi-energy point was made the origin of a rectangular uniform coordinate system (known as the RUCS diagram), and applied it to the specification of the colors of signal lights (railway, highway, marine, and airplane traffic):

$$\begin{aligned} x' &= \frac{0.82303x + 0.82303y - 0.82303}{1.00000x - 7.05336y - 1.64023} \\ y' &= \frac{3.69700x - 5.07713y - 1.36896}{1.00000x - 7.05336y - 1.64023} \end{aligned} \quad (4.4)$$

but the diagram is usually plotted with coordinates:

$$\begin{aligned} x'' &= 0.0750 - x' \\ y'' &= y' - 0.5000 \end{aligned}$$

as in Fig. 4.3, which puts the equi-energy white point (Illuminant E) at the origin.

A further advantage of this transformation is so chosen that the distribution coefficients  $x''$  and  $y''$  are zero for the greatest possible number of wavelengths.

### 4.1.3 Hunter $\alpha, \beta$ diagram and NBS unit of color difference

In an effort to reconcile difference between Munsell and CIE spacing, Richard Hunter, in 1941, proposed a projection of the CIE chromaticity diagram known as the  $\alpha, \beta$  uniform chromaticity scale (Fig. 4.4). Although this diagram has succeeded to some degree in incorporating data from the CIE and Munsell system it is still a compromise. At any rate, because of the great irregularities of the UCS triangle, the NBS (United States National Bureau of Standards) unit of color difference was redefined by Hunter on the basis of the  $\alpha, \beta$  chromaticity diagram [43][44]. Hunter's equation is as follows:

$$\Delta E_{NBS} = f_g \sqrt{\left[ 221Y_m^{1/4} \sqrt{(\Delta\alpha)^2 + (\Delta\beta)^2} \right]^2 + \left( k \sqrt{(\Delta Y)} \right)^2} \quad (4.5)$$

where  $Y_m = \frac{Y_1 + Y_2}{2}$ ,  $\Delta\alpha = \alpha_2 - \alpha_1$ ,  $\Delta\beta = \beta_2 - \beta_1$ ,  $\sqrt{(\Delta Y)} = \sqrt{Y_2} - \sqrt{Y_1}$ ,

$$\alpha = \frac{2.4266x - 1.3631y - 0.3214}{1.0000x + 2.2633y + 1.1054}, \quad \beta = \frac{0.5710x - 1.2447y - 0.5708}{1.0000x + 2.2633y + 1.1054},$$

$f_g = Y_m / (Y_m + 2.5)$  is factor to take into account the masking influence of a glossy surface on the detection of a color difference.

$k$  is a proximity factor - constant whose numerical value depends on the distance separating two colors being compared (obvious values are in range 10-12).

No other formula for  $\Delta E$  takes such factors in account, although the impact of gloss and other samples in the vicinity  $\Delta E$  is generally noticeable.

The  $\Delta E_{NBS}$  results computed for the bright colors are close to the results calculated according to the latest rules for the HunterLab and CIELAB color space. For dark colors, these differences are much more noticeable.

#### 4.1.4 Hunter - Scofield equation

Scofield proposed a simplification of Hunter's equation in 1943. He modified the coordinates  $\alpha$  and  $\beta$  by defining them in terms of  $a$  and  $b$ . Scofield's equation is as follows:

$$\Delta E_{H-S} = f \sqrt{(\Delta \bar{L})^2 + (\Delta \bar{a})^2 + (\Delta \bar{b})^2}, \quad (4.6)$$

where  $\bar{L} = 10\sqrt{Y}$ ,  $\bar{a} = 7\bar{L}\alpha$ ,  $\bar{b} = 7\bar{L}\beta$ ,

and  $\alpha, \beta$  are computed following NBS equation.

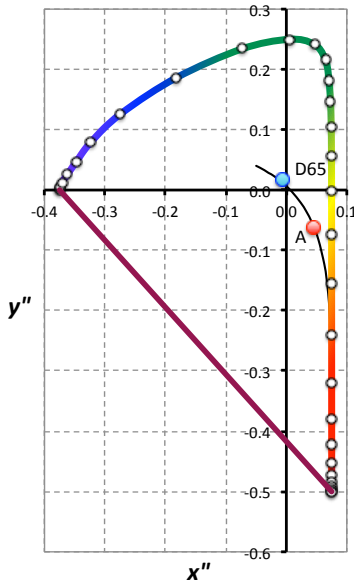


Figure 4.3 Breckenridge-Schaub RUCS diagram

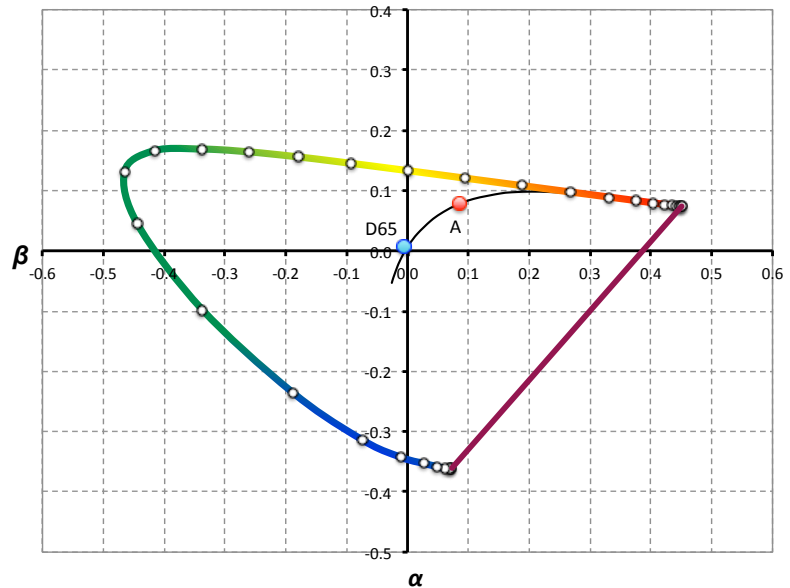


Figure 4.4 Hunter  $\alpha, \beta$  chromaticity diagram (Sometimes the Scofield-Judd-Hunter RUCS)

#### 4.1.5 CIE1964 U\*V\*W\*

The CIE 1960 uniform color scale (UCS) is a linear transformation of the  $xyY$  space in an attempt to produce a chromaticity diagram in which a vector of unit magnitude representing the difference between two chromaticities is uniformly visible [45], see Fig. 4.5. The color difference calculation and new chromaticity coordinates are obtained from  $x$  and  $y$  as follows:

$$\Delta E_{CIEUVW} = \sqrt{(\Delta U^*)^2 + (\Delta V^*)^2 + (\Delta W^*)^2} \quad (4.7)$$

where

$$W^* = 25Y^{1/3} - 17$$

$$U^* = 13W^*(u - u_0)$$

$$V^* = 13W^*(v - v_0)$$

$$u = \frac{4X}{X + 15Y + 3Z} = \frac{4x}{-2x + 12y + 3}$$

$$v = \frac{6Y}{X + 15Y + 3Z} = \frac{6y}{-2x + 12y + 3}$$

$u_0, v_0$  are the corresponding chromaticity coordinates of the ideal white for the used light source.

#### 4.1.6 CIE1976 L\*u\*v\*

The Uniform Chromaticity Scale (UCS) was developed to minimize the limitations of the 1931 system. It was intended to provide perceptually more uniform color spacing for colors at approximately the same luminance. The 1976 CIE-UCS chart uses  $u'$  and  $v'$  coordinates, Fig. 4.6. The symbols  $u'$  and  $v'$  were chosen to differentiate from the  $u$  and  $v$  coordinates of the similar but short lived 1960 CIE-UCS system, Fig. 4.5. The  $u'$  and  $v'$  chromaticity coordinates are also calculated from the  $XYZ$  tristimulus values according to the following formulae [46], [47]:

$$\Delta E_{CIELUV} = \sqrt{(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2} \quad (4.8)$$

where

$$L^* = 116(Y/Y_0)^{1/3} - 16 \quad \text{if } Y/Y_0 > 0.008856$$

$$L^* = 903.3(Y/Y_0) \quad \text{if } Y/Y_0 \leq 0.008856$$

$$u^* = 13L^*(u - u_0) \quad v^* = 13L^*(v - v_0)$$

$$u = \frac{4X}{X + 15Y + 3Z} \quad v = \frac{9X}{X + 15Y + 3Z}$$

Values with  $_0$  as subscript are related to ideal white.

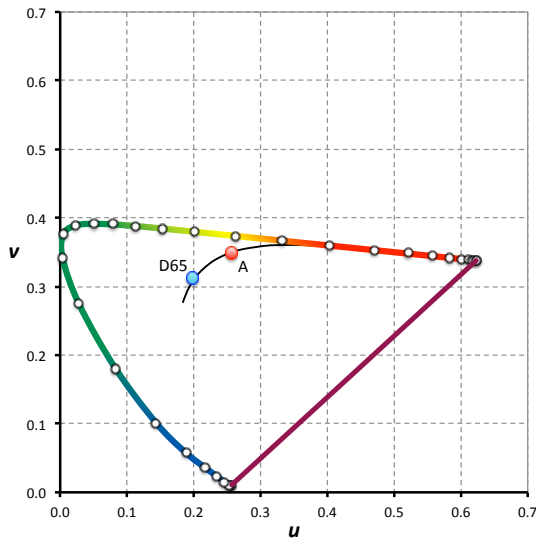


Figure 4.5 CIE  $U^*V^*W^*$  -  $uv$  diagram

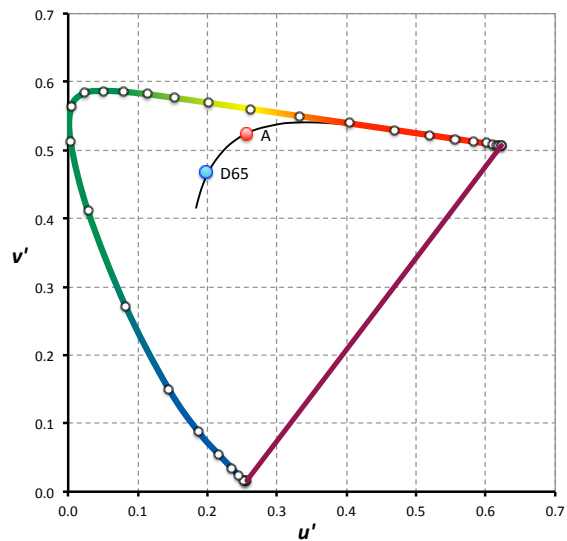


Figure 4.6 CIELUV -  $u'v'$  diagram

#### 4.1.7 FMC I

In 1942, MacAdam [48][49] set up an experiment in an attempt to relate perceived color differences to measurements in the chromaticity space. Small color differences are summarized with iso-discrimination contours as a result of approximately 25000 color matches made by one observer, P.G. Nutting, Jr (PGN). The apparatus used was a monocular colorimeter, which simplified diagram is shown on Fig. 4.7.

A trained observer viewed two different colors at a fixed luminance of about  $48 \text{ cd.m}^{-2}$ . One of the colors (the test color) was fixed, but the other was adjustable by the observer, and the observer was asked to adjust the second color until it matched the test color. For the variable stimulus, several straight lines intersecting in a common fixed chromaticity were used in turn. The resulting standard deviations of color matching were plotted as distance  $\Delta s$  along these lines; measured from the central fixed chromaticity point  $(x_0, y_0)$ , see Fig. 4.8 The end points fell closely on an ellipse whose size, shape, and orientation changed when the whole procedure was repeated with a new fixed chromaticity point.

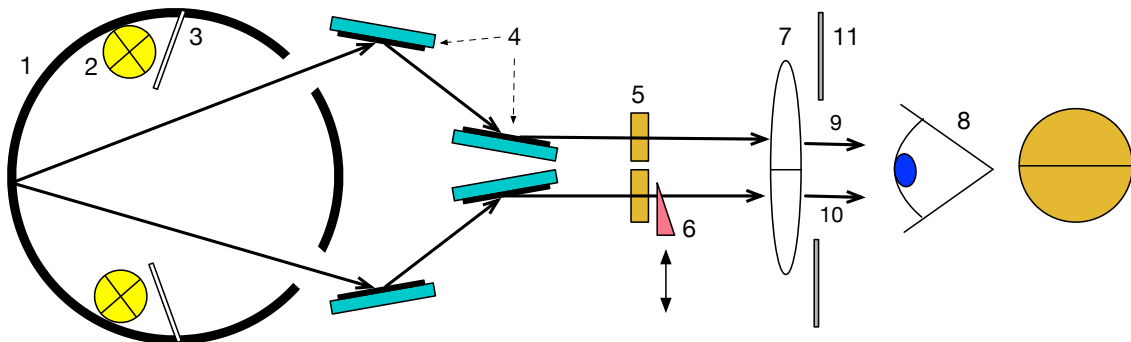
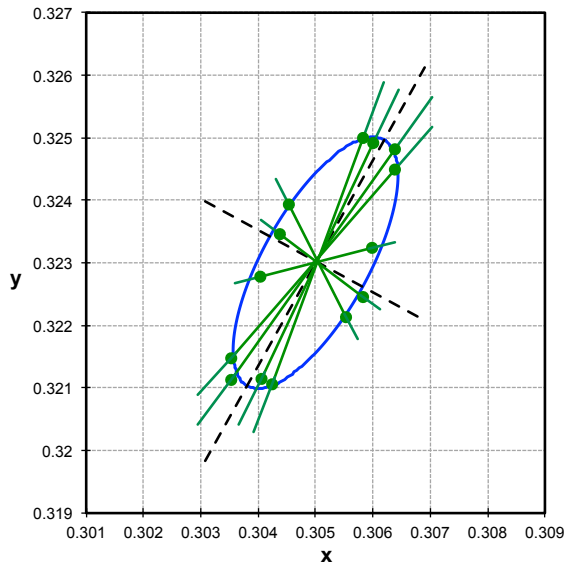
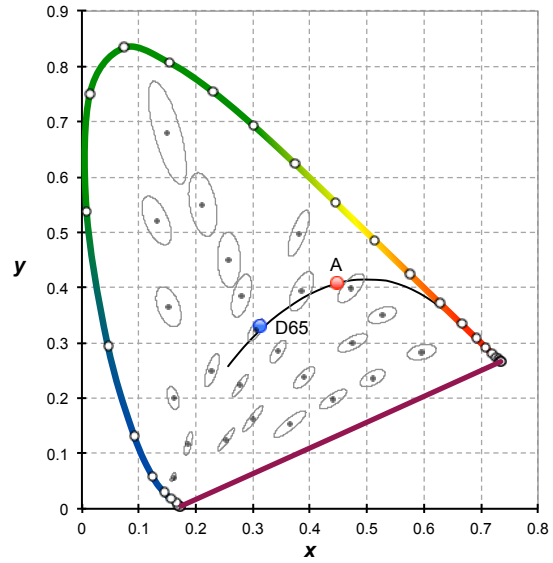


Figure 4.7 Simplified scheme of MacAdam measurement

1 - integrating sphere, 2 - lamps, 3 - baffles, 4 - mirrors, 5 - target set of filters, 6 - batch set of filters, 7 - split pupil, 8 - observer, 9 - target light beam, 10 - batch light beam, 11 - reducing aperture



**Figure 4.8** Example of experimental results, obtained by MacAdam's observer PGN, showing how standard deviations matching a fixed chromaticity  $(x_0, y_0)$



**Figure 4.9** Statistical variation of chromaticity matches in different parts of the CIE  $xy$  chromaticity diagram (each ellipse has been enlarged 10 times)

Measurements were made at 25 points on the chromaticity diagram, and it was found that the size and orientation of the ellipses on the diagram varied widely depending on the test color. The 25 ellipses are shown on the CIE chromaticity diagram (Fig. 4.9). Just noticeable differences can be obtained by modifying a color shown to an observer until they can only just tell it has changed in a comparison with the original color. When these differences are plotted on a color space, they form the boundary of a region of colors that are indistinguishable from the original colors. Usually, ellipses are fitted to the just noticeable differences. This experiment demonstrated that Euclidean distances in the  $xy$  chromaticity space are not well correlated with color differences perceived by human observers [50]. JND ellipses are small in size in the blue-violet region, and large in the green region as shown in Fig. 4.9.

Further investigation to include the luminance variable in the study of color discriminations by analysis of the errors of visual trichromatic colorimetry was made by Brown and MacAdam in 1949 [51]. Instead of the monocular colorimeter with a  $2^\circ$  field and dark surround, a binocular wide field colorimeter subtending  $10^\circ$  at the observer's position with a white surround was used. Results similar to those from MacAdam's original work were obtained using twelve different observers.

The size and shape of a discrimination ellipse depends on the choice of the reference light. Wyszecki and Fielder [52] showed that discrimination ellipses vary from individual to individual and from one measurement to the next one for a given individual, see Fig. 4.10

Combining MacAdam's findings with an appropriate weighting constant for lightness produces the well-known MacAdam equation for computing total color difference (metric coefficients  $q_{13}$  and  $q_{23}$  are frequently omitted [53]):

$$\Delta E_{B-MA} = \sqrt{q_{11}(\Delta x)^2 + 2q_{12}\Delta x\Delta y + q_{22}(\Delta y)^2 + 2q_{13}\Delta x\Delta Y + q_{33}(\Delta Y)^2 + 2q_{23}\Delta y\Delta Y},$$

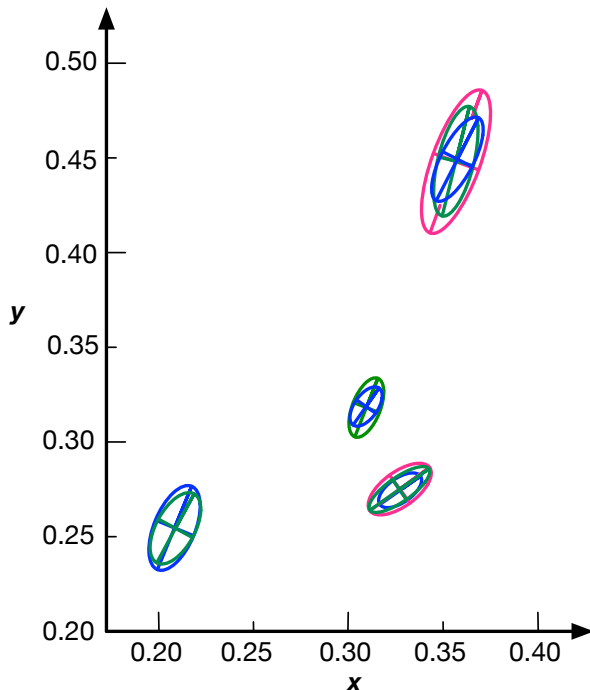
respectively:

$$\Delta E_{B-MA} = \sqrt{q_{11}(\Delta x)^2 + 2q_{12}\Delta x\Delta y + q_{22}(\Delta y)^2 + q_{33}(\Delta Y/Y)^2} \quad (4.9)$$

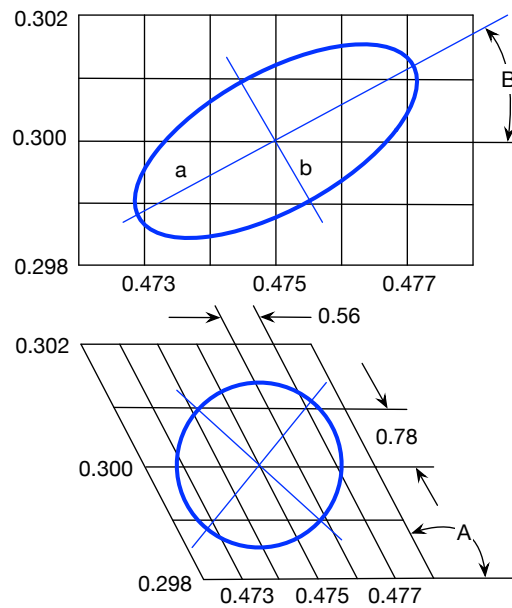
While the mathematics of equation (4.9) is quite straightforward, it is long time consuming a problem for conventional spreadsheet (MS Excel, etc.). It is an ideal on that were developed two graphical techniques for solving equation (4.9), and both has enjoyed widespread usage. One (Simon-Goodwin) is based on difference in CIE chromaticity coordinates and CIE  $Y$  between a sample and standard. The other (Foster) is based on the ratio of sample/standard values of R, G and B using a ratio measuring tristimulus colorimeter.

Simon and Goodwin published in 1957, a paper titled “Rapid Graphical Computation of Small Color Differences”, in which they described a set of charts designed to reduce differences in chromaticity coordinates  $x$ ,  $y$  and lightness  $Y$  between a sample and standard into  $\Delta C$  (total chromaticity difference),  $\Delta L$ , and  $\Delta E$  according to MacAdam’s equation (4.9) [55]. By obliquely transforming the rectangular CIE coordinates of  $x$  and  $y$  they were able to plot MacAdam’s discrimination ellipses as circles. A graphical example of this transformation is shown in Fig. 4.11.

This transformation provides a common radius, which represents the same visual magnitude of  $\Delta C$  in all directions. Since the orientation of the ellipse axes varies with dominant wavelength and colorant purity, the angle between the  $x$  and  $y$  coordinates for a chart representing a different sector.



**Figure 4.10** Results of Wyszecki and Fielder’s study of observer variability



**Figure 4.11** Example of transformation MacAdam’s ellipse into circle

The work of Friele [56], developed further by MacAdam and Chickering, resulted in FMC color difference formula (F for Friele, M for MacAdam, C for Chickering)[57]:

$$\Delta E_{FMC-1} = \sqrt{(\Delta C)^2 + (\Delta L)^2}, \quad (4.10)$$

where

$$\Delta C = \sqrt{(\Delta C_1)^2 + (\Delta C_3)^2},$$

$$\Delta C_1 = \frac{S(P\Delta P + Q\Delta Q)}{bD^2} - \Delta S/b,$$

$$\Delta C_3 = \frac{Q\Delta P - P\Delta Q}{aD},$$

$$\Delta L = 0.279 \frac{P\Delta P - Q\Delta Q}{aD},$$

$$P = 0.724X + 0.382Y - 0.098Z, \quad Q = -0.480X + 1.370Y + 0.1276Z, \quad S = 0.686Z,$$

$$D = \sqrt{P^2 + Q^2}$$

$$a = \sqrt{17.3 \times 10^{-6} D^2 / \left[ (1 + 2.73P^2Q^2) / (P^4 + Q^4) \right]},$$

$$b = \sqrt{3.098 \times 10^{-4} (S^2 + 0.2015Y^2)},$$

$$\Delta P = P_2 - P_1, \quad \Delta Q = Q_2 - Q_1, \quad \Delta S = S_2 - S_1, \quad (\text{subscript } 2 \text{ for sample, } 1 \text{ - target})$$

#### 4.1.8 FMC II

In 1971 Chickering published new color difference formula with name FMC II which supersedes FMC I equation [58]. The coefficients in this rather elaborate formula have optimal values in the sense that  $\Delta E_{FMC II}$  closely reproduces the PGN color-matching ellipses when the tristimulus value  $Y$  is kept constant and equal to 10.69 [58]. The results then nearly agree with an earlier formula (FMC I). The FMC II formula was designed so that by adopting the value of 1 it represents just noticeable difference in color.

The parameter  $K_1$  was developed for application to non-self-luminous stimulus objects for which tristimulus values are expressed on the CIE-recommended basis that for a perfect white  $Y$  is 100, that  $K_1$  was developed for application particularly to textile materials, and that  $K_1$  was developed for the specific purpose of simulating the swelling/shrinking behavior of Simon-Goodwin chromaticity differences (Fig. 4.12).

The parameter  $K_2$ , was introduced to convert Friele-type lightness differences to Simon-Goodwin-type lightness differences adopted in Simon-Goodwin graphical



method of determining color differences.

$$\Delta E_{FMC-2} = \sqrt{C_{11}(\Delta P)^2 + 2C_{12}\Delta P\Delta Q + C_{22}(\Delta Q)^2 + 2C_{13}\Delta P\Delta S + C_{33}(\Delta S)^2 + 2C_{23}\Delta Q\Delta S} \quad (4.11)$$

$$\text{where} \quad C_{11} = (e_1^2 + e_3^2)P^2 + e_4^2Q^2,$$

$$C_{22} = (e_1^2 + e_3^2)Q^2 + e_4^2P^2,$$

$$C_{33} = e_2^2,$$

$$C_{12} = (e_1^2 + e_3^2 - e_4^2)PQ,$$

$$C_{23} = -e_1e_2Q,$$

$$C_{13} = -e_1e_2P$$

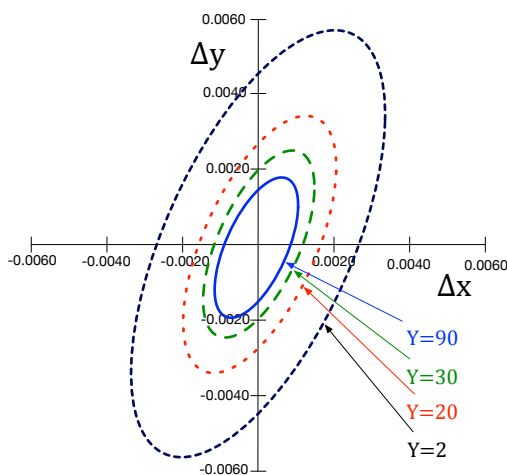
$$e_1 = K_1S/bD^2, \quad e_2 = K_1/b, \quad e_3 = 0.279K_2S/aD, \quad e_4 = K_1/aD,$$

$$K_1 = 0.55669 + 0.049434Y - 0.82575 \times 10^{-3}Y^2 + 0.79172 \times 10^{-5}Y^3 - 0.30087 \times 10^{-7}Y^4$$

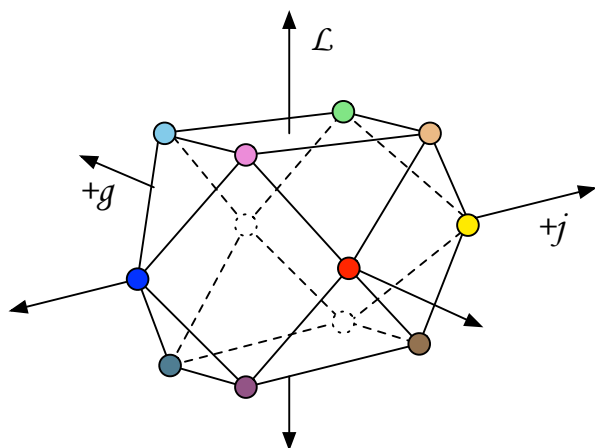
$$K_2 = 0.17548 + 0.027556Y - 0.57262 \times 10^{-3}Y^2 + 0.63893 \times 10^{-5}Y^3 - 0.26731 \times 10^{-7}Y^4$$

Simple expressions for  $K_1$  and  $K_2$  have been suggested by MacAdam and Simon, which reduce to some extent the complex calculations involved in finding  $\Delta E_{FMC II}$  for given pair of colors:

$$K_1 = 0.54 + 1.6\sqrt{Y/100} \quad K_2 = 0.456K_1 - 0.062$$



**Figure 4.12** Size dependence of FMC II tolerance ellipse on tristimulus value  $Y$



**Figure 4.13** Cub octahedral cluster sampling scheme of OSA – UCS

### 4.1.9 OSA-UCS

A committee of the Optical Society of America (OSA) undertook to review and supplement all available data on subjective magnitudes of color differences and to design a set of color cards that can be assembled to form uniform color scales of as many varieties as feasible [60]. To do this, the committee located about 500 equally spaced points in the  $\mathcal{L}, j, g$  coordinate system, according to the arrangement of atoms in a regular rhombohedral crystal, see Fig. 4.13.

The committee enlisted the aid of 76 normal observers who each reported judgments of ratios of hundreds of pairs of color differences. As a result of thorough analysis of those data, the committee derived the following set of formulas for coordinates  $\mathcal{L}, j, g$  in a 3-dimensional Euclidean space in which the ratios of separations of points that represent the pairs of colors judged by the committee's observers are as nearly as possible equal to the reported judgments:

$$\begin{aligned} \mathcal{L} &= 5.9 \left[ Y_0^{1/3} - \frac{2}{3} + 0.042(Y_0 - 30)^{1/3} \right] && \text{if } Y > 30, \\ \mathcal{L} &= 5.9 \left[ Y_0^{1/3} - \frac{2}{3} - 0.042(Y_0 - 30)^{1/3} \right] && \text{if } Y \leq 30, \end{aligned}$$

where:  $Y_0 = Y(4.4934x^2 + 4.3034y^2 - 4.2760xy - 1.3744x - 2.5643y + 1.8103)$

$$L = (\mathcal{L} - 14.4) / \sqrt{2}$$

$$\Delta E_{MALgj} = f \left[ 2(\Delta L)^2 + (\Delta g)^2 + (\Delta j)^2 \right]^{1/2} \quad (4.12)$$

where  $g = C(-13.7R^{1/3} + 17.7G^{1/3} - 4B^{1/3})$ ,  $j = C(1.7R^{1/3} + 8G^{1/3} - 9.7B^{1/3})$ ,

$$C = \mathcal{L} / \left( 5.9Y_0^{1/3} - 2/3 \right) = 1 + 0.042(Y_0 - 30)^{1/3} / \left( Y_0^{1/3} - 2/3 \right),$$

$$R = 0.7990X + 0.4194Y - 0.1648Z,$$

$$G = -0.4493X + 1.3265Y + 0.0927Z,$$

$$B = -0.1149X + 0.3394Y + 0.7170Z.$$

## 4.2 Munsell based scales

The second major group of uniform color scales was designed to simulate visually adjusted spacing of surface colors based on Munsell System. Conceived by Munsell, this system was developed not as an experiment in psychophysics, but to meet his needs as an artist for a means to identify and interrelate colors of surfaces [61]. As was written before the Munsell system consists of three independent dimensions, which can be represented cylindrically in three dimensions as an irregular color solid: hue, measured by "degrees" around horizontal circles; chroma, measured radially outward from the neutral (gray) vertical axis; and value, measured vertically from 0 (black) to 10 (white). Munsell determined the spacing of colors along these dimensions by taking measurements of human visual responses based on logarithmic relation of the Weber-

Fechner law [62]. Former visual spacing was re-measured and re-assessed based on visual experiments with a neutral gray background. The derived relationships between instrumentally computed Munsell colors and visual estimates are called the Munsell Renotation System [63][64].

It was written, that Munsell system is almost visually uniform [65], but the problem is, that this system isn't based on CIE colorimetry and relationship is based on converting tables [66] or nonlinear computing. Studies by an OSA subcommittee [67] based on a more precise measurement of the luminance factors of the samples of the 1929 Munsell Book of Color indicated the definition of Munsell value recommended by this subcommittee is given by the fifth-order polynomial function:

$$Y = 1.2219V - 0.23111V^2 + 0.23951V^3 - 0.021009V^4 + 0.0008404V^5 \quad (4.13)$$

The equation (4.13) is frequently called as Judd polynomial function [68], which is rather written in following form:

$$\frac{100Y}{Y_{MgO}} = 1.2219V - 0.23111V^2 + 0.23951V^3 - 0.021009V^4 + 0.0008404V^5$$

Due to change of reflectance standard from MgO to absolute white in 1969, it is necessary to correct coefficients in equation (4.13) as shown in following equation [69]:

$$Y = 1.1913V - 0.22533V^2 + 0.23352V^3 - 0.020484V^4 + 0.0008194V^5 \quad (4.14)$$

#### 4.2.1 ANLAB

In 1944, Nickerson and Stultz proposed replacing the Weber derivations of  $V_x$ ,  $V_y$  and  $V_z$  of the Adams chromatic value space by the Judd polynomial function [73]. They also suggested scaling the resulting lightness coordinate by a factor of 0.23 to make unit steps in lightness more consistent with those of the opponent chromatic scales [1][9][41][69]. The resulting formula was widely used, largely due to publicity given it by Nickerson, and as a result became known as the ANLAB (Adams–Nickerson *LAB*) formula, given in following equations:

$$\Delta E_{ANLAB} = \sqrt{(\Delta L_A)^2 + (\Delta a_A)^2 + (\Delta b_A)^2}, \quad (4.15)$$

$$\text{where} \quad L_{AN} = S(0.23V_Y) = 40(0.23V_Y) = 9.2V_Y, \quad (4.16)$$

$$a_{AN} = S(V_X - V_Y) = 40(V_X - V_Y), \quad (4.17)$$

$$b_{AN} = S[0.4(V_X - V_Y)] = 40[0.4(V_X - V_Y)] = 16(V_X - V_Y), \quad (4.18)$$

A number 40 is scaling factor  $S$ , which became the factor most widely used, although other factors have been applied (42, 43.909, 50...). Results from the ANLAB formula are therefore ambiguous unless  $S$  is clearly stated, mentioned the usual notation being (for  $S=40$ ) ANLAB (40) or one of abbreviations, AN(40) and AN40.

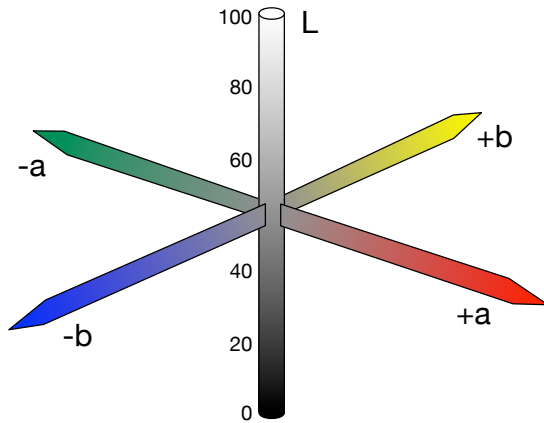


Figure 4.14 Lab color space

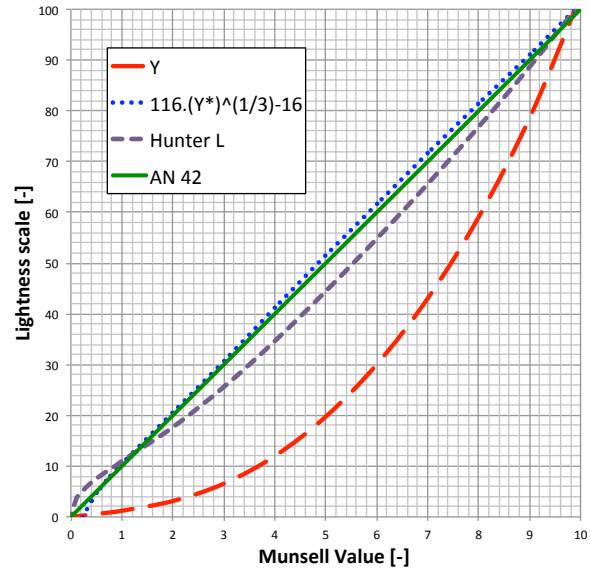


Figure 4.15 Comparison of different lightness scales L with Munsell value  $V$

At this time, several investigations came to consider the Judd polynomial function (Eqn. (4.13), it's modified form respectively) unnecessarily complicated, and suggested cube-root approximations of it. Other possibility was focused on simplified form of iterative calculations [74][75] or look up method based on tabulated values [76]. The approximation, which was finely used by CIE together with Hunter square-root approximation and Judd polynomial function as part of ANLAB with scaling factor 42, are visible in graph on Fig. 4.15

### 4.2.2 Glasser Cube-Root

Glasser, Reilly, and others developed scales that are designed to provide an approximation to the Adams chromatic value scales [79]. The formulas apply a lightness-response function to  $X$ ,  $Y$  and  $Z$  separately before taking differences:

$$L = 25.29G^{1/3} - 18.38, \quad (4.19)$$

$$a = K_a \left( R^{1/3} - G^{1/3} \right), \quad (4.20)$$

$$b = K_b \left( G^{1/3} - B^{1/3} \right), \quad (4.21)$$

where

$$R = 1.1084X + 0.0852Y - 0.1454Z$$

$$G = -0.0010X + 1.0005Y + 0.0004Z$$

$$B = -0.0062X + 0.0394Y + 0.8192Z$$

$$K_a = 105 \text{ for } R < G \text{ and for } K_b = 30.5 \text{ B} < G$$

$$K_a = 125 \text{ for } R > G \text{ and } K_b = 53.6 \text{ for } B > G$$

### 4.2.3 CIELAB

As in the case of the CIELUV color space, the CIELAB (1976) space is based on the CIE XYZ space and a white reference point [85]. It is a nonlinear transformation from XYZ; the nonlinearity is introduced to emulate the logarithmic response of the human eye. The lightness component  $L^*$  is calculated as:

$$L^* = 116Y^* - 16, \quad (4.22)$$

$$a^* = 500[X^* - Y^*], \quad (4.23)$$

$$b^* = 200[Y^* - Z^*], \quad (4.24)$$

where

$$X^* = \begin{cases} \left(\frac{X}{X_0}\right)^{1/3} & \text{if } \frac{X}{X_0} > 0.008856 \\ 7.787\left(\frac{X}{X_0}\right) + 0.138 & \text{if } \frac{X}{X_0} \leq 0.008856 \end{cases}$$

$$Y^* = \begin{cases} \left(\frac{Y}{Y_0}\right)^{1/3} & \text{if } \frac{Y}{Y_0} > 0.008856 \\ 7.787\left(\frac{Y}{Y_0}\right) + 0.138 & \text{if } \frac{Y}{Y_0} \leq 0.008856 \end{cases}$$

$$Z^* = \begin{cases} \left(\frac{Z}{Z_0}\right)^{1/3} & \text{if } \frac{Z}{Z_0} > 0.008856 \\ 7.787\left(\frac{Z}{Z_0}\right) + 0.138 & \text{if } \frac{Z}{Z_0} \leq 0.008856 \end{cases}$$

Although this new color space was intended to deal with reflective “color”, it was soon adapted for use in describing “luminous” colors as well. It has come into widespread use in various graphics software packages and for other color management purposes. It is a member of the luminance-chrominance family. The traditional designation of the space is  $L^*a^*b^*$ , where the asterisks remind us of the nonlinear nature of its three variables.

The luminance-like aspect of the reflective color is actually described by the variable *lightness*, indicated as  $L$ . It is nonlinearly related to the reflectance of the surface so as to more closely follow the human eye’s perception. In CIELAB computing of such nonlinearity is the exponent 1/3 (root-square) as replacement of fifth-order polynomial function in ANLAB color space. For all the above expressions, if any of the ratios  $X/X_0$ ,  $Y/Y_0$ , and  $Z/Z_0$  is less than or equal to 0.008856, then that ratio is replaced by linear relation as visible on Fig. 4.16. The purpose of the linear piece of the nonlinear function is that with the traditional function (stated just above), when the inverse function is used (to convert from  $Lab$  to  $XYZ$ ) the slope of the function becomes infinite

at the origin, thus leading to implementation difficulties. The linear piece avoids this complication.

As was noted at the beginning, a coordinate system, which most intuitively relates to the human perception of color, defines a color in terms of luminance, hue, and saturation. In the  $a$ - $b$  plane of the CIE  $L^*a^*b^*$  color space, the angular position of the chrominance point (with respect to the set of axes) in fact corresponds to hue, and the radius from the origin to the point, divided by  $L^*$ , is indicative of saturation.

To produce a more intuitive set of coordinates, we can recast the  $a$ - $b$  chrominance plane from Cartesian (rectangular) coordinates to polar coordinates, using the variable  $C$  to represent the radius to the chrominance point and the variable  $h$  to represent the angle in degrees to the point, measured counterclockwise from the positive  $a$  axis.  $C$  essentially indicates the product of saturation and luminance, and  $h$  essentially indicates hue. The resulting space is called the CIE LCH space [89][90] (see Fig. 4.17) and it is described by following equations:

$$L^* = 116Y^* - 16,$$

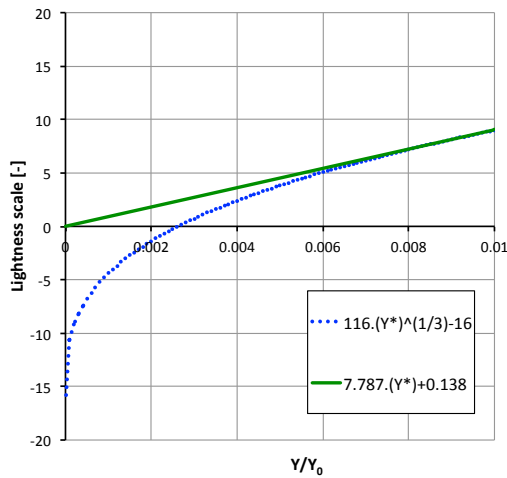
$$C^* = \sqrt{(a^*)^2 + (b^*)^2}, \quad (4.25)$$

$$h^\circ = \arctan\left(\frac{b^*}{a^*}\right), \text{ from interval } 0\text{-}360^\circ. \quad (4.26)$$

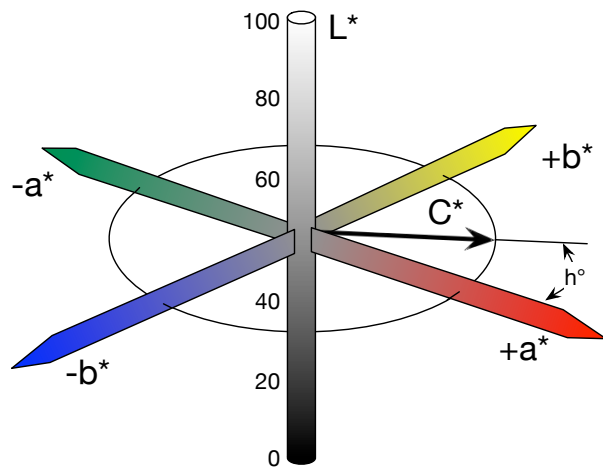
Because of its approximate perceptual uniformity, the distance in the CIE  $L^*a^*b^*$  space:

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (4.27)$$

is used to specify color tolerances.



**Figure 4.16** Derivation of the  $L^*$  curve



**Figure 4.17** Geometry of the CIELAB and CIELCH color model

Approximate correlates of certain perceived attributes of color and color difference (lightness, chroma, hue angle, and hue difference) could be calculated in CIELAB or CIELCH color space in the following manner:

$$\Delta L^* = L^*_{sample} - L^*_{target} \quad (4.28a)$$

$$\Delta a^* = a^*_{sample} - a^*_{target} \quad (4.28b)$$

$$\Delta b^* = b^*_{sample} - b^*_{target} \quad (4.28c)$$

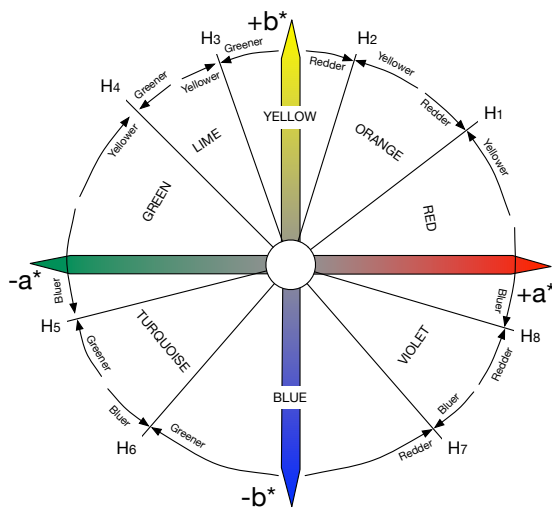
It is convenient to be able to express the same color difference in terms of differences in  $L^*$ ,  $C^*$ , and a measure that correlates with hue difference [91]. The sign convention for  $\Delta H^*$  ensures that  $\Delta H^*$  and  $\Delta h_{ab}$  will have the same sign. When these are compared with the other differences, it must not be neglected that  $\Delta h_{ab}$  is measured in degrees rather than CIELAB units, and thus has a different metric from these other differences. That means  $\Delta h_{ab}$ , being an angular measure, it cannot be combined with  $L^*$  and  $C^*$  easily [92]. What is used instead is:

$$\Delta L^* = L^*_{sample} - L^*_{target} \quad (4.29a)$$

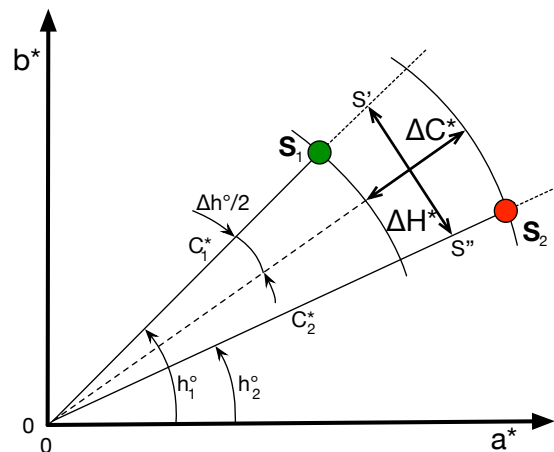
$$\Delta C^* = C^*_{sample} - C^*_{target} \quad (4.29b)$$

$$\Delta H^* = \sqrt{(\Delta E^*_{ab})^2 - (\Delta L^*)^2 - (\Delta C^*)^2} \quad (4.29c)$$

As can be seen  $\Delta H^*$  requires an indirect calculation method. This method shown above does not produce a negative sign and therefore is not generally recommended. Nevertheless, sign of  $\Delta H^*$  is possible to add based on Cooper's method determining appropriate hue-difference  $\Delta H^*$  descriptor, which is visible on Fig. 4.18. Generally speaking, counterclockwise direction of hue-difference  $\Delta H^*$  is positive and clockwise direction is negative sign.



**Figure 4.18** Cooper's method of determining appropriate hue-difference  $\Delta H^*$  descriptor in the CIELAB



**Figure 4.19** Geometric meaning of  $\Delta H^*$

Based on geometric meaning of  $\Delta H^*$  from Figure 4.17 an alternative calculation, direct definitions of  $\Delta H^*$  were suggested by Huntsman [93], Sève [94], Stokes and Brill [95], and can be used to replace the original indirect definitions:

$$\text{Huntsman [93]:} \quad \Delta H^* = \sqrt{2C_1^*C_2^*(1 - \cos \Delta h^\circ)} \quad (4.30)$$

$$\text{Sève [93][94]} \quad \Delta H^* = 2\sqrt{C_1^*C_2^*} \sin(\Delta h^\circ/2) \quad (4.31)$$

$$\text{Stokes-Brill [95]} \quad \Delta H^* = s\sqrt{2(C_1^*C_2^* - a_1^*a_2^* - b_1^*b_2^*)} \quad (4.32)$$

where  $s = 1$  if  $a_1^*b_2^* > a_2^*b_1^*$   $s = -1$  if  $a_1^*b_2^* \leq a_2^*b_1^*$

After the CIELAB and CIELUV color difference formulas were introduced by the CIE 1976, it quickly became apparent that, despite being as good or better than any other formulas then available, they could be further improved by adjusting the  $\Delta L^*$ ,  $\Delta C^*$  and  $\Delta H^*$  components, depending on their position in color space.

#### 4.2.4 Hunter LAB

Around 1958, Hunter developed a new formula, which was originally designed for use with illuminant C, and the 1931 2° standard observer. A general form of the equation suitable for use under other conditions is shown in equation [41],[97], [98]:

$$L = 100 \sqrt{\frac{Y}{Y_0}}, \quad (4.33)$$

$$a = \frac{K_a \left( \frac{X}{X_0} - \frac{Y}{Y_0} \right)}{\sqrt{\frac{Y}{Y_0}}}, \quad (4.34)$$

$$b = \frac{K_b \left( \frac{Y}{Y_0} - \frac{Z}{Z_0} \right)}{\sqrt{\frac{Y}{Y_0}}}, \quad (4.35)$$

where  $K_a = 175 \sqrt{\frac{X_{0i}}{X_{0C2}}}$  and  $K_b = 70 \sqrt{\frac{Z_{0i}}{Z_{0C2}}}$  are illuminant chromaticity coefficients.

$X_{0i}$  and  $Z_{0i}$  are co-ordinates of ideal white for the used illuminant,

$X_{0C2}$  and  $Z_{0C2}$  are co-ordinates of ideal white for the illuminant C and 2° observer.

$$\Delta E_{HLab} = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (4.36)$$



### 4.3 Color-difference formulas

A color-difference formula is an important quality control tool in the production of colored goods. The unsatisfactory uniformity of the CIELAB space prompted researchers to investigate other color-difference data and develop better color-difference formulas [99]. It was soon discovered that this equation had its shortcomings. These shortcomings were, that it was not taken into consideration that the human eye is more sensitive to small color differences in some regions of the color wheel and less sensitive in others. This means that a  $\Delta E$  of 1.0 could be a small visible difference in one area of the visible spectrum (i.e. dark blue colors) and a large visible difference in other area (i.e. light pastel type colors). After 1976, many attempts to develop more accurate color-difference formulas for evaluating small-to-medium color differences were made based on modifications to the CIELAB distance of  $\Delta E^*$  [100], [101], [102], [103].

#### 4.3.1 CMC( $l:c$ )

The CMC ( $l:c$ ) formula is based on the CIELAB color space and was recommended by the Color Measurement Committee of the Society of Dyers and Colourists [104]. This committee proposed the metric called the CMC color difference. The CMC color-difference formula, based on the CIELAB system, is defined as:

$$\Delta E_{CMC(l:c)} = \sqrt{\left(\frac{\Delta L^*}{l \cdot S_L}\right)^2 + \left(\frac{\Delta C^*}{c \cdot S_C}\right)^2 + \left(\frac{\Delta H^*}{S_H}\right)^2}, \quad (4.37)$$

where if  $L^* > 16$  then  $S_L = \frac{0,040975 \cdot L^*}{1 + 0,01765L^*},$

if  $L^* \leq 16$  then  $S_L = 0,511,$

$$S_C = \frac{0,0638 \cdot C^*}{1 + 0,0131C^*} + 0,638,$$

$$S_H = S_C \cdot (T \cdot f + 1 - f),$$

$$f = \sqrt{\frac{(C^*)^4}{(C^*)^4 + 1900}}$$

$$T = 0,56 + [0,2 \cdot \cos(h + 168)] \quad \text{for } 164^\circ \leq h < 345^\circ$$

$$T = 0,36 + [0,4 \cdot \cos(h + 35)] \quad \text{for } 345^\circ \leq h < 164^\circ$$

The ratio  $l : c$ , typically fixed at 2 : 1, controls the lengths of the axes of the ellipsoids representing color tolerance. The CMC formula is now the standard formula used in industrial color control [105], [106].

### 4.3.2 CIE1994

The complexity of the CMC formula has been criticized and after analyzing a large set of psychophysical data it was suggested that simple weighting functions,  $S_L$ ,  $S_C$ , and  $S_H$ , would be sufficient to improve the perceived color difference. Hence, CIE proposed a new formula, which is known as CIE94 [107], [108], [109], [110], and the color difference  $\Delta E_{CIE1994}$  is calculated by:

$$\Delta E_{CIE1994} = \sqrt{\left(\frac{\Delta L^*}{k_L \cdot S_L}\right)^2 + \left(\frac{\Delta C^*}{k_C \cdot S_C}\right)^2 + \left(\frac{\Delta H^*}{k_H \cdot S_H}\right)^2}, \quad (4.38)$$

$$S_L = 1, S_C = 1 + 0,045 \cdot C^*, S_H = 1 + 0,015 \cdot C^*.$$

The variables  $k_L$ ,  $k_H$ , and  $k_C$  are parametric factors to be adjusted according to different viewing conditions such as texture, background, and separation. In typical applications, the parameters  $k_L$ ,  $k_H$ , and  $k_C$  are set to unity. Present day is  $\Delta E_{CIE1994}$  abandoned.

### 4.3.3 M&S and Datacolor equations

In textile industry was used number of proprietary equations such as M&S and Datacolor. M&S 89 formula has been developed by Marks&Spencer in collaboration with Instrumental Color Systems (ICS now Datacolor International), England. This color difference formula is proprietary and has not been published, only number of comparisons with other formulas shows similar results as CMC ( $l:c$ ) [114][115]. Based on that Marks&Spencer recommends CMC ( $l:c$ ) equation as alternative during quality control process. Starting from 70-ties Datacolor International has offered a proprietary color tolerance formula. This formula has been field tested by customers with good success [111], later was this equation published [112]:

$$\Delta E_{DC} = \sqrt{\left(\frac{\Delta L^*}{F_L T_L}\right)^2 + \left(\frac{\Delta C^*}{F_C T_C}\right)^2 + \left(\frac{\Delta H^*}{F_H T_H}\right)^2} \quad (4.39)$$

$$F_L = \frac{0,092299 \cdot L^*}{1 + 0,051205 \cdot L^*} - 0,068156$$

if  $L^* < 16$  then set  $L^* = 16$

$$F_C = \frac{0,025963 \cdot C^*}{1 + 0,006236 \cdot C^*} + 0,232218 + 0,0026 \cdot L^* + 0,15 \cdot \sin(0,0805537 \cdot (L^* + 12,9))$$

$$F_H = \frac{0,008919 \cdot C^*}{1 + 0,001871 \cdot C^*} + 0,256594$$

$T_L$ ,  $T_C$ ,  $T_H$  are product specific parameters in both equations (4.39) a 4.40) provide product/production specific adjustments to the pass/fail limits. Values for these weights are obtained by statistical analysis of historical production data. The weight then incorporates both, any parametric effects present in the material being produced and an

overall sensitivity factor representative of the specific process or company making or purchasing the products. Thus, the commercial factors of CMC as recommended by the CIE are not required when using the Datacolor tolerance equation. Finally, the most unique feature is that the determination of these weights does not require historical data on FAIL batches but only on PASS batches. This can be a great advantage since most manufacturers do not keep records on their failures.

In 1995 was published enhanced Datacolor color tolerance equation with name DCI-95 [113], which is divided into two steps. First step is derivation of new color metrics and second one is color difference calculation.

1. Step shows compression, which is applied to the lightness and chroma scales:

$$L^{**} = G_1 \ln(1 + P_1 L^*),$$

$$C^{**} = G_2 \ln(1 + P_2 C^*),$$

$$a^{**} = C^{**} \cos(h_{ab}^*),$$

$$b^{**} = C^{**} \sin(h_{ab}^*),$$

where: 
$$G_1 = \frac{100}{\ln(1 + P_1 100)}, G_2 = \frac{100(1 - 0.2|\sin(h_{ab}^*)|)}{\ln(1 + P_2 100)},$$

and  $P_1$  and  $P_2$  are parameters (recommended values are:  $P_1 = 0.021$ ;  $P_2 = 0.060$ ).

2. Color difference equation:

$$\Delta E_{DCI-95} = \sqrt{\left(\frac{\Delta L^{**}}{T_L}\right)^2 + \left(\frac{\Delta C^{**}}{T_C}\right)^2 + \left(\frac{\Delta H^{**}}{T_H}\right)^2} \quad (4.40)$$

Optimization of  $P_1$ ,  $P_2$ ,  $K_L$ ,  $K_C$ , and  $K_H$  can provide a good match of DCI-95 to existing color tolerance equations, thus providing backward compatibility with existing production tolerances [112][113].

The coordinates of DCI-95 ( $L^{**}$ ,  $a^{**}$ ,  $b^{**}$ ) form a new color difference metric. The distinction between a color difference metric and a color tolerance metric are somewhat subtle but so significant. A big improvement between CIELAB and DCI-95 indicate the lack of global non-uniformity in the CIELAB metric. Just as it is believed that a color tolerance system, which produces visually uniform color differences is more elegant and of higher practical value than a non-uniform system, so it is believed that a color tolerance system, based on an approximately uniform metric, globally mapping distances equally across the bounds of color space, is more elegant and of greater practical value than a space which is locally distorted. DCI-95 appears to be such a global metric for object color space.

### 4.3.4 DIN99 color difference formula

The DIN99 color space, which was developed in 1999 and has been adopted as the German standard, is other representative of UCS based on nonlinear transformation of the CIELAB color space [116]. It originated from an idea by Rohner and Rich [113], who presented it as the DCI-95 formula. In general, the color differences in the DIN 99 color space will be smaller e.g. for higher chroma color pairs and therefore correlate better to the visual impression.

Temporary variable for redness:  $e = a^* \cdot \cos(16^\circ) + b^* \cdot \sin(16^\circ)$

Temporary variable for yellowness:  $f = 0,7 \cdot (a^* \cdot \sin(16^\circ) + b^* \cdot \cos(16^\circ))$

Temporary variable for chroma:  $G = \sqrt{e^2 + f^2}$

Temporary variable for hue angle (in radian):

$$h_{ef} = \begin{cases} \arctan(f/e) & \text{for } e > 0 \text{ and } f \geq 0 \\ \pi/2 & \text{for } e = 0 \text{ and } f > 0 \\ \pi + \arctan(f/e) & \text{for } e < 0 \\ 3\pi/2 & \text{for } e = 0 \text{ and } f < 0 \\ 2\pi + \arctan(f/e) & \text{for } e > 0 \text{ and } f \leq 0 \\ 0 & \text{for } e = 0 \text{ and } f = 0 \end{cases}$$

Then are computed co-ordinates of DIN99 color space:

$$L_{99} = (1/k_E) 105.51 \cdot (\ln(1 + 0.0158 \cdot L^*))$$

$$a_{99} = C_{99} \cdot \cos(h_{ef})$$

$$b_{99} = C_{99} \cdot \sin(h_{ef}),$$

were :  $C_{99} = (\ln(1 + 0.045 \cdot G)) / (0.045 k_{CH} k_E)$

$$h_{99} = h_{ef} \frac{180}{\pi}$$

The size of the perceived color differences can be influenced by external factors. The  $k$  factors can be used for this purpose (generally, it is not recommended to use factors different from 1).

$$\Delta E_{DIN99} = \sqrt{(\Delta L_{99})^2 + (\Delta a_{99})^2 + (\Delta b_{99})^2} \quad (4.41)$$

### 4.3.5 CIE2000

Additional attempts have been made to adjust the color difference equation to further improve the uniformity, and in 2001 a new color difference formula, CIEDE2000 ( $\Delta E_{CIE00}$ ), was proposed and adopted by the CIE [117]. CIEDE2000 is the latest CIE recommended color-difference formula based on CIELAB [118]. This color difference formula is based on the modeling of five aspects: chroma dependency, hue dependency, and a rotation term in the blue area, lightness transformation and neutral gray modeling. Among the new parameters, a term for improving the performance in the blue colors and a rescaling factor of the CIELAB  $a^*$  axis improving the performance for colors close to the  $L^*$  axis, can be mentioned. It is important to notice that even though small noticeable improvements compared to  $\Delta E_{CIE1994}$  could be made in some parts of the CIELAB color space the complexity of the  $\Delta E_{CIE00}$  formula may reduce the performance of the color difference prediction in other parts of the color space.

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2} + R_T \left(\frac{\Delta C'}{K_C S_C}\right) \left(\frac{\Delta H'}{K_H S_H}\right) \quad (4.42)$$

$$\bar{L}' = (L_1 + L_2) / 2$$

$$C_1 = \sqrt{a_1^2 + b_1^2}$$

$$C_2 = \sqrt{a_2^2 + b_2^2}$$

$$\bar{C} = (C_1 + C_2) / 2$$

$$G = \left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right) / 2$$

$$a'_1 = a_1(1 + G)$$

$$a'_2 = a_2(1 + G)$$

$$C'_1 = \sqrt{a_1'^2 + b_1^2}$$

$$C'_2 = \sqrt{a_2'^2 + b_2^2}$$

$$\bar{C}' = (C'_1 + C'_2) / 2$$

$$h'_1 = \begin{cases} \tan^{-1}(b_1 / a'_1) & \tan^{-1}(b_1 / a'_1) \geq 0 \\ \tan^{-1}(b_1 / a'_1) + 360^\circ & \tan^{-1}(b_1 / a'_1) < 0 \end{cases}$$

$$h'_2 = \begin{cases} \tan^{-1}(b_2 / a'_2) & \tan^{-1}(b_2 / a'_2) \geq 0 \\ \tan^{-1}(b_2 / a'_2) + 360^\circ & \tan^{-1}(b_2 / a'_2) < 0 \end{cases}$$

$$\bar{H}' = \begin{cases} (h'_1 + h'_2 + 360^\circ) / 2 & |h'_1 - h'_2| > 180^\circ \\ (h'_1 + h'_2) / 2 & |h'_1 - h'_2| \leq 180^\circ \end{cases}$$

$$T = 1 - 0.17 \cos(\bar{H}' - 30^\circ) + 0.24 \cos(2\bar{H}') + 0.32 \cos(3\bar{H}' + 6^\circ) - 0.20 \cos(4\bar{H}' - 63^\circ)$$

$$\Delta h' = \begin{cases} h'_2 - h'_1 & |h'_1 - h'_2| \leq 180^\circ \\ h'_2 - h'_1 + 360^\circ & |h'_1 - h'_2| > 180^\circ; h'_2 \leq h'_1 \\ h'_2 - h'_1 - 360^\circ & |h'_1 - h'_2| > 180^\circ; h'_2 > h'_1 \end{cases}$$

$$\Delta L' = L_2 - L_1$$

$$\Delta C' = C'_2 - C'_1$$

$$\Delta H' = 2\sqrt{C'_1 C'_2} \sin(\Delta h' / 2)$$

$$S_L = 1 + \frac{0.015(\bar{L}' - 50)^2}{\sqrt{20 + (\bar{L}' - 50)^2}}$$

$$S_C = 1 + 0.045\bar{C}'$$

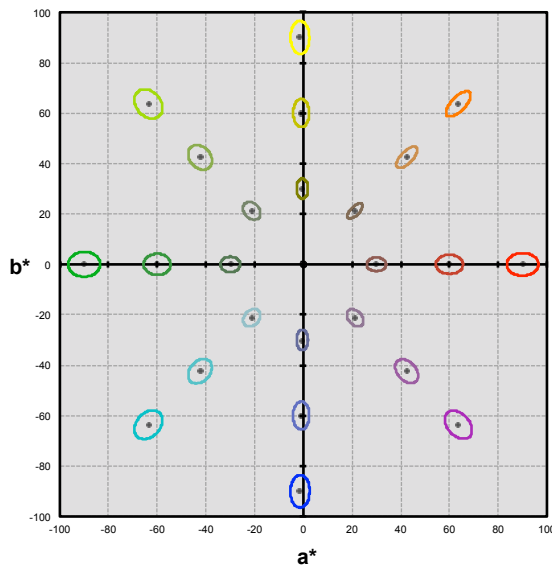
$$S_H = 1 + 0.015\bar{C}'T$$

$$\Delta\theta = 30 \exp\left\{-\left(\frac{\bar{H}' - 275^\circ}{25}\right)^2\right\}$$

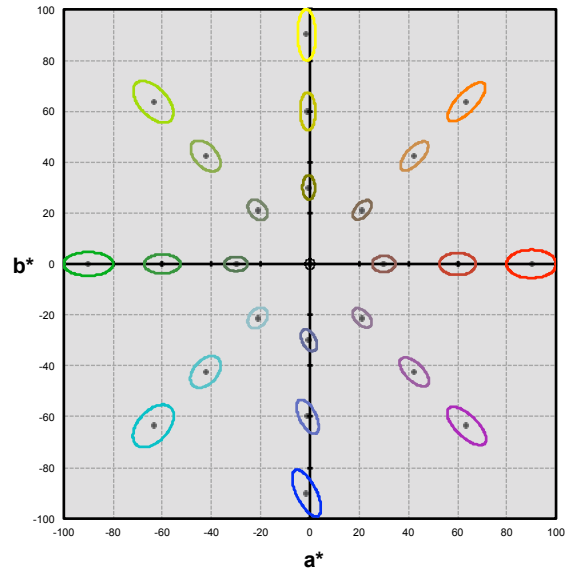
$$R_C = \sqrt{\frac{\bar{C}'^7}{\bar{C}'^7 + 25^7}}$$

$$R_T = -2R_C \sin(2\Delta\theta)$$

The weighting factors,  $K_L$ ,  $K_C$ , and  $K_H$  can be fitted to existing data sets, if they exist. For most applications, these weights are unknown and should be all set to 1.0. For the textile industry, the value of  $K_L$  may be considered as 2.



**Figure 4.20** Cross-section through their centroids of CMC ellipsoids in CIELAB chromaticity plane ( $\Delta E_{CMC} = 2$ )



**Figure 4.21** Cross-section through their centroids of CIE2000 ellipsoids in CIELAB chromaticity plane ( $\Delta E_{00} = 2$ )

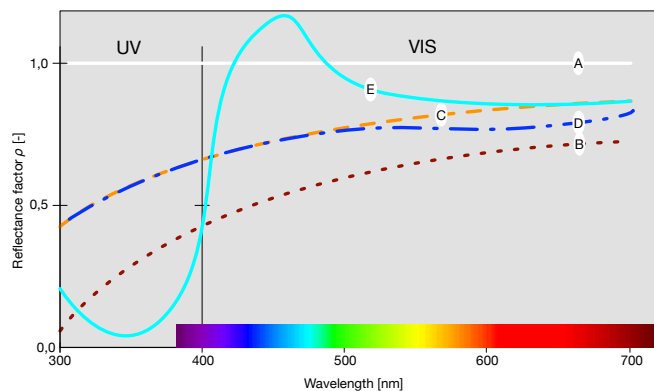
It should be noted that any such color difference formula or color space (even were it perfectly uniform) could only be strictly correct for one condition of viewing. Thus, as visual adaptation effects take place (in which the visual mechanism 'adjusts' as the level or color of the illumination changes), or simultaneous contrast effects are introduced (in which the sample is seen in context with other colors surrounding it) the uniformity of the space must deteriorate. Visual adaptation may reduce the significance of such differences, but they cannot be totally ignored when comparing colors on different media or when viewing conditions change radically (both of which are likely to happen with the reproduction of complex color images and hence when using color management). However, for many practical purposes, such as quality control, these problems are not relevant; the changes due to adaptation in controlled viewing conditions are small compared to the non-uniformity of the spaces themselves.

Nevertheless, it should be noted that the uniform color spaces are normally assumed to be 'uniform' for illuminant D65 with an illuminance level of 1000 lux. It is important to ensure that the 'uniformity' of this space also applies to any differences specified for graphic arts viewing conditions, using D50 with an illuminance level of 2000 lux. In future, it seems likely that color differences will be based on color appearance measurements (rather than simple measures of the stimulus) but there is much work to be done to get to that point. In the meantime, data is required to establish whether the existing formulae are satisfactory for our needs, and the extent to which the weighting of the various parametric constants in the models will improve them for graphic arts applications. That same data can also be used as a means of evaluating any future models, possibly including those based on appearance modeling if the experiments are sufficiently comprehensive.

## 5 WHITENESS MEASUREMENT

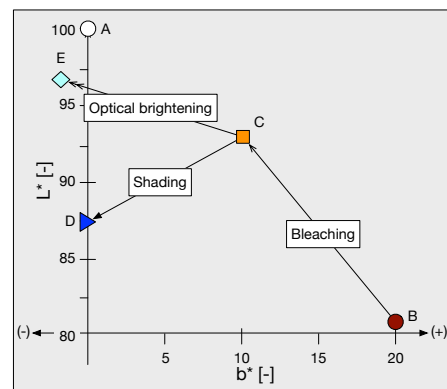
A number of materials such as cotton fibers, paper, etc. have a yellowish shade because of the lignin, which is present inside fiber or that organically binds individual fibers together. Final applications require substrates with the greatest possible whiteness and brightness. The consumer judges the whitest shirt to be freshest and cleanest and will automatically choose it from several on display. Why? A white is connected with purity, freshness, and cleanness. In some products whiteness is not only psychologically associated with purity but also is actually an indicator of freedom from contaminants, and as such it can be a measure of the quality of the product. This means that manufacturers have to find ways of whitening and brightening their products. This is done by bleaching and cooking the raw form of substrate (fibers, pulp, etc.), but this is a time-consuming and costly process. Another way of brightening a product is to add chemicals known as optical brightening agents (OBAs) or fluorescent whitening agents (FWAs) to the product to increase the shorter blue wavelengths, attempting to offset the natural yellowness. Fluorescence depends on the UV content of the light source and leads to brightness values well over the „ideal“ value of 100; shading dyes on the other hand have no influence on brightness, but a huge impact on perceived whiteness.

Whiteness is almost as nebulous a term as accuracy since no one has been able to define the perfect white. Whiteness is the visual perception of even reflectance of the entire visual spectrum. Some so-called whites may have a pinkish tint, some may have a bluish tint, and some may exhibit a more neutral shade (or lack of tint). For non-fluorescent whites a perfect white would have a CIE purity of 0 and  $Y$  of 100. Visually, whiteness is something more than mere lightness measured by  $Y$  or  $L$ . Special scales have been developed to measure it. In this chapter, the source and perception of white colors are discussed, and a number of scales used specifically in the measurement of whites are described.



**Figure 5.1** Spectrophotometric curves for a textile after bleaching, and addition of blue dye (shading) and OBA

*A – ideal white B – raw substrate  
C – bleached substrate (peroxide bleaching)  
D – bleached a shaded substrate  
E – OBA containing bleached substrate*



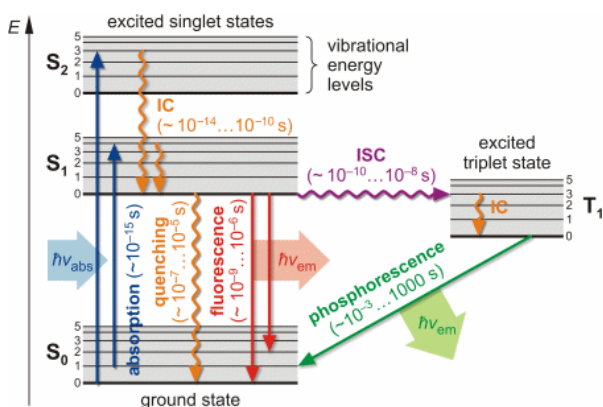
**Figure 5.2** Position of a white material on a lightness-yellowness diagram:

*A – ideal white B – raw substrate  
C – bleached substrate  
D – bleached a shaded substrate  
E – OBA containing bleached substrate*

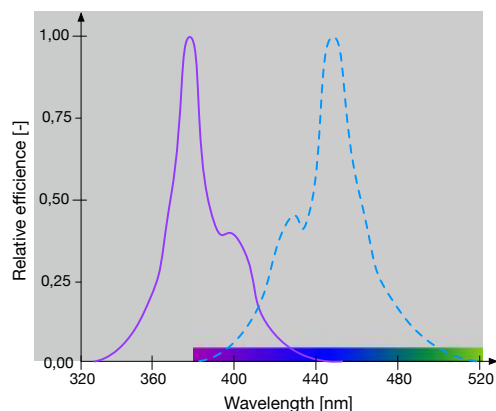


Most dyes and pigments owe their color to the selective absorption of incident light. In some compounds, color can also be observed as a result of the emission of visible light of specific wavelengths. These compounds are referred to as luminescent. The most commonly encountered luminescent effects are fluorescence and phosphorescence. The transitions, which can occur in a molecule exhibiting either fluorescence or phosphorescence, are illustrated in Fig. 5.3. When the molecule absorbs light it is excited from the lowest vibrational level in its ground state ( $S_0$ ) to arrange of vibrational levels in the singlet first excited state ( $S_1^*$ ). In the case of luminescent organic molecules, this is generally a  $\pi$ - $\pi^*$  electronic transition. During the time the molecule spends in the excited state, energy is dissipated from the higher vibrational levels, and the lowest vibrational level is attained (average live time  $10^{-12}$  s). Fluorescence occurs if the molecule then emits light as it reverts from this level to various vibrational levels in the ground state (live time  $10^{-8}$  s). Non-radiative processes, the most important of which is generally collisional deactivation, also gives rise to dissipation of energy from the excited state. As a result, there will be a reduction in the intensity of fluorescence and in many cases, it will be absent altogether. Another process, which may occur, is intersystem crossing to a triplet state. Emission of light from the triplet state is termed phosphorescence, a phenomenon that is longer-lived than fluorescence ( $>10^{-2}$  s).

As a consequence of the loss of vibrational energy in the excited state, fluorescent emission occurs at longer wavelengths than absorption, the difference between the wavelengths of maximum emission and maximum absorption for a fluorescent compound being referred to as the Stokes' shift [119], see Fig. 5.4. In the case of a fluorescent brightening agents that absorbs light in the UV region of the spectrum and re-emit the energy at the lower (blue) end of the visible spectrum. When incorporated into a white substrate, such as a textile fabric or a plastic article, OBAs provide a particularly appealing bluish cast. One of the most important uses of OBAs is in washing powders to impart a bluish whiteness to washed fabrics. Beside textiles, OBAs are used in many papers, especially high brightness papers, resulting in their strongly fluorescent appearance under UV illumination [120], [120], [122]. Optical brighteners have also found use in cosmetics. One application is to formulas for washing and conditioning grey or blonde hair, where the brightener can not only increase the luminance and sparkle of the hair, but can also correct dull, yellowish discoloration without darkening the hair.



**Figure 5.3** Energy transitions in fluorescent and phosphorescent molecules



**Figure 5.4** Example of excitation and emission spectra

The most prevalent question surrounding OBAs is the color management question, but this is not the only area of this issue that needs to be understood. An area of great interest is the stability of the OBAs contained in the fabric. The chemicals used do not work forever. Environmental concerns such as ozone and the chemical breakdown due to UV and air interaction quench the effects of OBAs over time, negating their effect.

When the effects of OBAs in fabric wear off, the fabric appears yellow. Many OBAs are not actually clear, but have a yellow tint to them naturally, so this yellowing is worse if the fabric had nothing added to it. This begs the question; do we color manage so that the fabric looks good tomorrow or a year from now?

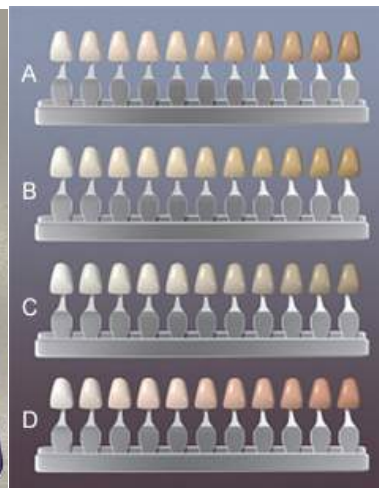
## 5.1 Visual evaluation of whiteness

The visual inspection of any sample depends on many factors, several of which can be controlled. The viewing condition is very important when it comes to a visual inspection of any product containing OBAs because the products itself is very sensitive to the light source to produce its effect. The amount of UV energy in the light source determines the amount of blue the OBAs will produce, and therefore how much yellow it is offsetting. If the lighting conditions are not exactly what has been predicted, then there can be a color cast in either the blue or yellow directions. This is most noticeable in the yellow and highlight areas.

Subjective whiteness rating is in the category of “matching”, which means tint compensation. In other words, task for the observer is to find standard for the sample, which is the best match from the scale of standards like in the case of color atlases. In industry, we use mainly white plastic standards from company CIBA since seventies of last century, Fig. 5.5 [123]. This scale was defined for visual whiteness rating and also for yellowing rating, which is typical due to aging of white plastics and paints by light. Visual rating was prescribed under the daylight simulator, which meets both color rendering index and spectral power distribution of CIE D65 illuminant.



**Figure 5.5** CIBA Plastic White Scale



**Figure 5.6** Tooth shade guide

*A reddish brown,  
B reddish yellow, C gray,  
D reddish gray*

Sample no. 1 appears most yellowish and sample no. 12 appears most white due to high content of FWA. Unfortunately, such scale isn't available on the market; therefore it is necessary to prepare own white scale or order similar FTS Acrylic White Standards at Avian Technologies LLC.

Typical cases of visual assessment of the whiteness also include the assessment of the whiteness of the teeth of patients for dental surgeries. The scale as can be seen in Fig. 5.6, respectively. Their reduced version, are used in determining the type of dentures and dental aesthetic modifications. During these checks should again be used illumination close to daylight D65, which is not always respected and dental surgeries are equipped with fluorescent lamps with a lower color rendering index CRI. The result is metameric Hue shift caused typically by using fluorescent lighting. Wherein it should be noted that the use of white LED, LEDs typically based on converters of light from a blue chip (B-LED), which are today the most widespread, is problematic. As documented in the graph in Fig. 4.10, the relative spectral distribution of the B-LED is containing practically no light energy below 420 nm, which results in inadequate perception of white materials, which contain PWD or yellowish pigmentation.

For this reason, there are various types of illuminators with high color rendering index. On Fig. 5.7 we see illuminator companies Addent [124], which is equipped with tri-band white LED. Six of them are set to substitute a color temperature of 5500 K and a color rendering index CRI = 92.2. Another six have then lower temperature 3900 K. During the visual assignment is possible between these two lights switch, which is above problem metameric hue shift partly offset because the dentist selects a standard that suits both light situations.

In Fig. 5.8, we can see a suitable approach to visual evaluation in this complex visual scene, which is covering the bottom of the teeth and oral cavity offset by the impact of surrounding and background on the assessed shade. Theoretically it would be possible to increase the resolution of the evaluator (dentist) with a covering mask, but it is not usual for practical reasons, because the tooth color is not uniformed. Finally, it is necessary to draw attention to the fact that most of dentures is a composite character, the combination of materials usually behave photochromic.



**Figure 5.7** The Rite-Lite 2 HI CRI Shade Matching Light, with color-corrected LEDs at a color temperature of 5500, 3200 and 3900K [124]



**Figure 5.8** Example of color matching arrangement by using of plastic strip with pink shade allowing minimize chromatic contrast [124]

## 5.2 Objective measurement of whiteness

Methods of objective evaluation of whiteness it is possible to divide into three groups:

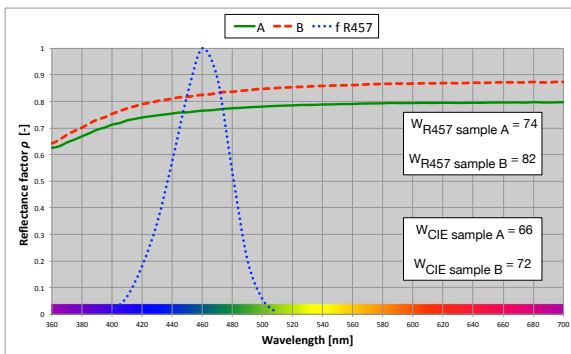
- Formulas directly computed from reflectance values (physical):  $W \approx R$
- One-dimensional whiteness formulas X, Y, Z:  $W = f(X, Y, Z)$
- Two-dimensional whiteness formulas:

$$W = f(Y, x, y) \text{ and } T = f(Y, x, y)$$

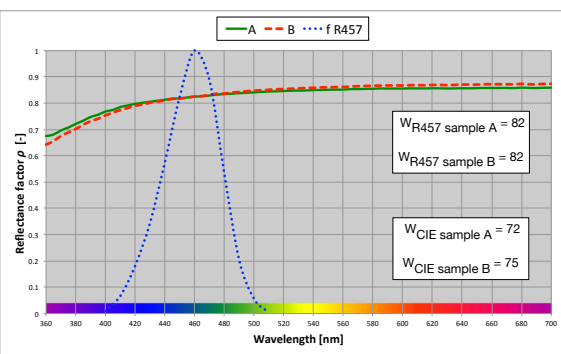
### 5.2.1 ISO Brightness

ISO Brightness, defined as the integral of reflectance values multiplied with a Gaussian-like profile peaking at 460 nm with a half-width of about 44 nm corresponds roughly to a method for the visual determination of the end-point of pulp or cotton bleaching by looking at a sheet through a blue filter. The method is very useful for this purpose, but the concept of brightness evolved to become a synonym of „white aspect“ and later of „whiteness“. It is logical to ask: Why it's necessary to use special blue filter? Why isn't used filter following CIE  $\bar{z}$  color matching function? The answer is interesting. Highly reflective white materials such as titanium dioxide, zinc oxide, etc., which absorb in the short wavelength violet region of visual spectrum represent one case in which two degree CIE standard color matching function insufficiently represent visual evaluation of whiteness. This was originally attained by observing the sample through a blue stained glass; in fact, the color observed through the blue filter appears with increasing brightness as bleaching progresses, the method is then strictly valid within a process step (same process, same pulp, same conditions) and it is a measure (expressed as number) that summarizes the action of the bleaching agent.

Two main types of brightness measurement are common. On the one hand, brightness can be measured by illuminating the product with a fixed angle of 45° relative to the angle of observation (TAPPI Method T 452). Alternatively, brightness can be evaluated by means of diffuse illumination, detecting the light that is reflected along a normal to the surface as described in T 571 and ISO Standard 2470.



**Figure 5.9** Example of two uncrossed reflectance curves of bleached substrate – evaluation by  $R_{457}$  is correct



**Figure 5.10** Example of two crossed reflectance curves of bleached substrate - evaluation by  $R_{457}$  is incorrect

The part of the spectral shape of filter  $R_{457}$ , respectively efficiency function  $F_{\lambda}$ , is shown in the graphs in Figs. 5.9 and 5.10. Given that currently use usually spectrophotometers are reflectance values being multiplied functions efficiency  $F_{\lambda}$  by  $R_{457}$  (tabular values are given in Annex C.1). The entire calculation of whiteness  $R_{457}$  notes equation 6.1

$$R_{457} = \frac{\rho_{400}F_{400} + \rho_{405}F_{405} + \dots + \rho_{510}F_{510}}{F_{400} + F_{405} + \dots + F_{510}} \quad (5.1)$$

It is clear that to calculate the value of ISO brightness  $R_{457}$  includes only the reflectance in the blue region of the spectrum. This fact leads to problems where the spectral characteristics of artwork and sample different characters. In cases where a crossing reflectance curves, as can be seen in the graph in figure 5.8, a situation may arise when the value of ISO brightness  $R_{457}$  are identical, although the sample B to us will act whiter appearance due to the higher reflectivity of this sample in the remainder of the visual spectrum. In the case of whiteness index-comprising evaluation within the entire visual spectrum (e.g., whiteness CIE - WCIE) is a measurement result in accordance with a visual assessment. For this reason, it may be advisable using ISO brightness  $R_{457}$  only for cases where the reflectance curves crossed. Regarding the use of this index for optically blazed materials is required in addition to the conditions observed even request to the correct setting the ratio of UV light used during measurement. As we show below, for this purpose they use special calibration standards. In addition to the ISO whiteness  $R_{457}$  were used in practice other simple indices such as Harrison, Stephansen, etc. [125], from today's perspective, however, have no practical significance.

### 5.2.2 One-dimensional whiteness formulas

This category includes a number of previously used formulas [126], such as formulas (5.2) to (5.5):

$$\text{Berger} \quad W_{Berger}(C/2) = Y + 3.452.Z - 3.908.X \quad (5.2)$$

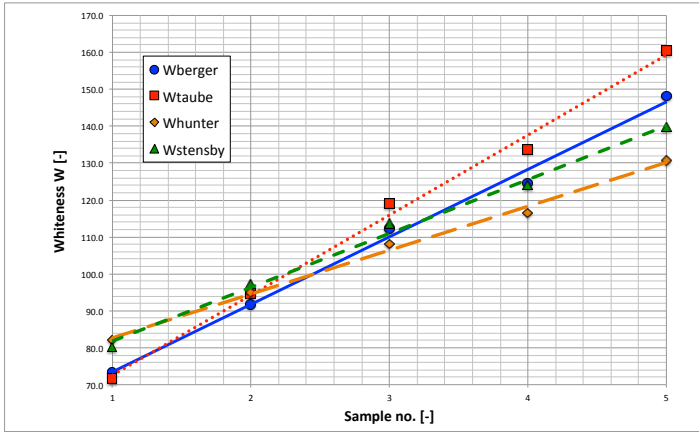
$$\text{Taube} \quad W_{Taube}(C/2) = 3.727.Z - 3.Y \quad (5.3)$$

$$\text{Hunter} \quad W_{Stensby}(C/2) = \frac{19.297.Z - 11.X}{\sqrt{Y}} \quad (5.4)$$

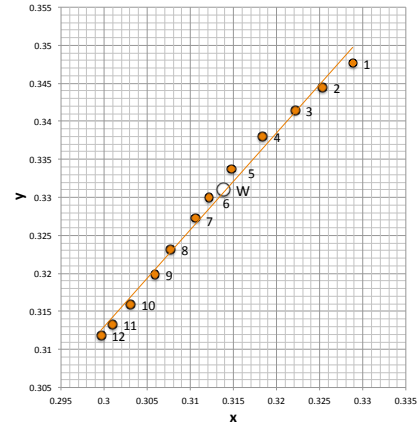
$$\text{Stensby} \quad W_{Stensby}(C/2) = \frac{19.297.Z + 55.251.X - 63.5.Y}{\sqrt{Y}} \quad (5.5)$$

It is apparent that samples bleached materials will give to each of these equations, slightly different results as can be seen from figure 5.11. For this reason, it is necessary to strictly control both for what whiteness index was calculated, but also for what lighting. Most published equations are referenced to the C light and a 2° observer.

Inconsistencies calculations whiteness of surfaces has been limited by introducing equation whiteness CIE, which belong to the third group of formulas to calculate whiteness materials [126] and based on Ganz-Griesser linear equation.



**Figure 5.11** Comparison of whiteness values calculated based on Eqs. 5.2-5.5



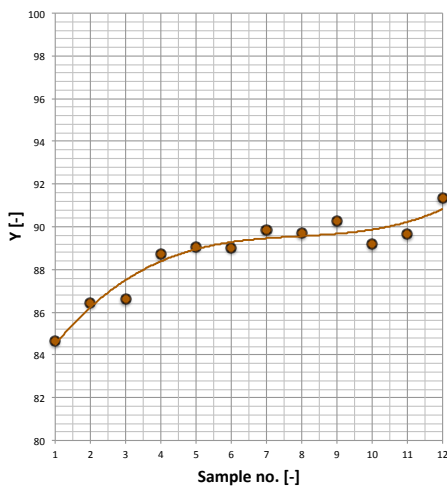
**Figure 5.12** Distribution of CIBA white scale samples in CIE xy diagram.

### 5.2.3 Two-dimensional whiteness formulas

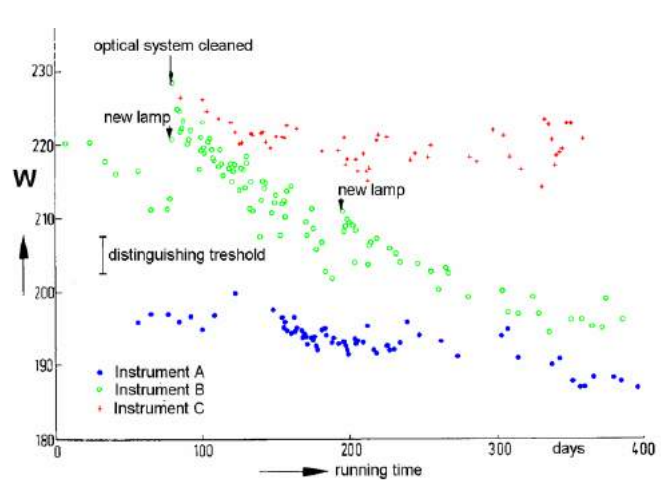
Whitening effect, respectively brightening the surface may also be considered a growth blue color and whiteness will rise on the basis of increasing the blue component during processing. The introduction of a second dimension resolves the problem posed by the existence of multiple preferred whites; a whiteness number and a tint or shade deviation value characterize each white sample.

Rise whiteness extends from the region of neutral point toward the blue zone of the CIE - x, y diagram to certain deviations and curving generally toward the green, as seen in the graph in Fig. 5.12.

Although the increase in the relative luminance Y nonlinear and is a relatively small increase in the perceived whiteness of the samples in a substantial portion of its linear course and the curvature occurs at higher concentrations of OBA. This has enabled companies Ciba and Geigy in late 60s to develop a special white calibration scale on cotton [128], from which was subsequently developed the plastic scale CIBA whiteness, as we can see it in Fig. 5.5.



**Figure 5.13** Relative luminance Y of CIBA white scale samples



**Figure 5.14** Long-term test with three instruments for whiteness measurement [129]



## Ganz – Griesser linear whiteness scale

Based on detail analysis of samples containing different concentration of FWA and measurement under daylight simulator D65 with different ratio of UV radiation was proposed equation, which known as Ganz-Griesser equation (sometimes called Ganz only). By analyzing the behavior of samples containing PWD at different ratios of UV radiation in the relative spectral composition of simulators daylight D65 was defined by the equation, which is currently known as Ganz - Griesser equation (sometimes shown only as Ganz equation) to measure whiteness. The basic shape of this equation defined Ganz 1971 [125] is as follows:

$$W_{Ganz} = D.Y + P.x + Q.y + C \quad (5.6)$$

wherein  $Y$  is brightness, and  $y$  are the coordinates of the sample measured in the CIE  $x, y$  diagram, and  $D, P, Q, C$  are adjustable parameters calculated from the regression analysis of the calibration measurement.

The reason for the introduction of adjustable parameters  $D, P, Q$  and  $C$  require a special calibration of measuring instruments, we can compare the data measured on different instruments. It turned out that only one calibration standard white (ceramic tiles, BaSO<sub>4</sub>, etc.) for fluorescent samples, enough. The cause is a method of imitation light D65. In Chapter 3.1 of the standard light source we were told that most used the simulator standard light source D65 for a xenon lamp complements the measurement device with a special conversion filter. However, it is important to realize that the xenon lamp has a limited lifetime and during use changes the relative spectral composition [129]. This is especially important for measuring fluorescent samples, as the UV intensity is affected not only by the state of discharge, but also contamination (soiling) device [130]. Fig. 5.14 shows the differences in the measured values of the brightness at three devices depending on the time of use, respectively operating devices. In particular, the apparent significant difference in measured values of whiteness for individual devices.

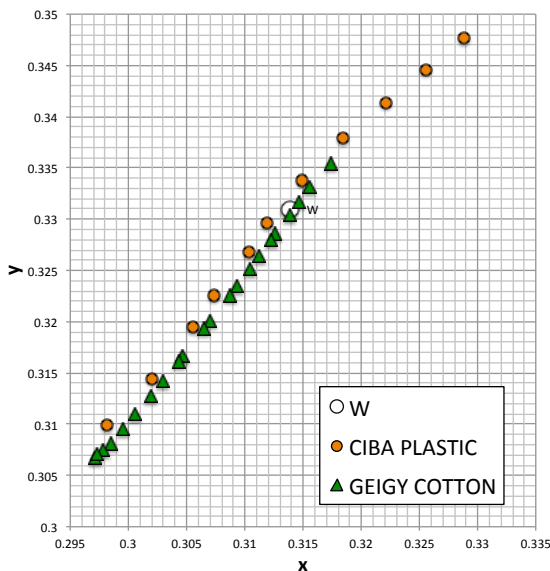
These reasons therefore led CIBA (created by merging the original company Ciba and Geigy) to develop special white scale that would allow accurate calibration of measuring instruments and comparability of measurement results. The original white scales Ciba was cotton and 18 steps (values), in the case of cotton scale Geigy even 22 steps. Fig. 15.5 shows that the scale is substantially linear and relatively uniformly graded. Later, particularly with regard to durability, came CIBA for producing white plastic scale, use of which is very soon spread [131] [132].

Given that this scale is not currently commercially available are used for calibration usually 4-5 membered scale of cotton or treated pulp. An example is 4 - membered cotton white scale, which is produced by a research institute Hohenstein (Hohensteiner Institute) [133]. The problem of scale is inferior durability, which results in that the reference brightness values for the individual samples are valid usually three months. After that you must use the new scale. For this reason, it is customary usage of plastic fluorescence standards for checking up of the UV spectrum Xe lamp between mandatory calibrations of measuring instruments, which instruments should be verified also with respect to the calibration coefficients in Ganz equation (5.6). These coefficients are individual and are not transferable between devices. In principle Ganz-Griesser calibration is inverse.

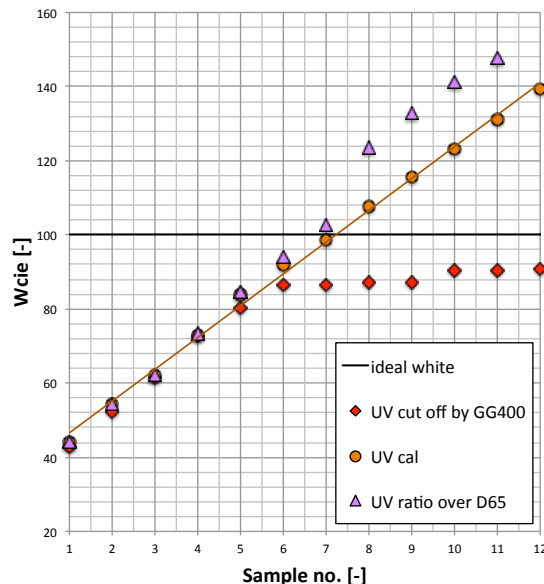
This means that the samples of the calibration scales are focused on a reference spectrophotometer with controlled D65 illumination simulator. This lighting is controlled by spectroradiometer that the measurements are not generally used for pulsed Xe lamp, but Xe arc lamp with continuous discharge stepped folded filters so as to achieve maximum approximation to the CIE standard light source (illumination) D65 [135]. At the moment when the calibration set samples measured using a commercial spectrophotometer operator is trying to achieve the same brightness value as in the case of a reference spectrophotometer. In the graph in figure 5.16 we can see that if the UV content is lower than with D65 illumination varies simple linear regression whiteness of each sample to a linear regression portions when the breaking point is below the ideal white. This makes it possible within normal tolerances (ratio) to reach a consensus on measured values of whiteness between individual devices within the range of 2.5 units Ganz whiteness.

The graph in figure 5.16 shows that the proportion of UV radiation must control the device that can be used for regular measurement of the whiteness of the material. Technically, there are two ways to achieve this. One method is based on decomposition of the measurement of the reflectance  $\rho(\lambda)$  on the individual parts. The curve of spectral reflectance  $\rho(\lambda)$  in the graph of figure 5.17 shows that in the spectral region from 420 to 500 nm can be measured spectral reflectance  $\rho(\lambda)$  is greater than the 1.

That would mean denial of the law of conservation of energy. Therefore, it is necessary to take into account the fact that in the case of luminescent (fluorescent and phosphorescent) materials with total radiance factor  $\beta_T$  uneven reflectance  $\rho$ , respectively  $\beta_R$ , but is equal to the sum of the contributions of the spectral radiance factor withdrawn  $\beta_R(\lambda)$  and the spectral luminescence factor  $\beta_L(\lambda)$  according to equation (5.7). In other words, **the assumption of equation (3.9) that affects luminescence measurements  $\beta_L(\lambda) \rightarrow 0$ , does not apply.**



**Figure 5.15** CIBA Plastic White Scale and Geigy Cotton Scale in CIE  $xy$  diagram



**Figure 5.16** Dependence of measured CIE Whiteness values of CIBA Plastic White Scale on amount of UV radiation in D65 illumination



$$\beta_T(\lambda) = \beta_R(\lambda) + \beta_L(\lambda) \quad (5.7)$$

Measurement of spectral luminescence factor  $\beta_L(\lambda)$  is done using either of two methods: two monochromators on device called spectrofluorimeters or using high pass filters. In 1998 he patented Imura [136] The method based on the use of three light sources with an excess of UV radiation (typically Xe lamp), when a filter was fitted high pass 400 nm, the second high pass filter 420 nm, and the third was without a filter. The resulting contribution spectral luminescence factor  $\beta_L(\lambda)$  was then calculated from the differences in spectral reflectance  $\rho(\lambda)$  in different types of lighting, respectively, according to equation (5.8):

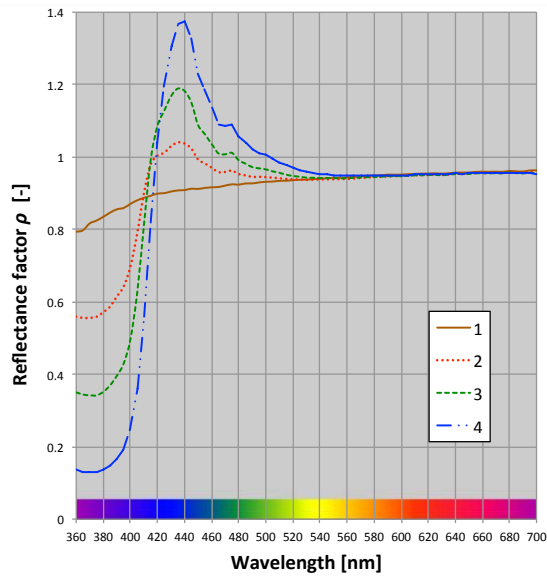
$$\beta_T(\lambda) = a_1(\lambda) \cdot \beta_{T1}(\lambda) + a_2(\lambda) \cdot \beta_{T2}(\lambda) + [1 - a_1(\lambda) - a_2(\lambda)] \cdot \beta_{T3}(\lambda) \quad (5.8)$$

where  $\beta_{T1}(\lambda)$  is called first total spectral radiance factor of (100% UV)  
 $\beta_{T2}(\lambda)$  is called second total spectral radiance factor (GG400)  
 $\beta_{T3}(\lambda)$  is called third total spectral radiance factor (GG420)  
 $a_1$  a  $a_2$  the first and second weighting factor

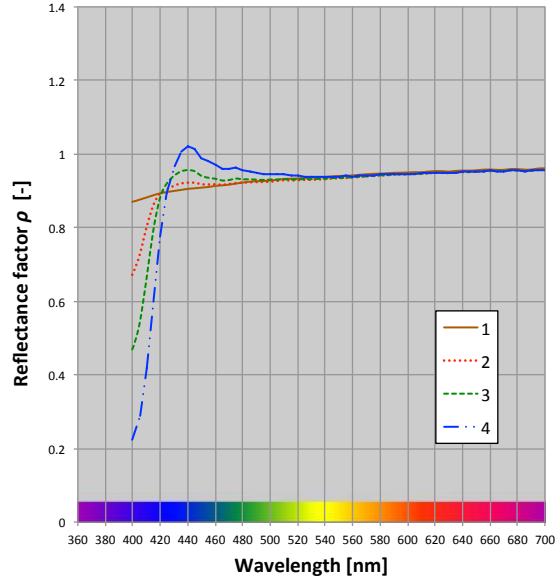
The graphs in Figures 5.18 and 5.19 show that this approach is flawed luminescence in the case of filters with a high pass 400 and 420 nm, as the OBAs also transform part of the light energy in the visual region of the spectrum. Curves of spectral reflectance  $\rho$  exhibit residual activity of OBA. As illustrated by the graph in Figure 5.20 only using a filter with a high pass filter of 460 nm, the curves are spectral reflectance  $\rho$  for all four samples equal, i.e. that there were "stalling" OBA. Despite the above-mentioned lack of firm Konica-Minolta launched the device under the name CM 3600, which is equipped with four-Xenon (two for di:8° and de:8°, two for 100% of UV filters and 400/420 nm), because in practical terms it is a mistake resulting in a normal tolerance for the evaluation of whiteness materials.

The second way accurate measurement of whiteness based on the Ganz-Griesser calibration procedure inverse proportion of UV, which are spectrometers equipped with a carousel with filters with high pass 400, 420 and 460 nm. In this case, the filter assembly GG400 such a way that the positioning of the filter to allow the platen cover opening integrating sphere ranging from 100% to 0%, as can be seen in the diagram in Figure 5.21. Thanks to multiple images within the integrating sphere containing UV radiation component is mixed with radiation without UV content. By high pass filter GG400 (SCHOTT) gradually covering the whole image setter of measuring device sphere there is a significant decrease of radiation below 400 nm so as to document the curves of relative spectral composition of light incident on the sample in the graph in Figure 5.22.

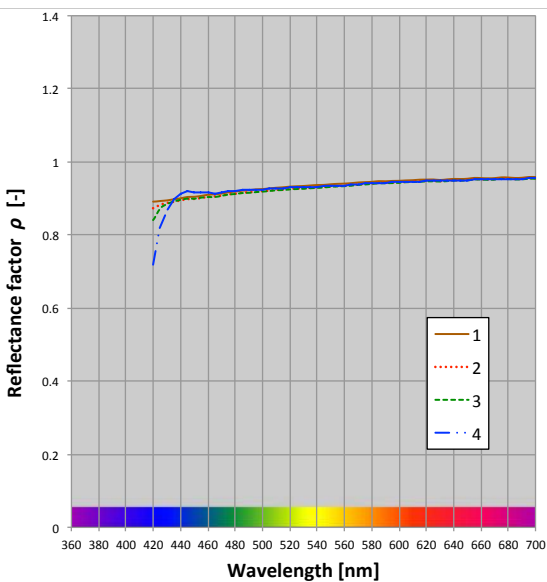
During Ganz-Griesser calibration, when the operator tries to achieve the same brightness values with calibration standards as a reference device with a controlled proportion of UV filter GG400 more or less inserted into a beam of Xe lamp. The resulting position of the filter is then either recorded service in case of spectrophotometers with manual feed of the filter GG400 or control program spectrophotometer when a servomotor controls the movement of the filter.



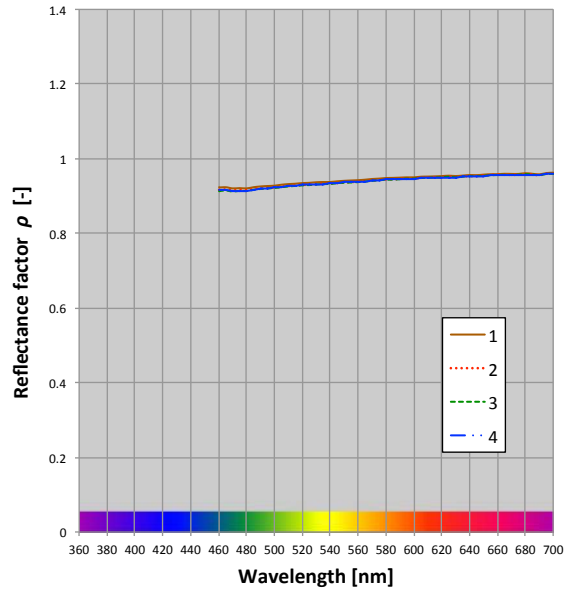
**Figure 5.17** Reflectance  $\rho$  of Hohenstein Cotton White Scale – UV calibrated



**Figure 5.18** Reflectance  $\rho$  of Hohenstein Cotton White Scale – cut-off GG400

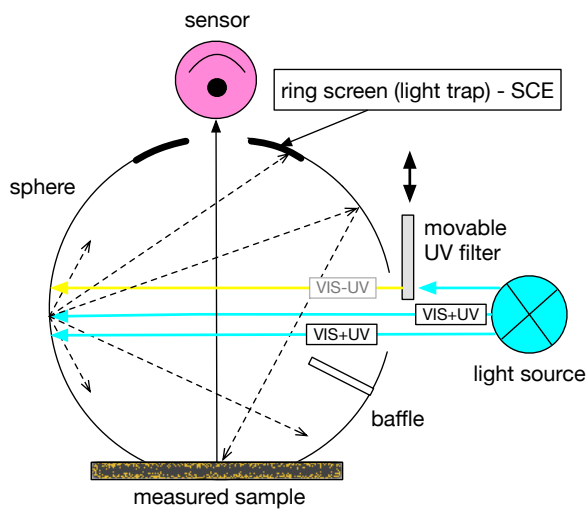


**Figure 5.19** Reflectance  $\rho$  of Hohenstein Cotton White Scale – cut-off GG420

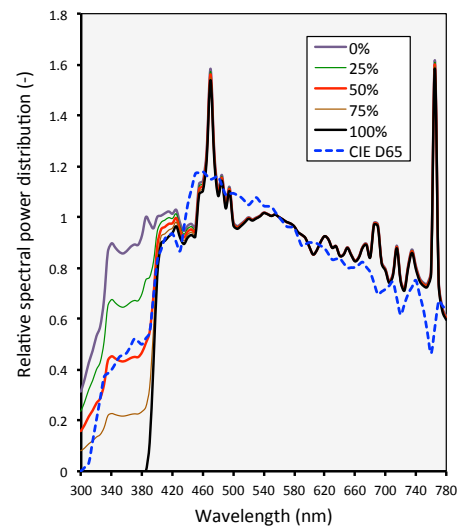


**Figure 5.20** Reflectance  $\rho$  of Hohenstein Cotton White Scale – cut-off GG455

The advantage of this approach is that the system can be controlled during measurement between regular annual calibrations with a plastic fluorescence standard (sometimes referred to as UV checker). The disadvantage of this method is that, unlike the approach Konica-Minolta, this method is more sensitive to the accuracy of the inverse calibration, thus the quality of the reference standards whiteness. This results in increase of the differences in whiteness measured with devices calibrated in different periods, and thus also on different scales whiteness. Besides the already mentioned problems apply to both Imura and Ganz method of measuring the whiteness of materials with optical brighteners is one important recommendations related instrument setting.



**Figure 5.21** Scheme of  $d:0^\circ$  SCE spectrophotometer with UV calibration capabilities



**Figure 5.22** SPDs of short arc 150W Xe discharge lamp (Oriol) – light beam is covered by different percentage by Schott GG395 filter

From the diagram in figure 5.21 shows that impinges on the sample mixture comprising a light containing no UV content. It is important to point out, that obvious recommendation for fluorescent samples is focused on directional geometry, respectively the spectrophotometer should employ a bidirectional optical measuring system with  $45^\circ:0^\circ$  or  $0^\circ:45^\circ$  illuminating and viewing geometry. The instrument may employ annular, circumferential, or uniplanar influx or efflux optics. When the specimen exhibits directionality, and an instrument with uniplanar geometry is used, information on directionality may be obtained by measuring the specimens at two or more rotation angles. If information on directionality is not required, then multiple uniplanar measurements may be averaged, or an instrument with annular or circumferential geometry may be used. However, even with annular or circumferential influx or efflux optics, some of the variability induced by specimen-optical system interactions may remain and the application of the practice for reducing the effect of variability of color measurement by the use of multiple measurements, which is described in chapter 7.2.

Hemispherical geometry using an integrating sphere is not recommended because of the spectral sphere error resulting from radiation emitted by the fluorescent specimen reflecting off the sphere wall and re-illuminating the specimen, thereby changing the spectral illuminance distribution on the specimen from that of the original instrument source. The spectral sphere error associated with hemispherical geometry decreases as the ratio of the internal area of the sphere to the measurement area increases. When the spectral sphere error is negligible, results obtained using hemispherical geometry may for some specimens under specific measurement conditions approach those obtained using  $45^\circ:0^\circ$  geometry. For this reason, all the whiteness measurement performed on the devices with an integrating sphere, which are obviously used in textile industry, in the setting  $d_e:8^\circ$  or, alternatively,  $d:0^\circ$  SCE, without specular reflection component must be set up. With regard to the geometrical arrangement used it is necessary to count also the influence of light reflected from a highly white material, which can

subsequently cause a triplet excitation and the fluorescence extinction typically in the interval 500-560 nm. Triplet effect is typically caused by pulsed-xenon light sources contrary to continuous arc, where this effect is invisible. Based on that instruments allowing reduced energy of flash (less than 70% of standard voltage at high voltage board of flash lamp) are preferred.

Assessing white samples with reference to a white scale generally are generally connected with projection of each on the white scale trajectory in the color space. Because exist smaller or larger differences in lightness, chroma and hue, it is necessary to quantify it. Hue differences have a much higher effect here than differences in lightness, and consequently it has been found useful to add to whiteness rating an indication as to a possible deviation towards green or red in CIE chromaticity chart. The white scale used is always neutral by definition, nevertheless its trajectory is never exactly that of a dominant wavelength, because no OBA behaves that way in its whiteness build up, and of course intrinsic color of the used substrate has some effect particularly at low saturation levels (low concentration of used OBA) and in the vicinity of the achromatic point [124]. Any tint assessment formulae whose neutral axis runs along a dominant wavelength hence be unpractical. The introduction of Ganz-Griesser equation for evaluating whiteness while allowing lay Hue touch sap called by the English word tint T:

$$T_{Ganz} = m.x + n.y + k \quad (5.9)$$

and where  $m$ ,  $n$  and  $k$  are again the adjustment parameters calculated from the regression analysis.

If is  $T = 0$ , the substrate has blue shade, respectively it is *neutral* ( B ),

If is  $T > 0$ , the substrate is *blue – green tinted* ( G ),

If is  $T < 0$ , the substrate is *red – violet tinted* ( R ).

More detailed specification shows the following table 5.1, including verbal description, which facilitates orientation in the codenames used.

**Table 5.1 Recommended terminologies of tint evaluation and abbreviations**

<i>Tint value T</i>	<i>Tint deviation TD</i>	<i>Meaning in coloristic terms</i>
< -5,5	RR	Tinted in red-violet direction
-5,5 till -4,51	R5	Very markedly more red-violet than the white scale
-4,5 till -3,51	R4	Markedly more red-violet than the white scale
-3,5 till -2,51	R3	Appreciably more red-violet than the white scale
-2,5 till -1,51	R2	Slightly more red-violet than the white scale
-1,5 till -0,51	R1	Trace more red-violet than the white scale
-0,5 till 0,49	B	No appreciable deviation in tint from the CIBA White Scale
0,5 till 1,49	G1	Trace more blue-green than the white scale
1,5 till 2,49	G2	Slightly more blue-green than the white scale
2,5 till 3,49	G3	Appreciable more blue-green than the white scale
3,5 till 4,49	G4	Markedly more blue-green than the white scale
4,5 till 5,49	G5	Very markedly more blue-green than the white scale
> 5,49	GG	Tinted in the more blue-green direction

That being said, the Ganz-Griesser calibration, respectively coefficients in equation (5.6) are device-dependent. In cases where either there is no corresponding set of fluorescent white standards (Hohenstein TITV, etc.), or in case of using portable spectrophotometers, which usually do not allow setting the proportion of the UV radiation can be used to calculate the Ganz-Griesser whiteness nominal coefficient values, presented in table 5.2.

**Table 5.2 Nominal values of regression coefficients for whiteness calculation based on Ganz - Griesser equation, illuminant D65 and**

<i>Coefficient</i>	<i>2° observer</i>	<i>10° observer</i>
P	-1866.340	-1868.322
Q	-3691.760	-3695.690
C	1808.570	1809.441
m	-1017.800	-1001.223
n	725.659	748.366
k	80.769	68.261

Ganz [137] recommends the use of equation limited to cases where the whiteness evaluated measured material has a minimum value of the specific luminance  $Y > 70$  and the range of tint in interval  $-6 < T < 6$ .

### CIE whiteness

To promote uniformity of practice in the evaluation of whiteness of surface colors, it is recommended that the formulae for whiteness,  $W$  or  $W_{10}$ , and for tint,  $T_w$  or  $T_{w,10}$ , given below, be used for comparisons of the whiteness of samples evaluated for CIE standard illuminant D65. The application of the formulae is restricted to samples that are called "white" commercially, that do not differ much in color and fluorescence, and that are measured on the same instrument at nearly the same time. Within these restrictions, the formulae provide relative, but not absolute, evaluations of whiteness, that are adequate for commercial use, when employing measuring instruments having suitable modern and commercially available facilities.

$$W_{CIE} = Y + 800.(x_0 - x) + 1700.(y_0 - y) \quad (5.10)$$

$$T_{CIE} = 900.(x_0 - x) - 650.(y_0 - y) \quad (5.11)$$

where  $x_0, y_0$  are coordinates of ideal white and  $x, y$  are coordinates of measured sample (in case of D65 and 10° observer  $x_0 = 0,31381$  and  $y_0 = 0,33098$ ).

For the perfect diffuser,  $W$  and  $W_{10}$  are equal to 100, and  $T_w$  and  $T_{w,10}$  are equal to zero. In case of FWA containing fabrics is obvious interval of whiteness 150 - 180. Linear whiteness formulae are applicable only within a restricted volume of the color solid. These formulae may be used only for samples whose values of  $W$  or  $W_{10}$  and  $T_w$  or  $T_{w,10}$  lie within the following limits:

$W$  or  $W_{10}$  greater than 40 and less than  $5Y - 280$ , or  $5Y_{10} - 280$ ;

$T_w$  or  $T_{w,10}$  greater than -4 and less than +2.

For a better idea, we can show the calculated values of whiteness according to ISO brightness R457 and patterns Berger, Taube, Hunter, Stensby, Ganz and CIE the same samples as we are documented in Table 5.3.

**Table 5.3 Whiteness and Tint values computed by using Eqs. (5.1-5.6, 5.9-5.11)**

Sample no.	$B_{ISO}$	$W_{Berger}$	$W_{Taube}$	$W_{Hunter}$	$W_{Stensby}$	$W_{GG}$	$T_{GG}$	$W_{CIE}$	$T_{CIE}$
1	91.5	83.3	82.7	88.1	87.4	75.5	0.5	85.3	-0.9
2	98.2	106.4	111.4	103.4	107.5	123.4	-0.2	107.2	-1.6
3	105.8	130.8	140.8	118.9	127.2	168.9	-0.4	128.3	-1.9
4	115.7	159.6	173.5	135.8	146.3	214.7	0.5	150.0	-1.1
5	103.9	127.7	134.0	115.8	119.1	163.1	2.1	123.6	0.4
6	104.2	119.9	134.0	115.8	130.7	162.2	-4.3	123.5	-5.3

It is obvious that with large differences between the samples (1-4), all discussed equation indicates the same sequence of samples. In the case when we compare two samples with near reflectivity (5-6) as indicated by the ISO brightness R457 may occur due to a considerable tint that lies outside the permitted tolerance for equations  $W_{CIE}$  paradox that equation based on a calculation using tristimulus will turn upside samples evaluated as we see in the case of equations  $W_{Berger}$  and  $W_{Stensby}$ . Moreover, it is obvious that the numerical difference between the two samples for these two equations disproportionately large. It is therefore necessary in the case of a combination OZP of disabilities and stains to monitor closely evaluated samples fall within the limits for the calculation of whiteness according to Ganz, or CIE.

### 5.3 Yellowness index

Yellowness index is in the evaluation of the material properties of great importance. Mainly because the materials may have the effect of external influences lose their original characteristics, may lead to degradation and yellowing of the surface layers of the material will become the first perceptible manifestation of such processes. Especially in the case of materials, which are exposed to UV radiation, moisture, water, and have a function as surface treatment, must be resistant to degradation and yellowing of the possible large to wasted product on the attractiveness and functionality.

It is known that the yellowing affects many materials in textile applications are not only natural fibers - wool, cotton and regenerated cellulose fibers but also synthetic fibers, such as PAD. Besides the effects of UV radiation are the main causes of degradation, which are manifested as yellowing with unstained fabric, respectively a hue change in the dyed fabric, heat treatment. These adjustments are primarily aims to stabilize the position of macromolecular chains within the fiber, the position of the fibers in the fabric, offset imbalances fiber-yarn-fabric and ensure knitted fabrics and more convenient processing and utility properties. Unsuitable process parameters such as the time-temperature regime, incorrect combination of chemicals, etc. lead to increased formation of yellow coloration of the resulting product.

Most however yellowing index is used in the case of paints and plastics, in the evaluation of light fastness with white materials. The degree of material fading is determined by the rate of yellowing. Finally, using the yellowness index of mining and paper industry to describe their basic products.

For the visual ratings of yellowness of the product before and after the accelerated weathering test, we can use the previously mentioned CIBA white plastic scale (Fig. 5.5), which also contains the standards for evaluating the degree of yellowing. As was mentioned before visually, yellowness is associated with scorching, soiling, and general product degradation by light, chemical exposure, and processing.

In the different sources, we can find a wide variety of formulas for calculating yellowness index [41] [54], such as the yellowing index BASF:

$$G_B = \frac{X}{0.7831} + 0.833Z \quad (5.12)$$

ASTM<sup>6</sup> D 1925 and DIN6167 yellowness index:

$$YI = \frac{1.2750X - 1.0584Z}{Y} \quad (5.13)$$

The ASTM D1925 method was withdrawn in 1995, but this formula still provides useful information. This index is always calculated for C/2°, regardless what illuminant and observer are chosen.

**ASTM E 313** yellowness index is calculated as follows:

$$YI_{E313} = \frac{100(C_X \cdot X - C_Z \cdot Z)}{Y}, \quad (5.14)$$

where  $C_X$  and  $C_Z$  are coefficients, which depend on the illuminant and observer as indicated in the table 5.4 below.

**Table 5.4 Eq. (5.14) coefficients under different conditions**

Coefficient	C/2°	D65/2°	C/10°	D65/10°
$C_X$	1.2769	1.2985	1.2871	1.3013
$C_Z$	1.0592	1.1335	1.0781	1.1498

As visible from Table 5.4, yellowness index E313 may be only calculated for illuminants D65 and C. Samples measured by method E313 must be nearly white and opaque. When items are being compared using YI E313, they must be similar in gloss, texture, translucency, and other physical attributes. If these criteria are not met, the yellowness values will not be meaningful.

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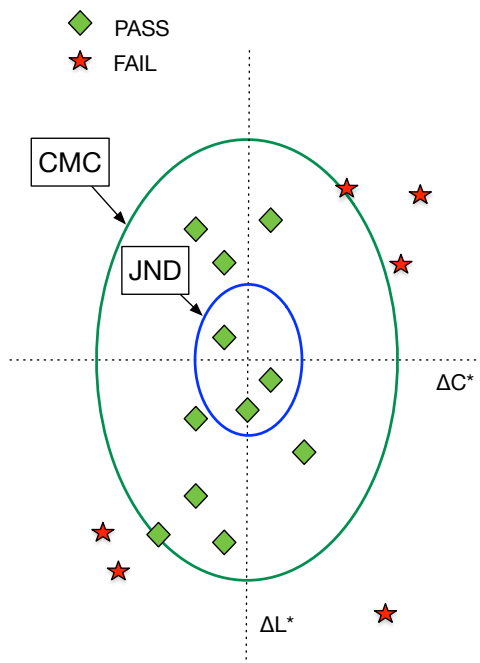
<sup>6</sup> ASTM - The American Society for Testing and Materials

## 6 SHADE SORTING

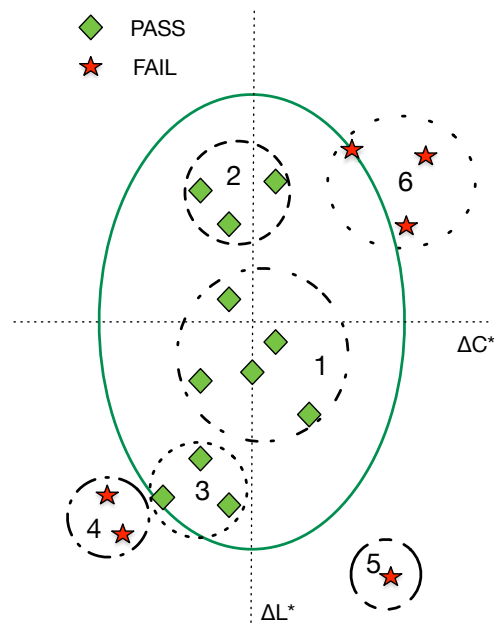
For several years, the textile and garment industries had difficulty in consistently classifying different fabrics on the basis of their color. Their variability of visual assessment over that time and the increasing demands of consumers concerning change of color, led to the need for solving this problem. A common quality problem in cut and sew operations is variation in color from one roll of fabric to another. If garment parts are cut from different rolls and sewn together without considering this variation, the end product may be unsatisfactory. One may well ask: Why is sorting necessary at all? First of all is important to understand that used tolerance ellipsoids are bigger than ellipsoids of color discrimination, as we can see on Figure 6.1.

Of course, we can adjust color difference formula by weighting factors and commercial factor to similar size as JND nevertheless it is raw technique. Why? Because end-customer has no possibility to check own product with industrial temporal targets, subsequently important information is color difference in individual batches (cutting lots typically). Based on that color difference between cutting lots is more important than color difference of individual cutting lots to temporal target.

One method used to avoid this problem is a process known as shade sorting. This operation is often performed by trained color sorters, who visually group the rolls of fabric to assure that those rolls cut together are similar enough in shade to be sewn into adjacent panels of a single garment. An example of possible visual sorting result is shown on Fig. 6.2, where was prepared 6 sorting groups.



**Figure 6.1** Ellipsoid of  $CMC(l:c)$ , which is frequently used during PASS/FAIL evaluation and JND ellipsoid



**Figure 6.2** Visual sorting (classification). Result: 6 sorting groups following JND requirement



However, advances in technology have produced color measurement instruments with sufficient accuracy and reliability to be used to measure color for numerical shade sorting. Numerical shade sorting refers to quantitative, objective methods for grouping rolls of fabric of similar color. It avoids the subjective aspects of visual shade sorting. Instrumental shade sorting, both at laboratory and production levels, is designed to allow an accurate identification of fabric which could be joined to make a garment without having marked color differences between parts that make it up.

Mention the word shade sorting to a textile person, and the most likely thought to come to mind is the *555 shade sorting* system so familiar to us for many years and was introduced by Simon [138].

This system of sorting goods by their color differences from standard using a grid arrangement has been an industry standard for almost 40 years. In spite of its wide acceptance and usage, it is a system, which is very inefficient, widely misunderstood, grossly misused, and falls short of meeting the needs of most textile operations.

In 555 shade sorting a 3-dimensional array of blocks (centered around the standard) are used to subdivide the acceptable matches to standard into smaller groups. Each group is designated with a three-digit code. Each digit varies from 1-9 and represents the distance from standard in each color difference dimension. The center block (containing the standard) is thus designated 555. Each member of a group is close enough in color to other members of the same group to prevent any noticeable color variation between them. The size of each block is set by the user (a tolerance) to limit the amount of shade variation within each group. The tolerance is a set of 3 numerical values that control the dimensions of each block, typically in  $dL^*$ ,  $dC^*$ , and  $dH^*$  (Figure 6.3) - although variations exist which use  $dL^*$ ,  $da^*$ , and  $db^*$  [139], to their respective digit after weighting by the sort tolerances [140]. These numbers are then scaled so that 5,5 becomes the middle of the series. If the weighted tolerance values are designated with the letter  $T$  ( $T_L$ ,  $T_C$ ,  $T_H$ ), the sort numbers can be calculated as follows:

$$S = 100.N_L + 10.N_C + N_H, \quad (6.1)$$

where

$$N_L = \text{Integer} \left( \frac{\Delta L^*}{T_L} + 5,5 \right), \quad (6.2)$$

$$N_C = \text{Integer} \left( \frac{\Delta C^*}{T_C} + 5,5 \right), \quad (6.3)$$

$$N_H = \text{Integer} \left( \frac{\Delta H^*}{T_H} + 5,5 \right), \quad (6.4)$$

Integer is function used to round a number down to the next lowest integer while removing the decimal portion of a number.

Tolerances in each of the color directions are best derived from experience and may differ for a variety of products. Set of tolerances can be expressed in term of a ratio, for

instance Simon recommends general ratio  $T_L : T_C : T_H$  as 4 : 2 : 1, in case of CIELCH such ratio is: 0.8 : 0.4 : 0.2. Aspland and Jarvis [141] recommends slightly differ ratio: 2.38:1.89:1.20 (0.50:0.39:0.25).

If we will have sample, which is, differ to target in following differences:

$$\Delta L^* = 0.5$$

$$\Delta C^* = 0.5$$

$$\Delta H^* = 0.5$$

Than based on equation (6.2) and Simon recommended ratio we obtain result:

$$NL = \text{Integer}(0.5/0.8+5.5) = \text{Integer}(6.13) = 6$$

Other equations result is shown in Table 6.1:

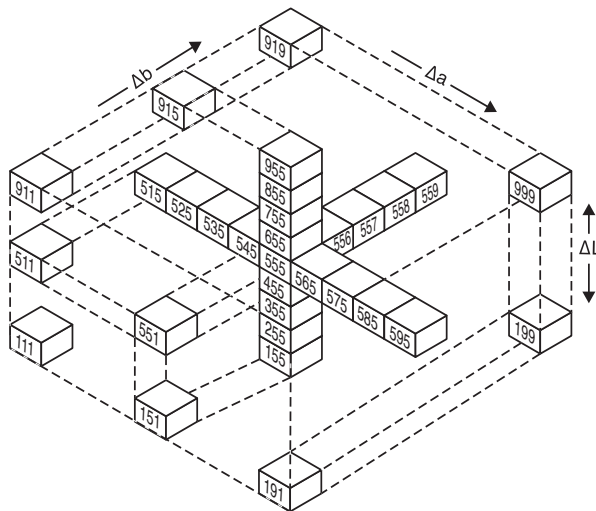
**Table 6.1 Setup and results of 555 shade sorting referred equations (6.1-6.4)**

	<i>SIMON</i>	(6.2;6.3;6.4)	555 (6.1)	<i>ASPLAND</i>	(6.2;6.3;6.4)	555 (6.1)
$T_L$	0.8	6.13	6	0.50	6.51	6
$T_C$	0.4	6.75	6	0.39	6.77	6
$T_H$	0.2	8.00	8	0.25	7.50	7

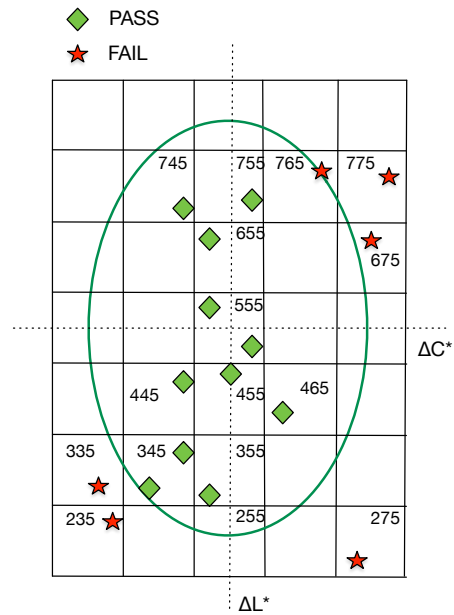
In this simple example is present “sensitivity” of 555 sorting system. The selection of the tolerances by the user is critical to the performance of the system. Tolerances, which are too large, will produce shade groups with excessive shade variation within each group. Tolerances, which are too small, result in too many subdivisions of the population with many of the shade blocks only containing one or two pieces.

Also, affecting the performance of the system is the user’s choice of color difference method. While the system was originally designed to use  $dL^*$ ,  $dC^*$ ,  $dH^*$  dimensions, most users opt for color differences using  $dL^*$ ,  $da^*$ , and  $db^*$ . The result is poor agreement with visual results for those colors that do not fall on or close to the  $a^*$  or  $b^*$  axis. Visual acceptability in CIELAB color space has been shown to be more critical of hue variation ( $dH^*$ ) than chroma variation ( $dC^*$ ), therefore the visual acceptability ellipsoid more naturally aligns itself with color differences (and tolerances) presented in  $dC^*/dH^*$  form than with  $da^*/db^*$  [142][143][144].

In typical use the system generates more sort codes than are necessary in order to effectively sort a set of pieces. Yet enlarging the size of the sort blocks (to decrease the total number of different sort codes) results in unacceptable variations between pieces placed into the same group. Furthermore, quite often pieces which fall into neighboring sort code blocks (and thus receive different sort codes) is in fact close enough to be indistinguishable from one another (Fig. 6.4). These problems result from the fact that 555 shade sorting is based on a fixed grid system. In addition, the shape of the 555 sort blocks (a rectangular volume similar to a brick) contains corners, which do not agree with the well-established ellipsoidal shape of visual acceptance in CIELAB color space. Another shape of the tolerance space that has been used is the truncated octahedron (TO) with 14 faces, six square and eight hexagonal faces, with each side having the same length, which was proposed by McLaren [145].



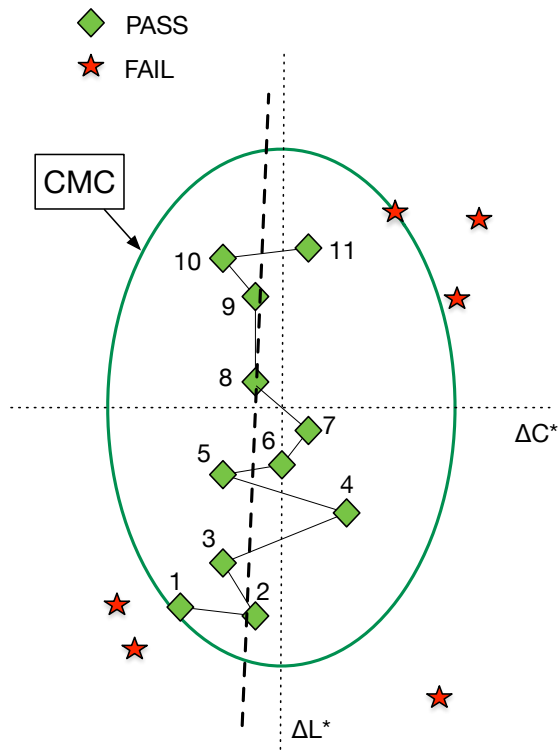
**Figure 6.3** Arrangement of sorting boxes of 555 shade sorting system in LAB color space



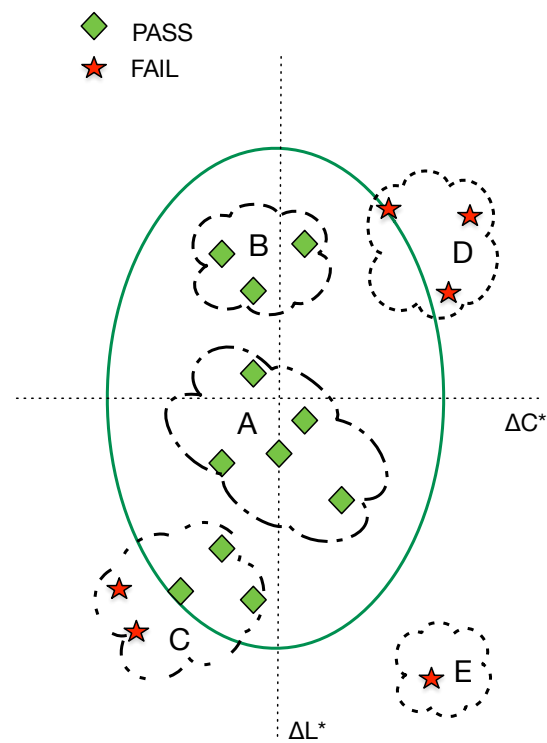
**Figure 6.4** Example of 555 sorting in CIELCH. Result 15 sorting groups!

All above-mentioned sorting methods are progressively replaced by statistical methods of shade sorting. Shade sequencing is a traditional process of manually arranging lots of dyed pieces so that the color difference between the adjacent pieces is not visually perceptible before stitching a garment. The shades can be sequenced by using visual tapering method, i.e. arranging lighter to darker or vice versa, which is a one-dimensional solution to the three-dimensional problem since colors are described in terms of three parameters, namely lightness, chroma and hue. Sequencing relies on the manner in which many textile goods are processed, and is similar in behavior to the visual method of **TAPERING** known in the denim industry. When tapering the person allocating pieces to fulfill a shipment visually arranges the pieces in a sequence to minimize shade variation between adjacent pieces. The pieces so arranged are shipped and used by the customer in that taper sequence. The problem of visual sequencing becomes complex when slight variation of hue is encountered along with the shade depth variation.

Numerical tapering determines where a *line-of-best-fit* can be drawn through the population (if possible), calculating an intercept point on an appropriate  $L^*C^*H^*$  axis, then arranging the pieces by increasing distance (in terms of  $CMC(l:c)$  color difference) from the intercept point. In this case, the two parameters with largest variation (such as  $\Delta L^*$  and  $\Delta C^*$ ) may be plotted by adding the minimum range of  $L^*$ ,  $a^*$  and  $b^*$  to each piece so that all the points lie in the first quadrant and the best-fit line can be worked out. Using the slope and intercept of this line,  $CMC(l:c)$  color difference between each point and intercept are calculated and arranged sequentially from highest to lowest along with the sample numbers to create a linear taper sequence. The samples so arranged may be divided into groups for stitching. While an excellent method for populations, which vary predominantly in one direction, it is very ineffective for more *random* populations. An example of a linear sequence is shown in Fig. 6.5.



**Figure 6.5** Tapering.  
Result: 11 numbered lots in sequence



**Figure 6.6** Cluster sorting.  
Result: 5 sorted groups

For taper sequencing of samples with random variation of color, was developed a method called Minimum Path, which mimics the type of pattern produced by human shade sorters. This approach uses a form of mathematics known as combinatorial minimization to produce a three-dimensional sequence through a random population using  $CMC(l:c)$  color difference of each piece from the previous piece as a measure of how good the sequence is. Even totally random populations can be sequenced in this manner. In addition, the nature of the algorithm tends to include pieces from the outside edges of the population whenever possible, having the effect of optimizing inventory by using up outlying pieces.

In clustering methods (Figure 6.6), the goal is to sort the given set of samples into the minimum number of clusters required to sort all of the samples. The user controls the size of each cluster, hopefully limiting its size to the maximum amount of variation acceptable within the intended process (for instance a cutting lot). The result is a set of samples which have been sorted into a small number of subsets, each of which can be treated as containing pieces which are visually acceptable to one another, respectively are smaller than size of JND. In practice, the most well-known method for accomplishing this technique is Clemson Color Clustering (CCC sorting), which uses a technique known as hierarchical complete linkage clustering [146]. In this method, distance and color difference are used interchangeably. Complete linkage refers to the property that the distance between two clusters is defined to be the maximum color difference between any two rolls, one from each cluster. The diameter of a cluster is defined to be the maximum color difference over all pairs of rolls in that cluster.

Aspland et al. [147][148] concluded that the samples in CCC clusters are distributed more uniform without any exception. Moreover, they later reported that the CCC method normally classifies a given set of samples into less than half the number of groups than the 555-shade sorting method. Nevertheless, some of observations [149] establish that the CCC method sorts a given set of samples into the minimum number of groups and the samples within the group have a more even distribution of samples of acceptable color difference. When assessed by this criterion, the CCC method has been shown to be far superior to the 555 and other block methods of shade sorting. The CCC shade sorting system is a *dynamic system*, in which the supplied lots (dyed rolls) or those in the stock grouped together initially may change when a new shipment is added to the inventory. This may change the number of groups and also the position of the initially grouped rolls from one cluster to another. As previously stated, it is the colorimetric values of the rolls which determine how they are grouped, not how they fall into a grid; while in the 555 system new rolls on evaluation fall into the previously created boxes (groups) on a grid. No need to re-group all the rolls of fabric.

Beside CCC system, modified CCC system respectively, are on the market now available other cluster sorting system such as K-means clustering, Scotsort, Datacolor SORT or adaptive clustering system SLI-Taper.

## 7 APPLIED COLORIMETRY

A question often asked is whether the operator has to know all the ins and outs of colorimetry when using color-measuring systems? The answer is not at all. The colorimetric approach of the color measuring systems means you are using measuring technology, which reproduces the way, the human eye works and how it perceives color and ensures that the perceived color difference between the batch and target is minimized through the use of control technology.

### 7.1 Visual assessment of color difference

A reliable method of assessment of color difference is extremely important as the incorrect rejection or acceptance of a batch of material has the consequence of extra cost and time in unnecessary color correction. In visual assessment, viewing conditions are extremely important if reproducible judgments are to be made. In particular, the following conditions should be arranged:

- **Choose the correct lighting condition.** The illumination should be a good simulation of one of the CIE standard illuminants. **Minimize surrounding light – turn off office light.** The only light in the room should be coming from within the light booth. Light is color, and even a little bit streaming through the window or from a table lamp can change the color perception of your sample. **Beware of metamerism.** To check for metamerism, view your samples under a variety of different light sources. The level of illumination must be sufficient to produce cone (photopic) vision. Range of **900-1700 lx** is used for evaluation of materials for medium lightness, very light materials can be assessed under illumination of 540 lx, and very dark material it may be as high as 2150lx (ASTM D1729). If is impossible to use lighting booth, then can be observation arranged under daylight of northern direction (on south hemisphere of south direction). It is recommended to do it from 10 a.m. to 3 p.m. (during winter season from 11 a.m. to 2 p.m.).
- **Surround Condition.** The nature of the background against which the sample is viewed must be controlled. It is important to understand that appearance of some colors is dependent on the lightness and color of the surrounding area. For example, simultaneous contrast will cause that grey sample will appear darker if is surrounded by white mask in comparison to black one. Similar problem is caused by colored surrounding area, which can beside lightness cause also hue and chromatic shift of assessed samples. Because of these effects, it is recommended that the background for visual assessments should be neutral grey of medium or higher lightness (a Munsell grey N7 - pale grey) and clean (without other samples, thinks, etc.). In case of critical evaluation category lightness of background should similar to standard. Nevertheless, in some of cases are specific requests, for example during visual cotton grading it is necessary to use black background due to correlation with HVI method.

- **Properly arrange your samples.** The field of view should be controlled; if the panels are of different size or shape then a mask should be cut from thin grey card and placed over the panels so that equal areas of the two panels are in view. The two panels should be positioned side by side, with no gap between them. Always position the standard on the same side of the pair, usually the left-hand side.
- **Look fast.** Allow a few moments for the eye to become adapted to the ambient illumination in the lighting cabinet before viewing the color-difference panels. If highly chromatic panels have been viewed, then allow a few minutes for the eye to readapt to neutral before judging the next pair of panels.
- **Use panel of observers.** The correct result as to whether a trial color matches that of the standard is taken as the majority decision of a group of colorists. On average an individual colorist will disagree with the majority decision about 17% of the time when judging pairs of panels with fairly small color differences (contrary to 30% of individual observer!!!).

In addition to the physical factors, which can affect the visual assessment, there are often psychological factors with strong influence. One of them is subjective color preference, for example some people prefer certain shades such as pink. If is sample, which is supposed to be white with pinkish tint, the person who likes pink would be offended, however, the customer who ordered white fabric and got pinkish one might have a vastly different opinion.

Visual assessment tends vary greatly from day to day. For example, a quality control person might happily accept a product, which is slightly out of tolerance on a Monday morning, when he or she is in a good mood, however, on Friday afternoon, when the classer is tired and grouchy, the same product would be rejected. Similar effect has good or bad news. During our investigation of selected psychological aspects of visual assessment, we found, that positive or negative emotion can shift evaluation with 1 unit of grey scale for assessment of color change.



**Figure 7.1** Lighting cabinet SpectraLight QC (X-Rite, USA)



**Figure 7.2** Example of wrong arrangement of number of “thinks” inside of lighting booth. Whole place should be clean, without another samples, etc.



**Figure 7.3** Example of correct conditions during visual assessment – office light is turn off, booth is placed in dark room

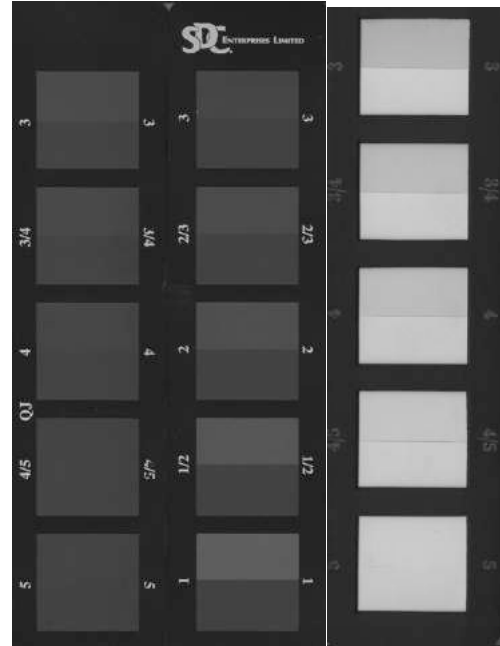
When discussing the visual assessments must indicate not only the applicable standard used in lighting, lighting intensity (illuminance), the geometry of illumination and observation ( $45^{\circ}:0^{\circ}$ ,  $0^{\circ}:45^{\circ}$ ), ordering samples, etc., but also the method of evaluation. In industry, we meet two basic methods of assessing the color differences. The first method is based on the finding that sample pass / fail certain tolerance; the second method is based on the assignment of the sample to the nearest standard range of approved standards. Because the preparation of such standards and time-consuming production, it is used typically in case of paints and plastic products, where it is not so frequent color change. Card production to agreed magnitude and direction of color differences for a given product usually deal with specialized companies. Sample discretionary cards with multiple standards are shown in Fig. 7.4. The advantage of these assessment cards is that they also allow a degree of color grading products; because they are the approved products are included in the respective groups during the assessment of color differences.

Two different grey scales are used to compare fading of specimen as well as staining of two adjacent white samples of different fibers placed and stitched on either side of the specimen. The grades are coded from 1-5, visually: *poor*, *moderate*, *good*, *very good and excellent*, respectively, e.g., if a dyed sample during wash fastness test shows no change in color, there will be no staining of white sample too – the wash fastness will be expressed as ‘change in color: 5 and degree of staining: 5 (no fading and no staining, i.e., excellent wash fastness or wash fastness rating 5) and so on. Look of a grey scale for a rate of fading as well staining 2 is depicted in Fig. 7.5 separately. In fact, the grey scales have nine possible grades of fading or staining for better precision, for example: 5, 4-5, 4, 3-4, 3, 2-3, 2, 1-2 and 1. Precision of result depends upon accuracy and expertise of evaluator and is also influenced by viewer’s vision standard as all colored specimen are to be compared with grey colored scales. Repeat ratings of the same specimen pair by one observer in one laboratory should give results agreeing to within one-half-the difference between the two closest reference pairs. Similarly, repeat ratings of the same specimen pair by different observers in different laboratories or by using different sets of reference gray scales should give results agreeing to within the difference between the two closest reference pairs.





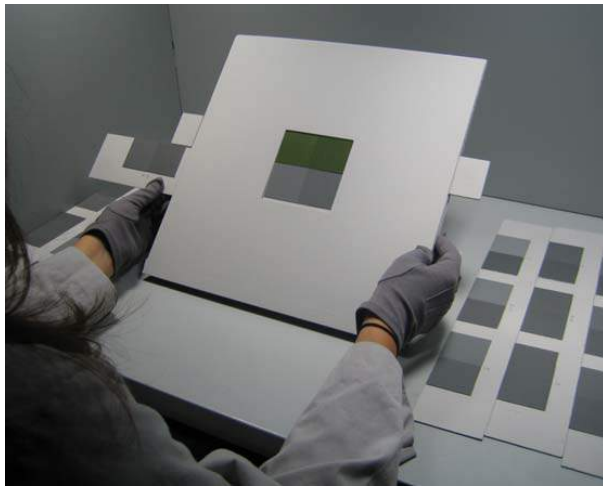
**Figure 7.4** Multiple standards evaluation card, which allows describe trend of color difference.



**Figure 7.5** Gray scale for assessing change in color (5 steps and 4 semi-steps) and example of five steps grey scale for assessing staining

Although these scales are designed for evaluating stability, in case of rating changes of shade there are typically used degrees 3 and 4. We must stress out, that this definition does not solve problem of color differences, because the transfer from gray difference to color difference depends on interpretation of referee and due to this is not objective. Put in other words there is very important experience of the referee, because in lot of cases typically with beginning (often called naive) referees, they very often work only with light difference from total visual perception of the color difference. This problem is more significant in cases when we use visual evaluation of virtual (soft) samples on computer screens and similar devices. Simulation of real (hard) samples, which have characteristic texture, was not successfully managed in industrial evaluation. Because there is in case of gray scale used combination of method evaluation pass/does not pass and assignment to some standard. Due to this reason, it is important to use covering masks like that we choose only the concrete degree of grey scale. In the Figs. 7.6 and 7.7 we can see usage of covering masks for evaluating color differences on the left side and on the right for rating the degree of dimpling.

Procedure of visual evaluation by using of Gray Scale for Color Change is follow: Place a piece of the target fabric and the tested specimen side by side in the same plane and going in the same direction in the lighting booth. Place the Gray Scale along the edges of the two fabrics, target and tested. Compare the visual difference between the two fabrics to the differences represented by the Gray Scale. Determine the grade by figuring out the grade that corresponds with the most appropriate change in color. A grade of 5 is given only when there is no perceived difference in color or contrast between the original and the tested specimen. Each person in the group needs to assign a grade to each specimen and then the group will come up with an average for their fabric for each test. It is very useful to use angular tables, which allow you more flexible placement, grey scale sample and relevant mask with help of magnets.



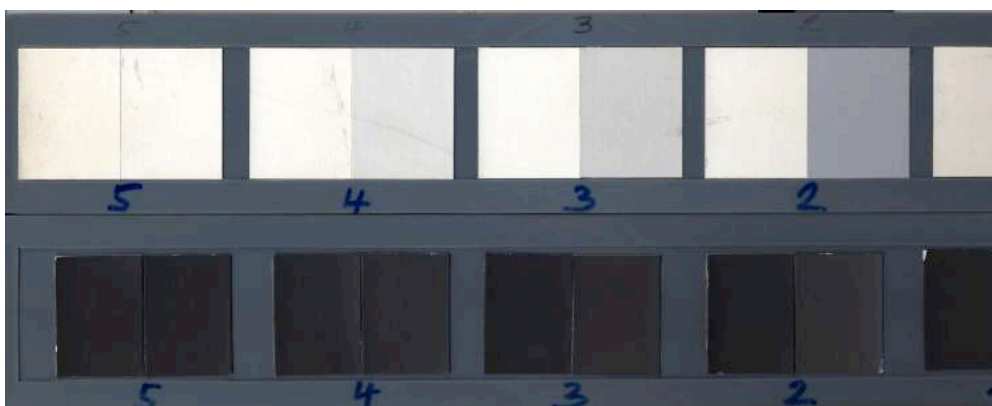
**Figure 7.6** Illustration of visual evaluation of color differences with square covering mask.  
 We can see also using a gray coat and protecting glows for elimination of chromatic contrast. Picture of Lina Cardenas from NC State University, USA



**Figure 7.7** Illustration of usage of angle table and rectangle covering mask in case of evaluation of diming in stability tests. Square mask is used for evaluating of color differences, picture is from materials produced by VeriVide, UK

Last, but not least, during the usage of gray scales it is important to care about their quality, more precisely on life expectancy. In industry, there is the life expectancy about one year, nevertheless controlling the gray scale on particular place holding the spectrophotometer can extend the life expectancy. If the gray scale is damaged as we can see on the Fig. 7.8 it is necessary to discard it. On the picture is besides dirty parts also depreciation of degrees 4 and 5 in the scale for evaluating shade changes.

As it was said, the majority of consistency tests ended with visual evaluation by normed gray scale until only recently. But it is known that visual methods are subjective, that means we can see differences in different evaluation by different referees. In recent time, there is effort to replace this type of evaluation by usage of machine testing for example by scanners (SmartScan by Mathis) or picturing systems as DigiEye by VeriVide.



**Figure 7.8** Example of damaged gray scales by daily use – fifth step of grey scale for evaluation of color change appears more differ than step 4. White samples of grey scale for assessing staining are scratched and soiled

Fastness Test Committee of SDC in Great Britain on the end of seventies of twenty century established sub commission responsible for replacement of visual assessment by instrumental one. First step was focused on replacement of grey scale for staining. It was carried out large-scale experiment, which evaluated 350 pairs of samples (color - accompanying uncolored fabric) against gray scale and instrumentally. The result was a formula that was presented at the ISO meeting in Copenhagen (June 1981), and since 1984 has been as an ISO standard used to transfer  $\Delta E$  (CIELAB) [150]:

$$SSR = 7,05 - 1,43 \ln(\Delta E^* + 4,4) , \quad (7.1)$$

where **SSR** is Staining Scale Rating .

This equation (7.1) was used in industry, nevertheless based on experience with huge set of samples company **Sandoz AG** [151], proposed own modification, which appeared as better:

$$SSR = 5 - 0,22727 \cdot (\Delta E_g) , \quad (7.2)$$

if  $\Delta E_g < 3,96$

$$SSR = 6,08496 - 1,44268 \cdot \ln(\Delta E_g) , \quad (7.3)$$

if  $\Delta E_g \geq 3,96$

where  $\Delta E_g$  is so called equivalent grey scale, which is calculated with usage of CIELAB color space:

$$\Delta E_g = \Delta E^* - 0,35 \cdot [1 + \cos(h)] \cdot (\Delta E^* - |\Delta L^*|) , \quad (7.4)$$

ISO then recommends in 1987 modification of SANDOZ formula as standard **ISO 105 - A03** [152] based on broad analysis of industrial data:

$$SSR = 5 - 0,23 (\Delta E_{GS}) , \quad (7.5)$$

if  $SSR < 4$  and if  $SSR \geq 4$ :

$$SSR = 6,01 - 1,45 \ln(\Delta E_{GS}) , \quad (7.6)$$

where

$$\Delta E_{GS} = \Delta E^* - 0,4 \sqrt{[(\Delta E^*)^2 - (\Delta L^*)^2]} , \quad (7.7)$$

Satisfactory results with the introduction of instrumentation evaluation stages dimpling led to the fact that the spotlight on the assessment of change in color of the test sample. Because the color change is normally much smaller than the visually perceived changes when lowered into the backing fabric used different gray scale. (For the first survivor level are either given  $\Delta E$  (CIELAB) = 13.6, whereas the corresponding evaluation dimpling first stage  $\Delta E$  (CIELAB) = 34.1).

Requirements instrument method for assessing change in color are more stringent than for evaluating the degree of staining in the sense that the color differences may include differences in any direction from any assessed coloration than the "white" in the case of accompanying fabric staining. Despite the fact that the basic requirement is that

the instrumentally determined survivor degree coincided with the average degree of visual large number of evaluators. Therefore, since 1985, mainly in Switzerland, attempts have been made to establish an appropriate instrument method for assessing change in color [153] [154].

In 1987 two experimental datasets were used to develop ISO formula for instrumentally assessing change in color. First set was made in UK and second one in Switzerland. The UK study concluded that the CMC(1:1) reasonably fitted data of SET1, nevertheless Swiss Fastness Committee (SEK) showed that proposed new formula give a good fit to the SET2, which contains many more data than the UK data (SET1). Mentioned tests have demonstrated that the SEK formula markedly outperformed the CMC(1:1) color difference formula and the average standard deviation  $SD$  when evaluating color change varies in visual evaluation of about 0.57, whereas the newly formulated formula, sometimes referred to as SEK, the value of the average standard deviation  $SD = 0.34$  (for comparison CIELAB was  $SD = 0.47$  and for CMC(1:1)  $SD = 0.44$ ). At a later stage a new set of specimens was prepared and assessed in variety labs in different countries, unfortunately was showed significant disagreement in visual results. Beside that were proposed different modifications of formula based on CIE2000 color difference formula, which any was accepted by ISO.

The main difference between the formula SEK and CIELAB is the introduction of the concept of medium saturation, by means of which was modified calculating variations in saturation (purity).

After some adjustments, which concerned the calculation of the difference in hue (color), was at the ISO meeting in Williamsburg modified formula SEK adopted. And since 1989, as part of the standard ISO 105-A02 used [155].

$$\Delta E_{F(SEK)} = \sqrt{(\Delta L^*)^2 + (\Delta C_F)^2 + (\Delta H_F)^2}, \quad (7.8)$$

where

$$\Delta H_F = \Delta H_k / [1 + (10 C_m / 1000)^2]$$

$$\Delta C_F = \Delta C_k / [1 + (20 C_m / 1000)^2]$$

$$\Delta H_k = \Delta H^* - D$$

$$\Delta C_k = \Delta C^* - D$$

$$D = [\Delta C^* \cdot C_m \cdot \exp(-X)] / 100$$

$$X = \left[ \frac{(H_m - 280)}{30} \right]^2 \quad \text{if } (|H_m - 280| \leq 180)$$

$$X = \left[ \frac{(360 - |H_m - 280|)}{30} \right]^2 \quad \text{if } (|H_m - 280| > 180)$$

$$C_m = (C_t^* + C_o^*) / 2 \quad \text{(average chroma)}$$

$$H_m = (H_t^* + H_o^*) / 2 \quad \text{if } (|H_t - H_o^*| \leq 180)$$

$$H_m = (H_t^* + H_o^*) / 2 + 180 \quad \text{if } (|H_t - H_o^*| > 180 \text{ a } |H_t + H_o^*| < 360)$$

$$H_m = (H_t^* + H_o^*) / 2 - 180 \quad \text{if } (|H_t - H_o^*| > 180 \text{ a } |H_t + H_o^*| \geq 360)$$

$C_t^*$ ,  $H_t^*$  = lightness, chroma, and hue of Test specimen

$C_o^*$ ,  $H_o^*$  = lightness, chroma, and hue of Original

$\Delta E_F$  is used to calculate Gray Scale using the equations below:

$$GSR = 5 - \frac{\Delta E_{F(SEK)}}{1,7} \quad \text{if } \Delta E_{F(SEK)} \leq 3,4 \quad (7.9)$$

$$GSR = 5 - \frac{\log(\Delta E_{F(SEK)} / 0,85)}{\log 2} \quad \text{if } \Delta E_{F(SEK)} > 3,4 \quad (7.10)$$

Table 7.1 provides the color difference values in CIELAB units and color difference units in SEK units for the grade pairs in each step of the Gray Scale for Color Change:

**Table 7.1 Gray Scale Color Change Step Values**

$\Delta E^*$	Difference	GSR	$\Delta E_{F(SEK)}$	GSR
0	0.2	5	0-0.40	5
0.8	$\pm 0.2$	4-5	0.41-1.25	4-5
1.7	$\pm 0.3$	4	1.26-2.10	4
2.5	$\pm 0.35$	3-4	2.11-2.95	3-4
3.4	$\pm 0.4$	3	2.96-4.10	3
4.8	$\pm 0.5$	2-3	4.11-5.80	2-3
6.8	$\pm 0.6$	2	5.81-8.20	2
9.6	$\pm 0.7$	1-2	8.21-11.60	1-2
13.6	$\pm 1.0$	1	>11.60	1

As well as the methodology for assessing stability in lowered into the fabric backing is instrumental method for evaluating the color change in the meantime alternative visual assessment, not a substitute! This means that the evaluation instrument using a gray scale has the same weight as a visual check. In terms of colorimetric practice, it is therefore important to any contractual relationship between the supplier and the customer include manufacturing tolerances using one of the commonly used formulas for calculation of color differences and not by specifying gray scale for assessing change in color. It is necessary to point out that graduation of gray tones in the scales is geometric. That means individual grades follows scaling in table below, which is in NBS units because ISO recommendation was made in 1950s. (Table 7.1 shows present day adaptation into CIELAB color difference).

Grade	Contrast	Former ISO recommended scale
5	0 NBS units	0.0 NBS units
4	$n$ NBS units	1.5 NBS units
3	$2n$ NBS units	3.0 NBS units
2	$4n$ NBS units	6.0 NBS units
1	$8n$ NBS units	12.0 NBS units

## 7.2 Measurement

**Color measurement saves money!** In practice, many industrial sectors work together within the production chain with a clear separation between the stages, from the suppliers of raw material to the producer. That means all companies involved must co-operate very closely within such a chain, especially with regard to keeping the agreed and stipulated tolerances and standard values of the products. The receiving and outgoing goods departments of the member companies are the actual links in the chain. Selective use of colorimeters in these key departments helps to check color conformity of semi-finished and finished goods in an indisputable way. Good co-operation between the departments within each company is indispensable for smooth co-operation with other chain members. The links between the members of a production chain are virtually the same as those within an individual company.

The main objective of a production plant is to produce uniform and optimum quality at minimum costs. Therefore, it would not make sense to assign color control to the outgoing goods department but to the receiving department. If color differences are detected there, they can be handled by:

- 1) Financial agreement with the supplier
- 2) Manipulating your own production process to correct deviating colors.

Detecting a deviation from the agreed color tolerance during the final inspection, i.e. after production, would increase costs. The goods must be reworked or offered at a lower price, if not rejected. Depending on the product, rejects may involve enormous disposal and environmental problems.

Color measurement is not only useful to check incoming goods but also during production. Management personnel who are responsible for the long-range planning of their company's future must be aware of, and implement where appropriate, new methods and equipment that can improve cost, product quality, reduce investment, etc. Treatments like calendaring, drawing, grinding, flattening, drying, sanding, curing etc. have decisive influence on the appearance of the product. At these production stages, color measurement helps to optimize the process flow and keep costs low. Thanks to modern opto-electronic components, color measurement is nowadays easy to handle and to understand - and less expensive than before. Nevertheless, inexperienced users should read the following fundamental information to learn what color measuring technology is about and how to use it best in their specific field of application.

### 7.2.1 Sample preparation

One color measurement method for sliver or yarn wound on a cone or bobbin is to measure the sliver directly. In this case, no sample preparation is required. However, a positioning device is typically used at the instrument measuring port to consistently present the wound of sliver to the instrument. Way to choose the best method of measurement of a sample, including a selection of the instrument type, the appropriate illumination geometry and measurement, sample preparation method, etc., is a multistage process. This process is not always straightforward, since the choice of the device is largely dependent on laboratory equipment, also a number of other factors may not be completely controlled. It is therefore important to ensure a maximum quality

measurement in a given time and economic conditions. That's why we always try to answer two basic questions:

**a) Is a given measurement aspects of the use of the sample?**

**b) Measuring the repeatable within tolerances required for the job?**

Correct answers to the above two questions need to be found before the foundation of the methodology of preparation and measurement of the sample. For example, the curtain can be measured on both the light transmission and light reflection depending on whether we are interested in the appearance or functionality in terms of shading.

For samples that are not opaque; prepare them by increasing sample thickness, so that they are opaque (or nearly so), unless one is intentionally measuring over white and/or black backgrounds.

Non-opaque samples such as textile substrates, most papers, and many printing ink substrates, usually must be measured as if they were opaque, to meet particular color application needs. In these cases, it is best to increase sample opacity by increasing sample thickness, so that the color measurement will not be influenced adversely by the “show-through” of a black (or white) background. Textile cloth can be folded multiple times, yarns and threads wound in multiple layers, and papers stacked, to meet the desired opaque (or most nearly so) requirement. If multiple sample folds’ result in sample “billowing” into the sphere, then it is best to limit the thickness, and use a white sample background.

For samples with directional surface orientation; measure them always at the same single orientation, or measure them at the same four (4) orientations (90 degrees apart) with data averaged.

Optically directional samples (such as corduroy fabric, calendared vinyl, and card wound yarns and threads), typically measure differently in D/8° spectrophotometers, as they are rotated in the sample port. The directional geometric properties of these samples can result in measurement errors, whenever the standard and batch are measured differently. The measurement errors can be virtually eliminated by always measuring with the same sample orientation, or by measuring the sample 4 times (at 90 degree intervals) and averaging the data.

For samples with inconsistent color and/or surface effects; measure them multiple times (moving the sample between reads to increase the effective area measured), with data averaged.

Inconsistent (or irregular) samples can yield different measurements, depending upon what part of the sample is measured. This measurement variability can be virtually eliminated by measuring the sample multiple times and averaging the results, moving the sample between measurements. This technique can also be successfully employed in cases where the sample may appear to be uniform, but may not be.

As practical, utilize the largest sample measuring area available (LAV, SAV, USAV), to achieve averaging over a larger sample area. The largest viewing area (aperture value) available should generally be utilized, as it extends the measurement over a larger portion of the sample.

If possible, always measure standards and batches (of colors to be compared), using

the same sample measuring area. Use the same viewing area for measuring the standard, as will be used in measuring production batches. This technique is desirable since different viewing areas (even of the same spectrophotometer), will typically not measure exactly the same.

If possible, always measure standards and batches (of colors to be compared), using the same spectrophotometer, under the same conditions. If possible, use the same spectrophotometer, under the same conditions, to measure any samples to be compared, since no two spectrophotometers agree exactly.

As already mentioned, in the construction of measuring instruments, it is envisaged that the sample will be equal and will not penetrate through the metering orifice into the integrating sphere, since this measurement was incorrect. In cases where we need to measure subtle patterns such as soft fiber flake, pile fabrics, etc. Leads to their penetration through the aperture, as can be seen in Fig. 7.9.

In many cases, the sample may be penetration into the interior of the integrating sphere even greater, since most of the apparatus is equipped with a specimen holder with thrust. Penetration of the sample can be avoided either by using the cover glass, as can also be seen in Fig. 7.9, or by using a aperture of smaller diameter as shown in Fig. 7.10.

When measuring samples, which may penetrate through the measuring aperture into the space in the integrating sphere is necessary increasingly to observe the number of measurements from which are then calculated the corresponding colorimetric values. As will be shown in section 7.2.7 Measurement uncertainty, particularly in Table 7.4, perform only one or two measurements, such as is happening in practice often leads to high measurement uncertainty. For this reason, the measuring aperture 30 mm recommended that at least four measurements, since three measurements are insufficient number of materials as documented in Table 7.2:

Table 7.2 also shows that the use of the metering orifice of smaller diameter on the one hand partially solves the problem of intrusion of the sample into the space in the integrating sphere, on the other hand it must be remembered that the measured sample area is significantly smaller (area of aperture of 5 mm diameter is 36 times! smaller than the area of aperture of 30 mm diameter). The practice should therefore apply the rule that during the measurements we use the largest possible aperture, which allows the instrument and sample. Otherwise, we theoretically should increase the number of measurements so that the total measured area of the sample matched.



**Figure 7.9** Example of sample inherece through measuring aperture without cover glass (right side) and effect of cover glass (left side) on sample



**Figure 7.10** Amount of inhereed sample it is possible to reduce by application of measuring apertures with small diameter



**Table 7.2 Dependence of standard deviation of measured values on size of aperture and presence of cover glass**

Used aperture	30 mm with glass		30 mm without glass		20 mm without glass		5 mm without glass	
	4	3	4	3	4	3	4	3
canvas	0.03	0.11	0.02	0.09	0.03	0.10	0.05	0.19
sanded terry cloth	0.08	0.15	0.04	0.07	0.04	0.07	0.18	0.27
corduroy	0.12	0.27	0.17	0.61	0.13	0.31	0.66	0.98
velour	0.15	0.34	0.13	0.52	0.20	0.59	0.73	1.19
fleece	0.09	0.17	0.21	0.71	0.25	0.83	0.37	1.04

Since during the measurement apply other factors increasing measurement error, the usual practice is such that for the comparison of samples among each other the following is true a number of measurements per sample:

- 4 measurements using the aperture of diameter 30 mm
- 8 measurements using the aperture of diameter 20 mm
- 12 measurements using the aperture of diameter 10 mm
- 20 measurements using the aperture of diameter 5 mm

If we look at the specific case of the three textile products listed in Figs. 7.11 and 7.12, we can see two different approaches. Already mentioned, that a variant of the cover glass over the measuring opening of the device to ensure correct measurement within the integrating sphere, but it is necessary to count the change in appearance of the measured material to compression. Therefore, preparation for the measurement of the notch carpet equipped with a spring with a relatively small pressure of about 10 cN during contact.



**Figure 7.11** Yarn winded on small cavity, Card Wound, free sliver and sliver inside of skein holder



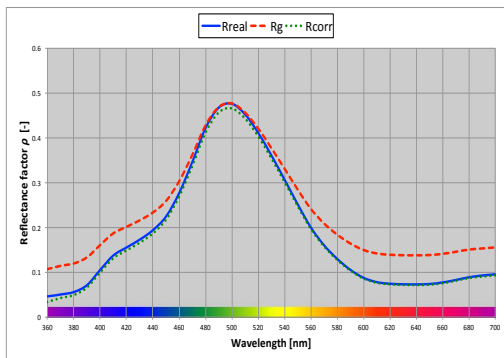
**Figure 7.12** Accessory with cover glass for measurement of carved carpets – sample is protected about penetration into measuring device

As previously mentioned, since the yarn is being measured through a glass interface, the instrument will measure the sample as a duller color than it actually is. This is because glass causes low reflectance values to be higher, and high reflectance values to be lower. For quality control applications when the color difference is being measured and the “standard” was measured the same way, the error introduced by the glass is less significant. However, accuracy can be improved by calibrating the instrument through glass, or when a higher absolute accuracy of measurement is desired, a glass correction can be used Eq. (7.11):

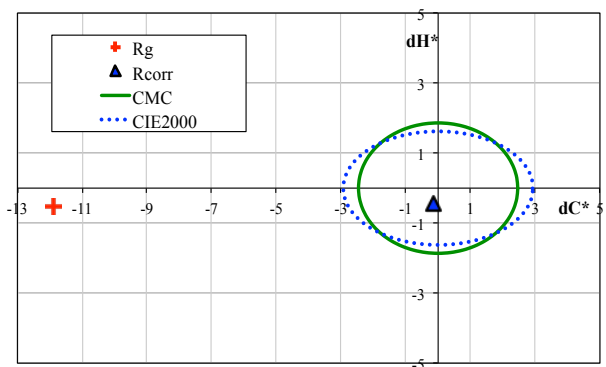
$$R_{corr.}(\lambda) = \frac{R_g(\lambda) + T_c - 1}{R_g(\lambda) + T_c - 1 - T_d \cdot R_g(\lambda) + T_d}, \quad (7.11)$$

where  $R_{corr.}(\lambda)$  is corrected value of spectral reflectance  
 $R_g(\lambda)$  is value of reflectance behind glass  
 $T_c$  = transmittance of glass to collimated light (based on Fresnel equation for glass with refractive index 1.5 is this value 0.92)  
 $T_d$  = transmittance of glass to diffuse light (nominally equal to 0.87 (result from Fresnel’s equations for diffuse illumination in case of common glass with refractive index 1.5<sup>7</sup>))

The above calculation assumes a spectrophotometer with a diffuse measuring geometry, preferably di:0°, however the variant di:8° is applicable as documented spectral reflectance curves in the graph of Fig. 7.13, hence colorimetric evaluation in disjoint graph of Fig. 7.14. Correlation with data measured on the template (sample without cover glass -  $R_{real}$ ) is high, as documented in the graph in Figure 7.13. Error spectral reflectance in this case was 2.8% compared to 24% for uncorrected data. Also, measured color difference between the corrected measurement and the draft was  $\Delta E_{CMC} (2:1) = 0.3$  versus  $\Delta E_{CMC} (2:1) = 5$  in the uncorrected measurement.



**Figure 7.13** Reflectance chart of sample measured with ( $R_g$ ) and without cover glass ( $R_{real}$ ) and corrected reflectance factor by using of Eq. (7.11) –  $R_{corr}$



**Figure 7.14** Sample measured with cover glass ( $R_g$ ) and sample with corrected reflectance factor ( $R_{corr}$ ) projected on  $dC^*dH^*$  plane (as target was used sample measured without cover glass ( $R_{real}$ ))

<sup>7</sup> Precise calculation of corrected reflectance index is dependent also on used wavelength because refractive index is also wavelength dependent value. This value is measured at the yellow doublet D-line of sodium, with a wavelength of 589 nanometers.



**Figure 7.15** Example of individual trials of polypropylene filament wound on Card Wound by parallel method

The graph in Fig. 7.14 we show is that the main difference between the corrected and uncorrected measurement is specific purity  $\Delta C^*$ . This is because the influence of the primary reflection (gloss) on the measured spectral data. As noted in section 3.2, the primary reflection uncolored respectively. It has the same spectral composition as the incident light, which in our case is white.

If we return to the samples shown at Fig. 7.11, it is clear that in the case of a textile strand, which could be measured by using the cover glass, we can measure sample ingress to the interior of the integrating sphere measuring limit by the clamping of which makes it possible to pre-stress the spring. If yarns are usually used two measurement techniques. One is a laboratory where yarn rewind to different paper cards (template), as can be seen in Figs. 7.11 and 7.15. The advantage of this approach is reproducible measurements in addition to the possibility of archiving for future use. The second technique for measuring the yarn is typically used for operational controls when using fixation products (Fig. 7.16) can be advantageously measured cross Rewind packages, warp beams, etc. Directly, without having to scroll to the paper originals. The task of the positioning device, as its name implies, is fixing the mutual position of the device and the sample, which is not planar. According to the diameter of the winding choose a suitable preparation for the measurement is performed several times, if possible, around the perimeter of the sample. Although cross Rewinding coils have a slightly conical shape, fixing the sample is sufficient and convenient measurements as shown in Fig. 7.16. Most yarn samples will have some level of directionality. Directionality is when the sample has distinct lines or texture that when measured at different angles of rotation (yield varying results). Averaging multiple placements of the sample with a  $90^\circ$  rotation between readings will minimize the effect of directionality.



**Figure 7.16** Set of accessories (positioning device) for measurement of tubular samples with different diameter (HunterLab)



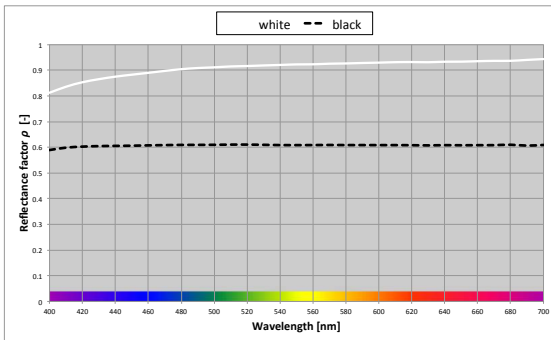
**Figure 7.17** Measurement of X-bobbin by using of accessory from Fig. 7.16

## 7.2.2 Background effect

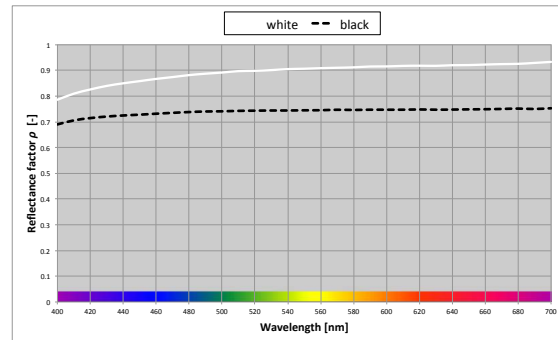
Very often the differences between measurements taken at different sites is due to different background used in the measurement. Already it mentioned, that a number of samples falls within the category of translucent objects where it is necessary to consider also the amount of light is able to pass through the material. So, if we measure one sheet of paper, one layer of fabric or some plastic moldings for various backgrounds will result in a difference in colorimetric data as shown in the graph in Fig. 7.18. Other graphs in Figs. 7.19 to 7.21 is clearly seen reducing differences between measurements on the black a white background with an increase in the number of layers.

It is therefore clear that, where we can ensure a sufficient number of layers of the sample, the measurement is not influenced by the substrate. This is especially important for portable devices because of desktop devices are used specimen holders that have a white or light gray contact area. If the measurement result compared with portable instruments by which we measure the same sample again on a light table, once on a dark table or tables with different designs, it is logical that depending on the degree of light transmission will be confronted with different spectral reflectance and colorimetric coordinates.

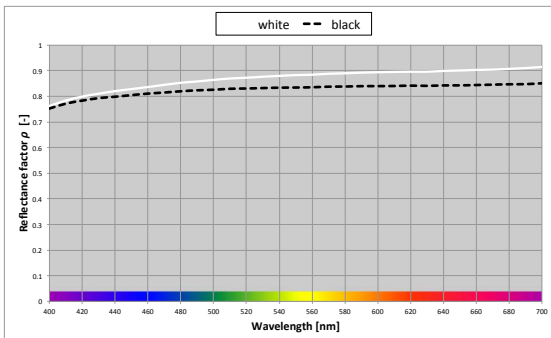
As already mentioned, this problem is usually solved so that measuring multiple layers of material, which is important to the supplier and the customer mutually agree on the number of measured layers. The easiest way to determine number of layers is based on coverage of device measuring port.



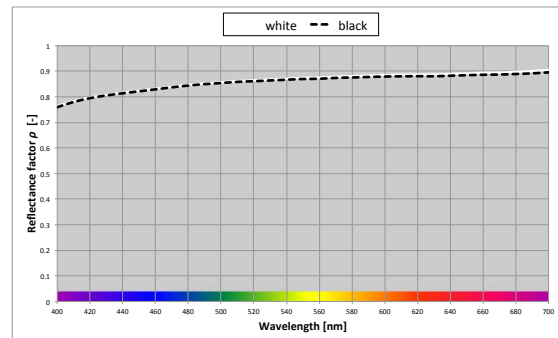
**Figure 7.18** Plot of reflectance factor on black and white backgrounds for 1 layer of sample



**Figure 7.19** Plot of reflectance factor on black and white backgrounds for 2 layers of sample



**Figure 7.20** Plot of reflectance factor on black and white backgrounds for 4 layers of sample



**Figure 7.21** Plot of reflectance factor on black and white backgrounds for 8 layers of sample

Measuring hole cover with one layer of material that we hold hands so we do not cover the test port and perform measurements. If during the measurement was seeing a flash of light measurement, attach the test port another layer of material. This process is repeated until no light pattern visually fails. In the case of fabrics, it is usually 4-8 layers. If for various reasons this procedure is unusable, it is necessary to use correction procedures to eliminate the effect of background on the measured values. For this purpose, is used for measuring the black and white background. Method monochrome background is also often referred to as a method of contrast ratio (CR - Contrast Ratio method), typically, the method used to determine CR opacity.

The Fig. 7.22 we can see a schematic representation of three materials with different light transmission, as we talked about them in section 2.3, the ability not to lay light is call opacity, or in the case of paint covering power.

Opacity (hiding power) is the characteristic ability of a material to hide from view a non-active backing material. For example, when reading a book one prefers to read one page at a time rather than read all of the pages at once. Each page must have sufficient opacity to obscure the printing on subsequent pages. Similarly, clothes can protect the visibility of underwear.

In pulp and paper industry the most commonly used measurements of opacity are defined as shown in equations (7.12) – (7.14):

$$Opacity_{T425} = \frac{Y_B(A/2)}{Y_W(A/2)} \cdot 100, \quad (7.12)$$

where  $Y_B$  is tristimulus value  $Y$  of sample obtained with zero reflectance backing (reflectance of black backing is less 0.5%)

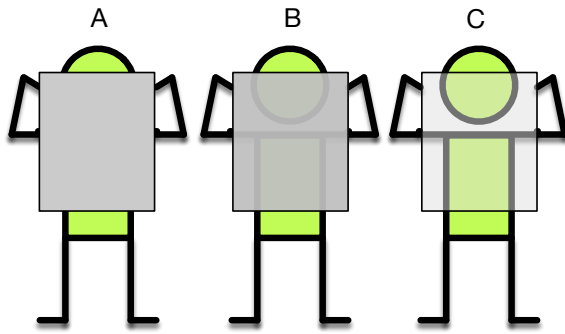
and  $Y_W$  is tristimulus value  $Y$  of sample obtained with white background backing (reflectance of white backing is higher than 89%)

and A/2 means CIE standard illuminant A and 2° observer<sup>8</sup>

Unlike brightness, which is measured in the blue region of spectrum, opacity is predominantly weighted in the green or greenish-yellow part of the spectrum with some response throughout the entire visible spectrum. The objective is to measure opacity using a spectral response, which correlates closely with human sensitivity. It should also be noted that the opacimeter's response is very low in the blue part of spectrum where FWA excite fluorescence, because such devices are obviously equipped by halogen lamps. For this reason (in addition to the itself rationing effect of equation computing opacity), the presence of optical brighteners has little or no effect on measured values of opacity.

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<sup>8</sup> In many cases equations (7.12 až 7.15) are written in form of reflectance  $R$ , nevertheless such values are than weighted by the spectral sensitivity of the average human eye – luminous efficiency function  $V_\lambda$ . It is known that tristimulus value  $Y$  in CIE XYZ system, which is computed following equation (3.12), is used as luminosity metric, that means results of weighting reflectance by  $V_\lambda$  will be the same as  $Y$ .



**Figure 7.22** Different opacities:  
 A – ideally opaque sample,  
 B – translucent sample,  
 C – semi-transparent sample



**Figure 7.23** Example of hiding power measurement on Gardner contrast paper board – increasing the amount of paint in small increments until reaching the point of essentially complete hiding at which the of visual contrast was considered negligible

Alternatively counts diffuse opacity to paper by a sufficient number of sheets, so that the condition simulation infinitely thick layer ( $R_\infty$ , respectively  $Y_\infty$ ). Unlike the use of monochrome substrate for this method simply light trap ( $Y_B$ ) because the value  $Y_\infty$  is usually measured on the layer 20 of sheets:

$$Opacity_{DIN\ 53146} = \frac{Y_B(C/2)}{Y_\infty(C/2)} \cdot 100 \quad (7.13)$$

$$Opacity_{T\ 519} = \frac{(A-1)}{(A-Y_\infty^2)} \cdot 100 \quad (7.14)$$

$$A = \left[ \frac{Y_\infty(1-Y_B(w_1) \cdot Y_\infty)}{(Y_\infty - Y_B(w_1))} \right]^{w_2/w_1} \quad (7.15)$$

$w_1$  is the density of the paper of known opacity and  $w_2$  is the density of an unknown paper opacity. In the case of fabrics usually we use the corrected spectral reflectance of translucent materials  $R_T(\lambda)$ , which is described by the equation:

$$R_T(\lambda) = a - \sqrt{a^2 - 1} \quad (7.16)$$

$$a = \frac{1}{2} \left[ R_W(\lambda) + \frac{R_B(\lambda) - R_W(\lambda) + R_{WB}(\lambda)}{R_B(\lambda) \cdot R_{WB}(\lambda)} \right] \quad (7.17)$$

where

$R_W(\lambda)$  is reflectance of measured fabric on white background

$R_B(\lambda)$  is reflectance of measured fabric on black background

$R_{WB}(\lambda)$  is reflectance of white background

### 7.2.3 Errors of measurement

In practice, not measurements, measuring methods or measuring instruments absolutely accurate. To assess the results in physical and technical measurements can be chosen different approaches. When determining the measurement inaccuracies, there are two basic approaches: older and simpler fault, newer and more comprehensive evaluation process through the measurement uncertainties. Currently preferred second method. During the measurements are applied to influences, which affect the deviation between the actual measured value and actually measured value. The resulting difference between both values is sometimes formed by a complex combination of individual factors. Put simply, the difference between correct and the measured value depends on the accuracy of measuring instruments, precision measuring methods, but also the actual measured sample. The errors, which are the results of the colorimetric measurements always burdened with the most clearly manifested when we make a series of parallel measurements of the same perfectly homogeneous sample (e.g. color calibration standard): we get results that are up to exceptional cases (typically due to rounding) somewhat different [156].

#### Important points to remember

1. A measurement without units is meaningless.
2. A measurement without an estimated range of uncertainty (or error) is also meaningless.
3. Always quote the final result of a measurement in the form  $\mathbf{a} \pm \mathbf{b}$ , with  $\mathbf{a}$  (measurement) and  $\mathbf{b}$  (error) given to the same number of decimal places. For example, a measurement of the color difference:  $\Delta E^* = 0.94 \pm 0.14$ . This expression means that the true value is likely (the probability being approximately 68%, see below) to lie between 0.80 and 1.08, i.e. if you repeat the measurement a large number of times about 68% (i.e. two-thirds) of the results will lie between 0.80 and 1.08.
4. Errors are usually only known roughly, so quote your errors to no more than two significant figures. One significant figure is usually sufficient. (i.e.  $0.94 \pm 0.14$ , or possibly  $0.942 \pm 0.137$ , but not  $0.94217 \pm 0.13794$ ).

Errors are expressed in absolute or relative terms. According to their operation errors can be divided into systematic, random and gross. According to my sources are divided on the instrument errors, methods, observation and evaluation. As an absolute error  $\Delta(x)$  indicates the difference between the measured value  $x_y$  and real  $x_s$ .

Measurement uncertainty characterizes the range of readings about the result of the measurement, which can reasonably be assigned to the value of the measured variable. Uncertainty concerns not only the actual measurements, but also includes inaccuracy METRIC instruments, the value of the constants, corrections, etc., Where the overall uncertainty of the result depends.

For the purposes of this paper are given only basic information particularly important for setting user tolerances and subsequent work with the reports pass / fail.

Already mentioned, that the errors are classified according to the nature and effect of the three categories [157]:

**Systematic Errors, Bias** (another sign the outliers and outlier data) are caused by an exceptional cause, typically incorrect typing result, the sudden failure of the meter, incorrect settings of measurement conditions, and the like. The measured value is significantly different from other values obtained in repeated measurements, as we can see in the graph in Fig. 7.24. Such measurements are to be excluded from processing to falsification of the result. A number of control programs for spectrophotometers allows for instant comparison of measurements during the so-called. Repeated measurement. The operator thus has the possibility of deviating measurements exclude from the calculation of the arithmetical average estimate, typically, when a movement of the sample or instrument measuring aperture being outside the specific part of the sample, or a sample of significant inhomogeneity, etc.

**Random (or indeterminate) errors** are unpredictable and cannot be ruled out. When repeating measurements are changing their size and sign of how the law with the expected probability distribution. For the determination of their size is based on repeated measurements using statistical methods corresponding to the respective probabilistic model, represented by the appropriate distribution law of random errors. In practice, very often it is a normal-Gaussian (Fig. 7.25), which is used in most applications.

Let  $X$  be a randomly varying quantity, of which  $n$  independent measurements were obtained under the same conditions. In most of the practical cases, the best estimate of the value of  $X$  ( $x_1, x_2, \dots, x_i, \dots, x_n$ ) is the *arithmetic mean*  $\bar{x}$  of the results of all measurements:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (7.18)$$

The observations in the sample vary as the result of random fluctuation in the measurement instrument, the measured matter and others. The *standard deviation*  $s(x)$  is calculated by taking the square root of the variance [159]:

$$s(x) = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}} \quad (7.19)$$

The value of the standard deviation, unlike variance, has the same units as the measured quantity, and therefore often is more convenient for use as the measure of dispersion of values about the mean. The *experimental standard deviation of the mean*  $s(\bar{x})$  is equal to square root of its variance [160]:

$$s(\bar{x}) = \frac{s(x)}{\sqrt{n}} = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n(n-1)}} \quad (7.20)$$

As was mentioned before Systematics Errors are errors, whose value under the same conditions of measurement does not change is constant in magnitude and sign, or who are changing the measurement conditions vary according to the particular addiction and



a way "systematically" influence the measurement result. Unlike random error bias we cannot be characterized on the basis of repeated measurements. To determine their size usually just a formula for calculating the absolute error:

$$\Delta(x) = x_m - x_s \quad (7.21)$$

From the perspective of the user measurement techniques are systematic errors sympathetic that it can largely be identified and their effect can be reduced by appropriate compensation, to eliminate the causes, which give rise, eventually a combination of these methods. Survey and removal of systematic errors is difficult and expensive, and therefore carried out only where it is inevitable. The ability to identify systematic errors is relatively limited (actually only know some of its estimate and not the actual value), and therefore only removes its estimate, while always remaining portion whose value we do not know. This part is called fixed systematic errors. The resulting measurement error is expressed as the sum of systematic and random components of  $\varepsilon$ , which can be written:

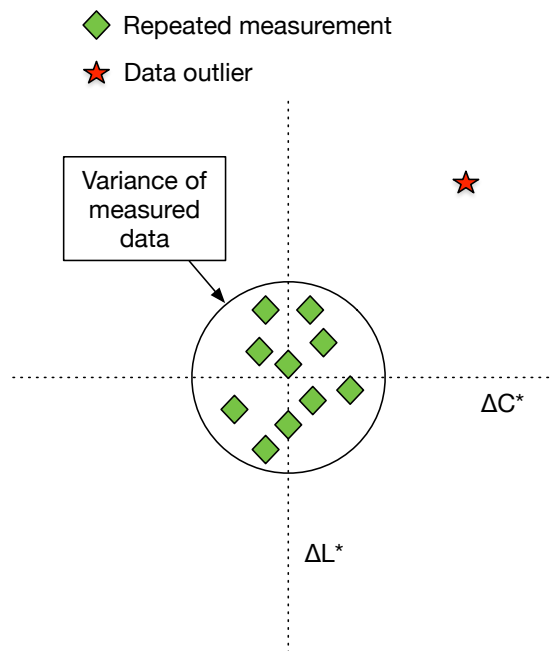
$$\Delta(x) = |e| + |\varepsilon| \quad (7.22)$$

and its maximum value can be estimated as:

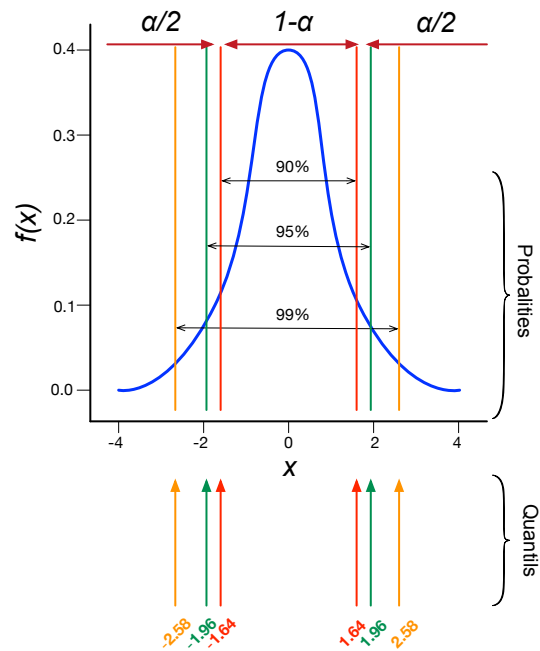
$$\Delta_{\max} = (\bar{x} - x_s) + 2s \quad (7.23)$$

where systematic component is  $e = x - x_s$  and the random component is  $\varepsilon = s$ , respectively  $\varepsilon = 2s$

The coefficient of expansion of the standard deviation is related to the probability coverage interval and the type of distribution. Pair with Gaussian distribution for the commonly used 95% probability (exactly 1.96 as shown in the graph in Fig. 25.7).



**Figure 7.24** Example of outlier in measurement of color differences



**Figure 7.25** Key quantiles of standard normal density, bell-shaped probability density (Gaussian)

## 7.2.4 Source of errors

Already mentioned, that the entire measurement process is encumbered with a number of imperfections and problems that inevitably be reflected in the results of measurements and errors. According to their sources can be divided into the following items:

*Instrument error* – Conventional spectrophotometers are of the double-beam configuration, where the output is the ratio of the signal in the sample beam to the signal in the reference beam plotted as a function of wavelength. It is incumbent upon the experimenter to ensure that the only difference between the two beams is the unknown. Therefore, if liquid or gas cells (cuvettes) are employed, one should be placed in each beam. For gas cells, an equal amount of carrier gas should be injected into each cell, with the unknown to be sample placed in only one cell, destined for the sample beam. For liquids, an equal amount of solute should be placed in each cell. A critical issue with liquid and solid samples is the beam geometry. Most spectrophotometers feature converging beams in the sample space. If the optical path (the product of index of refraction and actual distance) is not identical for each beam, a systematic difference is presented to either the entrance slit or the detector. In addition, some specimens (e.g., interference filters) are susceptible to errors when measured in a converging beam. Most instruments also have a single monochromator, which is susceptible to stray radiation, the limiting factor when trying to make measurements of samples that are highly absorbing in one spectral region and transmitting in another. Some recent instruments feature linear detector arrays along with single monochromator to allow the acquisition of the entire spectrum in several milliseconds; these are particularly applicable to reaction rate studies. Conventional double-beam instruments are limited by these factors to uncertainties on the order of 0.1 percent. For lower uncertainties, the performance deficiencies found in double-beam instruments can largely be overcome by the use of single-beam architecture. The mode of operation is sample-in–sample-out. If the source is sufficiently stable with time, the desired spectral range can be scanned without the sample, then rescanned with the sample in place. Otherwise, the spectrometer can be set at a fixed wavelength and alternate readings with and without the sample in place must be made. Care should be taken to ensure that the beam geometry is not altered between sequential readings.

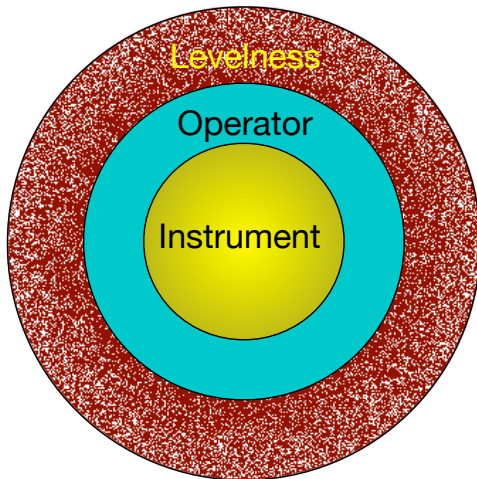
*Errors of installation* – such kind of errors are affected by wrong connections and setup of measuring device, by interferences between devices mainly if two devices are connected with one computer.

*Errors of method* – errors that are caused by imperfection of method, by using of physical constant approximation and inadequate model of measured properties.

*Errors of assessment* – source of these errors are limitation of human sense, current health condition of observer, low concentration, etc.

*Errors of evaluation* – errors relating to data treatment (approximate relations, rounding, less number of used constant, errors of interpolation, extrapolation, linearization, etc.)

*Influence of environment* – variation of temperature and humidity. Consider that almost all dyes and pigments change color as temperature changes. Measure samples at the same temperature each time, if possible.



**Figure 7.26** Simplified scheme of relationship of uncertainty parameters



**Figure 7.27** Set of ceramic tiles CCS II

The facts that pigments and dyes change their color properties, as there are temperature changes, potentially a major source of errors in any color measurement operations. Almost all colorants (except white and black and some blues) change color as their temperature changes. The color changes can be significant, and it is typically in the range of about 0.6 to 1.1  $\Delta E_{\text{CIELAB}}$  for most high chroma colorants, for a 10°C temperature change. If production samples (batches) must be measured at a temperature different from that when the standard was measured, then (if possible) re-measure the standard at the new temperature.

The effects of humidity are less dramatic. Still, as a wet road appears darker than when dry, so too will physical standards alter their look if they are not maintained under standard condition.

In point of view of colorimetry all mentioned errors it is possible to reduce into three main parts as visible on scheme in Fig. 7.26. These three factors are most frequent in industry. In scheme on Fig. 7.26 we can see obvious size of such errors. It is visible that high effect is caused by specimen itself (unevenness, levelness respectively).

The specimens must be visually checked for inhomogeneity of the grain and gloss level. The surface must be free of foreign matter. Areas showing damage not intentionally caused for testing purposes must be excluded from the measurement. It is important to remember:

*If you are able to see inhomogeneity, device is able to read it also!!!*

Textiles sensitive to stroking must be brushed prior to starting the measurement. In commercial standard VW 50190 is recommendation: start with 1-times against the pile direction (specimen appears darker), then 10-times in the pile direction (specimens appear lighter and structure appears more homogenous).

Remember some of samples have hidden unevenness due to continue change in color, which are frequently invisible, but will be measured as high standard deviation between individual readings. The best of materials will have point-to-point non-uniformities in the reflectance factor on the order of 0.1% and as high as 0.5%.

Precision measurements exist only where the individual instruments are carefully maintained and checked. As was mentioned before standard deviation expresses the degree of dispersion of values of one-dimensional variable about the mean. With two- or three-dimensional variable, equivalent expression takes form of covariance matrix rather than a single value. Color values in CIELAB space have three-dimensional distribution; however, expressing their dispersion as covariance matrix is impractical and inconvenient for everyday use. Instead, it is possible to express it in familiar units of CIELAB color difference as Mean Color Difference From Mean (MCDM).

Let us have  $n$  sets of CIELAB vectors  $\mathbf{C}_i$  representing a set of measurements of the same color stimulus. The dispersion of these values about the mean can be computed as follows:

$$MCDM = \frac{\sum_{i=1}^n \Delta E(\mathbf{C}_i, \bar{\mathbf{C}})}{n} \quad (7.24)$$

where  $\Delta E$  is the color difference calculated with any chosen CIELAB-based formulae (i.e. (4.27) or (4.43)), and  $\bar{\mathbf{C}}$  is the mean vector of CIELAB values.

The calculation of MCDM as an alternative to standard deviation assumes perceptual uniformity of the color space, i.e. that the distribution of color deviations about the mean is spherical. Naturally, use of advanced color difference formulae improves the perceptual uniformity of color difference calculation. Thus, use of CIEDE2000 formula in equation (4.43) is expected to lead to more reliable MCDM estimation than the use of standard CIELAB Euclidian distance formula.

The British Ceramic Research Association (present day LUCIDEON) produces a set of twelve colored tiles, Fig. 7.27. These tiles are almost used by instrument manufacturers to establish traceability of colorimetric devices to national standards laboratories. These tiles may be used to verify instrument operation in a corporate color lab and for improvement of measured data traceability between different devices in company (supportive software such as Datacolor Guardian or X-Rite NetProfiler it is necessary to order). To profile a color-measuring or color-producing device means to quantify its input-output relationships. In spectrophotometry, profiling is used to effect instrument correction whereby a spectrophotometer is characterized parametrically and corrected to measure like a reference instrument by software and a series of reflectance standards. Profile-based correction (PBC) typically starts from a model equation such as the following:

$$R_0(\lambda) = \beta_0 + \beta_1 R_T(\lambda) + \beta_2 \frac{dR_T(\lambda)}{d\lambda} + \beta_3 \frac{d^2 R_T(\lambda)}{d\lambda^2} \quad (7.24)$$

where  $R_0(\lambda)$  is corrected reflectance,  $R_T(\lambda)$  measured reflectance.

Greek characters mean corrections:  $\beta_0$  is offset;  $\beta_1$  is gain change;  $\beta_2$  is wavelength-scale change and  $\beta_3$  is bandwidth change. All variables implicitly depend on wavelength. Equation 7.24 is used twice in profile-based correction: once with known specimens such as the BCRA tiles with parameters  $\beta_i$  in the solve state, and again with measured reflectance, now-known  $\beta_i$ , and  $R_C$  in the solve state [162].

Nevertheless, as all highly-colored materials are subject to thermochromism to varying degrees. This reversible change in color with temperature has been a problem with many standards but can be overcome in the CCSII by use of Thermo chromic Correction data determined by the National Physical Laboratory. The basic data is supplied free with sets of CCSII. In 1997 Malkin and others [161] published article, where was published “Master spectral reflectance and thermochromism data”. Approximate correction of measured colorimetric values can be calculated by following equation:

$$C_c = \left[ \frac{(T_c - T_M)}{10} \cdot \Delta TC \right] + C_M \quad (7.25)$$

where  $C_c$  is the corrected color coordinate ( $L_c^*, a_c^*, b_c^*$ )

$C_M$  is the color coordinate as measured ( $L_M^*, a_M^*, b_M^*$ )

$\Delta TC$  is the thermochromic change ( $\Delta L^*, \Delta a^*, \Delta b^*$ ) in Table 7.3

$T_M$  is the temperature of the measurement

$T_c$  is the temperature to which color coordinate is to be corrected

It is important that recommended range of the temperature is 25°C till 35°C. Outside of this range corrected values can be out of real thermochromic data. In relation to this item, it is advisable to check for temperature difference between the textile sample placement position and the room temperature. Up to 12 °C temperature difference has been found in an instrument, but two or three degrees is acceptable.

**Table 7.3 Thermochromism measure  $\Delta TC$  - The changes in CIEL\*a\*b\* for a 10°C rise in temperature for Specular Included, Illuminant D65/10 degree Observer**

<i>Tile color</i>	$\Delta L^*$	$\Delta a^*$	$\Delta b^*$	$\Delta E^*$
Pale Grey	-0.03	-0.02	0.02	0.04
Mid Grey	-0.03	-0.02	0.04	0.05
Difference Grey	-0.04	0.04	0.03	0.06
Deep Grey	0	0.01	0	0.01
Deep Pink	-0.1	-0.44	-0.19	0.49
Red	-0.37	-0.71	-0.61	1.01
Orange	-0.45	0.56	-0.66	0.98
Yellow	-0.27	0.7	-0.11	0.76
Green	-0.18	0.66	-0.04	0.69
Difference Green	-0.18	0.69	-0.05	0.71
Cyan	-0.1	0.31	0.01	0.33
Deep Blue	0	-0.04	0.05	0.06

## 7.2.5 Measurement procedure

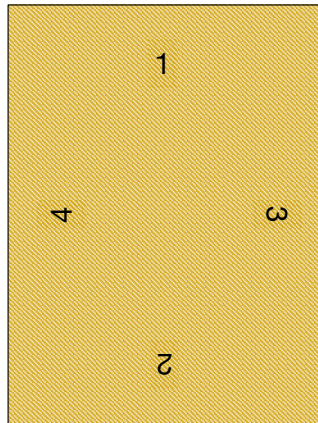
A repeated reading only serves as a quality check of the sample or standard. The measurement opening must be matched to the specific specimen shape. In the case of textile specimens, as large a measuring aperture as possible must be selected (means in case of uniform color samples). Flat-plane surfaces with no pressure marks or damaged parts must be selected for the measurement areas. When selecting the measuring points, it must be ensured that they are distributed over the entire specimen and are at least 3 cm from the edge where possible. For translucent textiles, an underground that corresponds to the backing of finished part must be selected, in other cases it is possible to follow procedure of calculation of corrected reflectance factor for translucent materials by using of Eq. (7.16) and Eq. (7.17).

The sample (target or batch) must be subjected to at least 4 individual measurements distributed over the entire area of the defined surface (see Figs. 7.28 and 7.29). If are measurements taken by 45°:0° geometry devices, then it is no necessary to use rotation of sample after individual readings. In case of devices equipped by spherical geometry is recommended to use rotation.

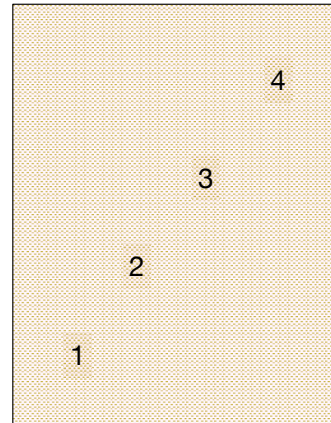
Another recommendation is focused on measuring aperture size. As was mentioned before large possible aperture (LAV) must be used, nevertheless diameter of aperture can be highly variable if we compare desktop and portable devices. If general recommendation is at least 4 individual readings, then in case of desktop device can be diameter of LAV 30 mm and fixed apertures equip many of portable devices by 5 mm diameter. By this reason is reduced traceability of measured data. As solution of this problem it is possible to use simple method of enhancement of number of reading, which is described in following table:

Aperture diameter [mm]	Recommended number of reading [-]	Resulting measured area [mm <sup>2</sup> ]
30	4	2827
20	8	2513
10	12	942
5	16-20	314-393

It is visible that for fulfillment of rule to have the same measured area intendment on aperture diameter is necessary to have 36 readings in case of 10 mm diameter and 144!! individual reading when aperture value is 5 mm. Such number of reading is of course too much, based on that is used reduced number. That means if we compare results from diffuse geometry with 30 mm aperture, where we will measure with rotation of sample as visible on Fig. 7.28 (90° rotation after every reading) with portable device equipped by diffuse geometry and aperture 5 mm, then it is necessary to choose similar 4 measuring points as visible on mentioned figure and add one in the center of sample. At each measuring point we will do 4 reading with 90° rotation and as result we will obtain 20 individual readings. By this simple method, we will have reproducible measurement made by both devices and this measurement will be also traceable (not identical).



**Figure 7.28** Methodology of sample rotation during repeatable measurement - 4 times multiple measurement typically by using devices equipped by diffuse measuring geometry



**Figure 7.29** Methodology of sample positioning during measurement - 4 times multiple measurement typically by using devices equipped by measuring geometry  $45^\circ \text{a}:0^\circ$

What is important also is a method used for data presentation. That means some of portable devices present to you result with precision at one decimal place. Why? Multiple reading appears then more stable. It is important to understand what happened! As scientists or engineers, we get a large amount of the numbers we report, and use in our calculations from measured observations, as was mentioned in chapter 7.2.3. In this instance, a number is determined to be significant or not by the accuracy and precision of the measuring device. With a number derived from a measurement the last digit to the right expresses the uncertainty. For example, if you are sure that your spectrophotometer can deliver an accurate measurement to a tenth of a colorimetric coordinate unit ( $L^*$ ,  $a^*$ ,  $b^*$ ) then you would be justified in reporting color to a tenth of a colorimetric coordinate unit. For example, if one measured a lightness value of 90.1 this number would contain three significant figures with the last digit expressing the uncertainty. The uncertainty would be plus or minus 0.05 u (unit). Even if the instrument could spit out 10 digits passed the decimal point one should only report the significant digits. Errors can arise in calculations if insignificant figures are used in a calculation. If a number resulting from a measurement is used in a calculation that involves multiplication or division all significant figures should be carried through the calculation and then the result should be rounded at the end of the calculation to reflect the term used in the calculation with the fewest significant figures. For example,  $10.4 \times 5.0$  should be reported as 52 and not 52.0. If the calculation involves addition and subtraction a different rule applies, one should preserve common decimal places of the numbers involved. For example, if two numbers obtained from a measurement are used in an addition,  $10.1 + 1000.234$  the reported number should be 1010.3, not 1010.334!!! Notice that 10.1 has 3 significant figures and 1000.234 has 7 significant figures and the result of the addition has 5 significant figures.

General rules for determining the number of significant figures in a number:

- All non-zero numbers are significant.
- All zeros between significant numbers are significant, for example the number 1002 has 4 significant figures.
- A zero after the decimal point is significant when bounded by

- significant figures to the left, for example the number 1002.0 has 5 significant figures.
- Zeros to the left of a significant figure and not bounded to the left by another significant figure are not significant. For example, the number 0.01 only has one significant figure.
  - Numbers ending with zero(s) written without decimal place possess an inherent ambiguity. To remove the ambiguity writes the number in scientific notation. For example, the number 1600000 is ambiguous as to the number of significant figures it contains, the same number written  $1.600 \times 10^6$  obviously has four significant figures.

*Several Notes:*

- 1) It is important to know the accuracy and precision of the measuring device one is using and it is important to report only those digits that have significance.
- 2) It is generally accepted that the uncertainty is plus or minus 0.5 unit at the level of the uncertainty, for example the "true value" for the number 0.003 can be described as being bounded by the numbers 0.0025 and 0.0035. It is important to note that in some instances scientists or engineers will want to express an uncertainty that exceeds 1 at the level of the uncertainty and this should be noted explicitly in the following fashion,  $0.003 \pm 0.002$

Examples:

$$\begin{array}{lll}
 L^* = 91.5 \pm 0.92 & \rightarrow & L^* = 92 \pm 1 \\
 L^* = 91.5 \pm 0.81 & \rightarrow & L^* = 91.5 \pm 0.9 \\
 \Delta L^* = 1.1 \pm 0.09 & \rightarrow & \Delta L^* = 1.10 \pm 0.09 \\
 \Delta L^* = 1.104 \pm 0.09 & \rightarrow & \Delta L^* = 1.10 \pm 0.09 \\
 \Delta L^* = 1.105 \pm 0.09 & \rightarrow & \Delta L^* = 1.11 \pm 0.09
 \end{array}$$

## 7.2.6 Maintenance of measuring systems

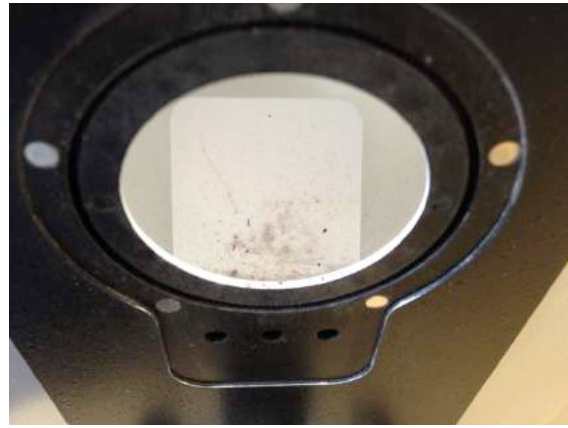
Maintain the spectrophotometer according to manufacturer recommendations, including periodic testing and preventative maintenance, by qualified service personnel. Qualified regular preventative maintenance will assure that the spectrophotometer's integrating sphere coating is within acceptable reflectance parameters, and that the instrument continues to operate within specification.

Operate the spectrophotometer in a temperature-controlled, clean environment, and (if possible) leave it under power at all times. A constant temperature environment will eliminate measurement variability caused by thermal changes within the instrument. Therefore, it is best to maintain power to the spectrophotometer (to eliminate warm-up thermal drift), and to keep the room environment at nearly constant temperature. Maintaining a clean operating environment will extend the life of the sphere coating, and reduce the chance of long-term drift caused by dirt accumulating in the instrument's optical components. An example of pulp particles, which affects reflectance properties of integrating sphere, is visible on Fig. 7.30.





**Figure 7.30** Heavy dust of pulp particles inside of measuring sphere



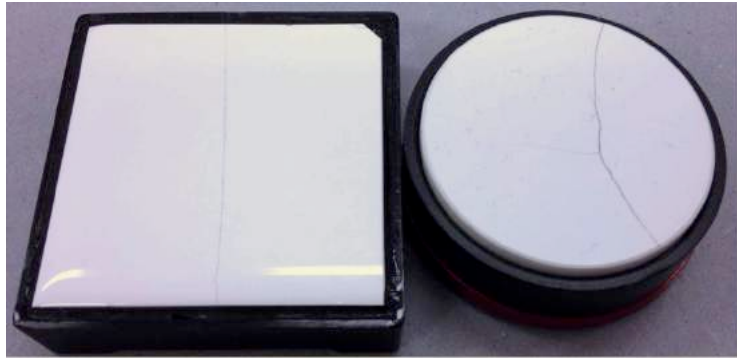
**Figure 7.31** Fiber fragments, dust particles, etc. on baffle of measuring sphere is typical problem of horizontal orientation of device

Second way for the pollution of measuring devices is fragmentation of samples. As we can see on the Fig. 7.31, the fragments of samples like parts of yarn, fibers, particles from a surface of sample and so on are passed into the device usually in the places of contact like the opening of coverings and the same way through cuvette space if we measure transmittance. In both cases, it is possible to clean devices with help of pure pressured air (without particles, oil or water). If we cannot use clean-pressured air it is possible to use containers with compressed air or balloons for optic cleaning from optics store. In case, that the impurity cannot be cleaned by pressured air, do not use mechanical removal and we should consult this problem with service worker. Surfaces of lenses are provided with antireflexive layers and could be damaged by mechanical cleaning same way as the spraying of integration sphere. It was stated, that correctness of measurement is significantly influenced by actual state of calibration standards and user should therefore anxious to ensure their proper maintenance. This means that the calibration standards are kept clean usually light protective boxes or carrying case. In addition, it is necessary to verify the calibration standards. This is done almost exclusively in white ceramic standards. Practice where these standards are automatically exchanged after one year of use is not always necessary, as these standards are relatively non-fading and operating conditions, measurements can satisfy more than 5 years. In the case of other white standards such as compressed tablets barium sulfate should be that intact and stored in a desiccator standard should be used for maximum 1 month.

Maintain the white and black calibration standards so that they are clean, and safe from potential damage. Maintain carefully the white and black standards, since the photometric scale (0 to 100%) of the spectrophotometer is calibrated to these standards. Handle and store the white tile so that it does not become soiled or scratched. If soiled, clean the tile using water (and if necessary a mild soap), drying with a clean non-abrasive, non-optically whitened paper towel or cloth. If dirt or dust enters the black trap, clean it using a compressed air flows. If they become very dirty then, before the above procedure is followed, they should be cleaned first with lens tissue or a soft tissue soaked in ethanol or propanol, followed by rinsing in deionized or distilled water for 1 minute and drying with a soft tissue.



**Figure 7.32** White tile that was damaged by daily use



**Figure 7.33** Example of some white tiles, which was broken with help of impact – falling, etc.

Recalibrate more often, perhaps every 2 to 4 hours and immediately before important jobs, even if the manufacturer normally suggests that recalibration is necessary only every 8 (or more) hours. Recalibrate more often (less than 24 hours or other recommendations) because the photometric scale (0 to 100%) of any spectrophotometer may “drift” over time between calibrations, due to temperature, light source and/or photo detector factors. Any “drift error” is eliminated at calibration, and greatly reduced by recalibrating often.

### 7.2.7 Uncertainty in measurement

The objective of a measurement (or any other quantitative investigation) is to determine an estimate for the true value of the measurand. This estimate, i.e. the measurement result, may be an individual measured value. The term uncertainty represents a concept, according to which the true measurement value is unknowable because, after all the known sources of error are being corrected for, there will always be uncontrollable variations in measurement. The value of uncertainty is “...associated with the result of the measurement, that characterizes the dispersion of the values that can be reasonably attributed to the measurand” [160].

Guide to the Expression of Uncertainty in Measurement (GUM) classifies uncertainty components according to their method of determination into type A and type B:

Type A: Evaluation using statistical analysis of measurement series,

Type B: Evaluation using means other than statistical analysis of measurement series.

With respect to the suggested methodology, GUM does not differentiate between uncertainty components due to systematic effects and uncertainty components due to random effects. It is however assumed that, as far as possible, recognized systematic errors are either eliminated by technical means or corrected by calculation. For the uncertainty budget a component remains which accounts for the uncertainty arising from any such action.

A typical example for a **type A evaluation** is the determination of an estimate of the standard deviation  $\sigma$  of an assumed normal distribution. If  $x_1, x_2, \dots, x_n$  are the results of repeated measurements of the quantity concerned, then the experimental

standard deviation  $s$  of the measurement series  $\{x_1, x_2, \dots, x_n\}$  can be used as an estimate of the standard deviation  $\sigma$  of this normal distribution.

The *Standard Uncertainty*  $u_A(y)$  is given by the experimental standard deviation of the mean:

$$u_A(y) = s(\bar{y}) = \frac{s(y)}{\sqrt{n}} = \sqrt{\frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n(n-1)}} \quad (7.26)$$

If we are doing less number of individual reading then ten ( $n < 10$ ), the standard uncertainty calculated as standard deviation of the mean (7.26) is less reliable, therefore we need to use *Expanded Uncertainty*, i.e. product of the standard uncertainty  $u_A(y)$  and an appropriate coverage factor  $k_A$  from table 7.4:

**Table 7.4 Size of coverage factor  $k_A$  for different count of repetitive readings**

Number of reading $n$	10	9	8	7	6	5	4	3	2
Coverage factor $k_A$	1	1.2	1.2	1.3	1.3	1.3	1.7	2.3	7.0

If we imagine obvious number of multiple readings for example 4, which was mentioned in section 7.2.5 as measurement of color difference, when following table shows individual data:

Number of reading $n$	1	2	3	4
$\Delta E^*$	1.1	0.9	1.1	0.8

Then result of expanded uncertainty by use of equations (7.18) and (7.26) with coverage factor will be following:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i = \frac{1}{4} (1,1 + 0,9 + 1,1 + 0,8) = 0,975$$

$$u_A = k_A \cdot s(\bar{y}) = 1,7 \cdot \sqrt{\frac{(1,1 - 0,975)^2 + (0,9 - 0,975)^2 + (1,1 - 0,975)^2 + (0,8 - 0,975)^2}{4(4-1)}} = 0,1275$$

$$x = \bar{x} \pm u_A = 0,98 \pm 0,13$$

Again, the more readings you use, the better the estimate will be. In this case, it is the estimate of uncertainty that improves with the number of readings (not the estimate of the mean or ‘end result’). In ordinary situations 10 readings is enough. For a more thorough estimate, the results should be adjusted to take into account the number of readings.

A typical example of a **type B evaluation** is the transformation of a maximum/minimum into a standard uncertainty. Suppose that only a minimum value  $x_{\min}$  and a maximum value  $x_{\max}$  are known for the characteristic value (reference value) attributed to a reference material. If all values in this interval are equally likely candidates of the true value, the mean and the standard deviation of a rectangular distribution with boundaries  $x_{\min}$  and  $x_{\max}$  can be used for the reference value  $x$  and its standard uncertainty  $u(x)$ .

$$x = \frac{(x_{\max} + x_{\min})}{2} \quad (7.27)$$

$$u(x) = \frac{(x_{\max} + x_{\min})}{\sqrt{12}} \quad (7.28)$$

However, if there is reason to believe that values in the center of the interval are more likely than values at the boundaries, then e.g. a symmetrical triangular distribution with boundaries  $x_{\min}$  and  $x_{\max}$  can be chosen instead of the rectangular distribution (uniform distribution). This gives:

$$u(x) = \frac{(x_{\max} + x_{\min})}{\sqrt{24}} \quad (7.29)$$

A Type B evaluation of standard uncertainty is usually based on scientific judgment using all of the relevant information available, which may include:

- previous measurement data,
- experience with, or general knowledge of, the behavior and property of relevant materials and instruments,
- manufacturer's specifications,
- data provided in calibration and other reports, and
- uncertainties assigned to reference data taken from handbooks.

Generally, if the manufacturer provides the standard uncertainty, it is used directly. If very little information is available on an input quantity and its supposed variation interval comes under the form:

$$u_B(z_j) = \frac{z_{j\max}}{k_S} \quad (7.30)$$

where  $k_S$  is factor depended on probability laws that are connected with source of uncertainty and  $z_j$ , which indicate the number of standard deviations that a particular value may be distant from the mean of the distribution. In case of normal distribution is  $k_S = 2$  for 95% of the distribution, or 3 for 99,7% of the distribution. Where the information is insufficient (in some Type B estimates), you might only be able to estimate the upper and lower limits of uncertainty. You may then have to assume the value is equally likely to fall anywhere in between, i.e. a rectangular or uniform distribution. The standard uncertainty for a rectangular distribution is found from:  $k_S = \sqrt{3} = 1,73$ , for triangular  $k_S = \sqrt{6} \doteq 2,45$  and for U-shaped  $k_S = \sqrt{2} \doteq 1,41$ .

If there are several sources of uncertainty, they should be combined to produce the combined standard uncertainty. This is done by taking square root of sum of squares of all the uncertainty values associated with the measurand, e.g.:

$$u_B(y) = \sqrt{\sum_{j=1}^p A_j^2 u_B^2(z_j)} \quad (7.31)$$

where  $u_B(z_j)$  are uncertainties of individual sources,  $A_j$  it's expansion factors.

Similarly, individual standard uncertainties calculated by Type A or Type B evaluations can be combined validly by 'summation in quadrature' (also known as 'root sum of the squares'). The result of this is called the *combined standard uncertainty*, shown by  $u_C(y)$ . Summation in quadrature is simplest where the result of a measurement is reached by addition or subtraction.

### How to reduce uncertainty in measurement?

Always remember that it is usually as important to minimize uncertainties, as it is to quantify them. There are some good practices, which can help to reduce uncertainties in making measurements generally. A few recommendations are:

- Calibrate measuring instruments (or have them calibrated for you) and use the calibration corrections, which are given on the certificate.
- Make corrections to compensate for any (other) errors you know about.
- Make your measurements traceable to national standards - by using calibrations, which can be traced to national standards via an unbroken chain of measurements. You can place particular confidence in measurement traceability if the measurements are quality-assured through a measurement accreditation
- Choose the best measuring instruments, and use calibration facilities with the smallest uncertainties.
- Check measurements by repeating them, or by getting someone else to repeat them from time to time, or use other kinds of checks. Checking by a different method may be best of all.
- Check calculations, and where numbers are copied from one place to another, check this too.
- Use an uncertainty budget to identify the worst uncertainties, and address these.
- Be aware that in a successive chain of calibrations, the uncertainty increases at every step of the chain.

Remember that there are many more sources of elemental uncertainty. If you need to classify them, apply the logic that if the analysis of the uncertainty can be done with statistics it is a Type A uncertainty. If statistics cannot be used (for example, if the uncertainty is systematic and repeatable) then it is to be treated as a Type B uncertainty.

If you wrongly classify a Type A elemental uncertainty as Type B, or vice versa, the consequences may not be significant. While the mistake will change the attribution of uncertainty to different components of the uncertainty analysis, the final estimated uncertainty would be the same, irrespective of wrong Type A/B classification!

### 7.3 Color tolerance specifications

The specification of a color tolerance can result in mutual satisfaction of both supplier and customer if handled properly. What is meant “handled properly”, it can provoke bitter controversy and perhaps loss of customer or supplier. Usually, one cannot reproduce colors exactly. This means it is important to know whether a color difference would be noticeable to a human viewer; it is generally useful to be able to compare the significance of small color differences. Just noticeable differences can be obtained by modifying a color shown to an observer until they can only just tell it has changed in a comparison with the original color. When these differences are plotted on a color space, they form the boundary of a region of colors that are indistinguishable from the original colors. Usually, ellipses are fitted to the just noticeable differences. It turns out that in CIE chromaticity diagram these ellipses depend quite strongly on where in the space the difference occurs. It was written that MacAdam ellipses, which are used as JND, allow determine limits for color difference. Nevertheless, we need to clearly discuss problem of perceptibility and acceptability. No other element of color management causes so much confusion as the establishment of metric standards. There is an assortment of valid reasons. There is also a great deal of misunderstanding. First, as mentioned in chapter 1, the assessment of color is essentially subjective. Second, measuring techniques are imperfect and may lack repeatability. Third, the good being measured do indeed have measurable differences in what appears to be a constant colored field. Fourth, each device (colorimeter, spectrophotometer, etc.) measure slightly differently. That means traceability of measured data is obviously guaranteed inside of model line of manufacturer not between competitive models of different manufacturers, where it is necessary to improve it via correlation matrixes, special software respectively. Fifth, production facilities are rarely test for process capability. Add to this the idea that “one size fits all”, i.e., that one metric color tolerance can be applied holistically and there arises quite a chaotic scenario [157].

In an ideal world, tolerances would be set at zero or well below perceptible color difference. Nevertheless, manufacturers are generally concerned about the maximum acceptable difference rather than a minimum perceptible difference, and the color tolerances are usually based on the former. As was mentioned before two levels of visual color differences between standard and sample are used to establish color tolerances:

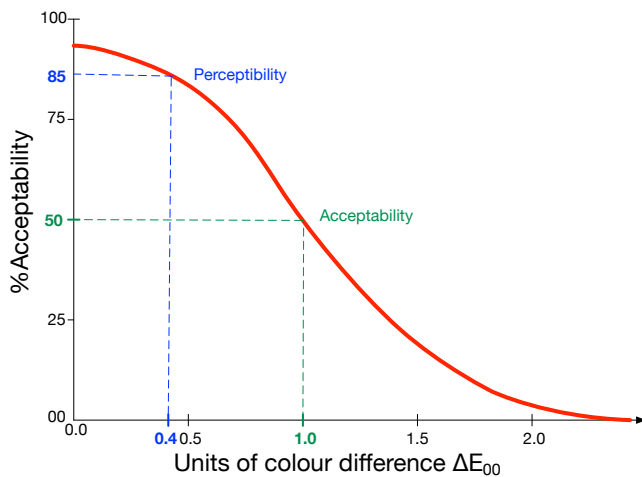
- Minimum perceptible difference, i.e. a just noticeable difference.
- Maximum acceptable difference, which is the largest acceptable difference.

The setting of tolerances always represents an economic compromise. In the commercial world, tolerances concern ultimate customer satisfaction in terms of value received for the price paid. To be competitive, the manufacturing process has to be streamlined and the cost minimized. That means management obviously set product must not necessarily excellent, but good enough.

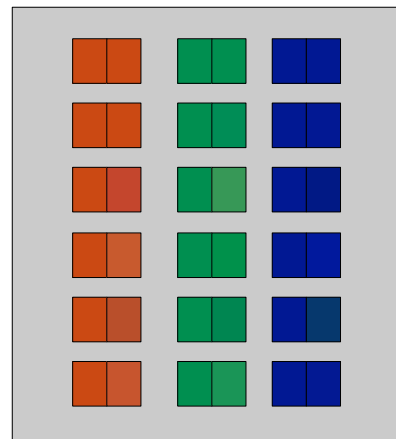
When the color difference between a standard and a sample is marginal, it may be either a just noticeable difference (JND) or just acceptable difference to an observer or a set of observers. The first depend on the perception capabilities of the observer. The perceptible difference refers to the smallest discernible difference under most favorable

conditions. As was mentioned in industry, it is often required to specify the acceptability of color variations between a given standard and its reproduction. Whereas the perceptibility of a color difference is strictly a visual judgment, the acceptability is biased by several considerations involving the intended application of the product and its price.

The relationship between acceptability and perceptibility is illustrated in Fig. 7.34. This curve represents an average of large number of observations by a wide variety of observers. It can be seen from this curve that approximately 50% of observers consider a  $\Delta E_{00} = 1.0$  to be an acceptable match. It is interesting to note that even though color differences smaller than  $\Delta E_{00} = 0.4^9$  are generally imperceptible, not all observers judge these matches to be acceptable. **In fact, there was not 100% acceptance even when the measured color difference was equal to zero!** The establishment of tolerances at or below perceptibility limits isn't only prohibitively expensive but also not guarantee acceptance by your customer.



**Figure 7.34** Illustration of relation between acceptability and perceptibility



**Figure 7.35** An example of color differences on the border of acceptability and perceptibility

Finding an acceptable instrumental method of determining ratings of color difference was expected to be rather more difficult. It would have to be capable of quantifying a change, not just from grey level, but also from whatever was the color of the specimen under test. It would also have to be able to quantify a change in any direction from that color. The method currently used for most visual assessments of color differences between batch and target relies on comparing the contrast between tested and untested specimens with those of the relevant one of two internationally agreed physical scales, each consisting of pairs of grey chips having graded contrasts – Grey Scale for Assessing Change in Colour (ISO 105: Textiles – Tests for Colour Fastness, Part A02), and the Grey Scale for Assessing Staining (ISO 105: Textiles – Tests for Colour Fastness, Part A03), which typical in fastness tests.

<sup>9</sup>  $\Delta E_{00} = 0.4$  is an approximate size of MacAdam's observer PGN deviation ellipse, which is used as an example of just noticeable color difference.

As was mentioned before the contrast between members of the pairs increases the farther to the right the pair, so that the pair on the far right denoted 1, has the greatest contrast. In the Part A02 scale the right-hand chip of each pair is progressively lighter the lower the grade the pair represents, while in the Part A03 scale it is darker. Grade 5 of the Part A03 scale is sensibly white.

In the assessment, the appropriate scale is placed as near as possible to the batch and target specimens and in the same plane, which is illuminated at an intensity of at least 1500 lux and at about 45° by a source representing north sky light (in the northern hemisphere). Viewing is made approximately normally to the plane with the color of the surrounding field approximating Munsell N5 till N7. The contrast between the batch and target specimens then most closely resembles either the real contrast of one of the five pairs in the grey scale, in which case the rating is recorded as the denotation of that pair, or the imaginary contrast midway between those of two adjacent pairs, when the rating accorded is those of both pairs separated by a hyphen (for example, 3–4). Grade 5 is given only when there is imperceptible contrast. There is increasing use of nine-step scales, as was shown on Fig. 7.5, in which the imaginary contrasts of the five-step scales are replaced by corresponding real pairs of chips; the number of possible ratings remains nine.

This method is called “grey scale method” of color difference evaluation, beside that we can have method of constant stimuli, haploscopic, etc. Nevertheless, grey scale method allows simple transformation of assessment into visual color difference by using color difference values of CIELAB, which are shown in Table 7.1 or by using simple fitting function of these tabulated data. Because obvious agreement of acceptance of visually assessed color difference between manufacturer and customer is set on 4 step of grey scale for assessing color change it is possible to define tolerance limit for instrumental evaluation by following equation:

$$\Delta E \leq \Delta E_{tol} \quad (7.29)$$

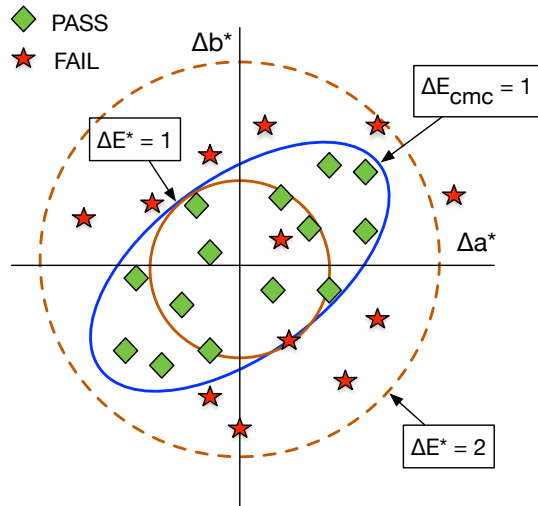
During adaptation period of CIELAB, means Eq. (4.27) was recommended by CIE to use as industrial limit for acceptable color difference in range 1 to 2 units, that means:

$$\Delta E_{tol}^* \supset \langle 1-2 \rangle \quad (7.30)$$

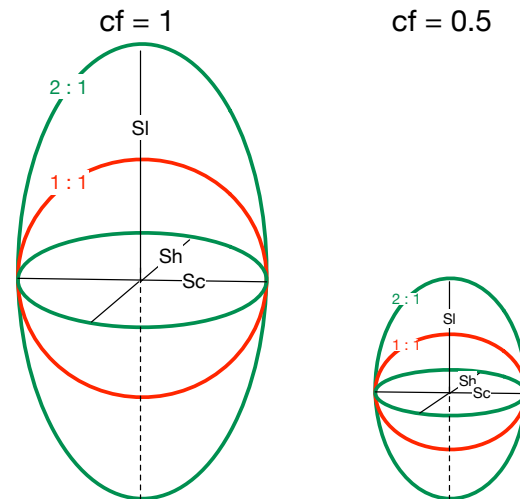
Reason for this range was on one side nonuniformity of CIELAB color space, second reason was insufficient adaptation of total color difference  $\Delta E^*$  on different surface effects as texture, etc. Present day recommendation is focused on color difference formula, where general set up of tolerance lit is **1 unit**.

Chart in Fig. 7.36 shows that distribution of color samples (projection of color coordinates of individual batches on difference chromaticity plane) isn't even, that is obviously caused by combination of dyes in used recipe and low number of samples. It is also shown that visually accepted samples are possible to cover by ellipsoidal tolerance. Beside that we can see problem of CIELAB: if we will use tolerance set up on  $\Delta E_{tol}^* \leq 1$ , then instrumental evaluation of color differences will be too strong and number of samples, which are visually accepted will be rejected by this criterion. On the other side use of tolerance limit following  $\Delta E_{tol}^* \leq 2$  will be problematic, because number of samples, which will be accepted instrumentally will be rejected by customer during visual assessment. In our case samples will be rejected mainly due to big difference in hue. Of course, it is necessary to remember that this figure is projection.





**Figure 7.36** An example of total color differences based on CIELAB  $\Delta E = 1$  and  $\Delta E = 2$  and comparison with CMC( $l:c$ ) color difference formula



**Figure 7.37** An example of commercial factor  $cf$  on size of CMC( $l:c$ ) tolerance ellipsoid

The following general rules we can apply on human assessment of color differences:

- Hue differences  $\Delta H$  are most objectionable.
- Observers will tolerate a little more difference in chroma  $\Delta C$  than in hue  $\Delta H$ .
- Observers will tolerate lightness differences  $\Delta L$  more easily than difference in chroma  $\Delta C$  or hue  $\Delta H$ .

This principle form the basis for elliptical tolerancing – color difference formulas such as CMC, DIN99 and CIE2000, and they operate on the principle that the limit of the region of color space surrounding a target for which color differences are not visually detectable forms an ellipsoid with axes in direction of lightness, chroma and hue. That means above mentioned color difference formula are not new color spaces—they are simply tolerancing systems that are based on the  $L^*a^*b^*$  color space. The overall volume (size) of the ellipsoid is the overall color tolerance. For default, commercial factor of one this volume equals one  $\Delta E$  unit of the elliptical scale of interest:

$$\Delta E_{tol} \leq 1$$

This volume may be adjusted in order to tighten or loosen the overall tolerance. This reduces the amount of disagreement between the observer and the instrumental values. Nevertheless, it is important to understand the problem of change of commercial factor  $cf$ . Drawing on Fig. 7.37 show that reduction of commercial factor  $cf$  will caused reduction of volume of tolerancing ellipsoid. In other words, it is visible that value of commercial factor  $cf$  is equal to size of maximal tolerance in color difference of selected formula. Similarly we can change ratio between lightness and chroma  $l:c$  or  $k_L:k_C$ <sup>10</sup> which will affect change of shape of tolerancing ellipsoid.

<sup>10</sup> It is possible to change also  $k_H$ , but obviously is used constant value 1.

It was written; that pass-fail decisions based on CIELAB tolerance is affected by non-uniformity of this color space. Number of companies defines own tolerance, which are dependent on color coordinates of target or colors of target are grouped in categories with specific size of tolerance. Obviously, these tolerances, groups, are dependent on measuring conditions (angle or diffuse):

**Table 7.6 General tolerances to be applied using 45°:0°, 0°:45° and di:8° geometries with spectrophotometer in paint industry (ECCA)**

Color tolerance recommendations	Geometry used		
	45°:0° or 0°:45°		di:8°
	CIELAB $\Delta E^*$	$\Delta E_{CMC}$ $cf = 1$ $l:c = 2:1$	
Category 1: light colors	$\Delta E^*_{tol} \leq 1.0$	$\Delta E_{CMC} \leq 1.0$	$\Delta E^*_{tol} \leq 1.0$
Category 2: medium colors	$\Delta E^*_{tol} \leq 1.3$		
Category 3: dark colors	$\Delta E^*_{tol} \leq 1.5^*$		$\Delta E^*_{tol} \leq 1.5^*$
Category 4: saturated colors	$\Delta E^*_{tol} \leq 1.5^*$		
Category 5: metallized colors	Visual control required**		

\*  $\Delta E^*_{tol} \leq 2.0$  can be accepted for specific colors

\*\* as alternative, it is possible to use AUDI2000 color difference formula

Of course, the supplier has the final responsibility of defining the color category of his products. This applies particularly for special, demanding colors and cases where the color is close to a limit between two categories, or where a color shade falls out of any category.

Generally, the success of using selected color difference formula such as CMC, DIN99 or CIE2000 depends primarily on three things:

- a) Choice of lightness: chroma ratio ( $l : c; k_L : k_C, \dots$ )
- b) Choice of size of acceptable color difference, commercial factor  $cf$  respectively.
- c) Performance of color difference formula with customer judgments

(CIE 217:2016)

The ratio of the adjustment factors specific brightness and purity usually resizes tolerance measurement lightness. Generally, the coarser the texture of the measured surface, the higher the ratio. In the case of smooth shiny surfaces usual adjustment  $l : c = 1 : 1$ , for dull surfaces is  $1.5 : 1$ , lightly textured surfaces  $2 : 1$  (typically textiles) and for coarse texture  $3 : 1$ . It follows the general recommendations for setting up a commercial factor  $cf$ , and the ratio of the adjustment factors specific brightness and purity for different industrial applications, as shown in Tables 7.5 and 7.6:

**Table 7.5 Choosing the proper  $l : c$  ratio (recommended)**

Typical use and the products	$l : c$
Most common – uniform, minor textured materials, low gloss or matte (most fabrics, plastics, paper, paint, ceramic tiles, etc.)	2 : 1
Construction industry and some of textiles - coarse, textured products textile industry and civil engineering (carpets, leather, rough coating, etc.)	3 : 1
Automotive and glass industry – smooth, shiny materials, very high gloss (lacquers, decorative tile and satins, etc.)	1-1.5 : 1

**Table 7.6 Recommended size of  $cf$**

Level of P/F requirements	Typical products	$cf$
Extremely critical	Cut and sew, seam to seam Automotive plastic parts Laminated paper	0.40
Critical	Yarn dyeing Automotive paints (absorption pigments, colors relating to basic models such as red, ...)	0.50
Intermediate	Glazed ceramic tiles	0.75
Average	Apparel fabrics Metallic automotive paints Plastics Unglazed ceramic tiles	1.00
Loose	Matching garments, tops and bottoms	1.20
Very Loose	Food products – chunky, granular, etc.	2.00+

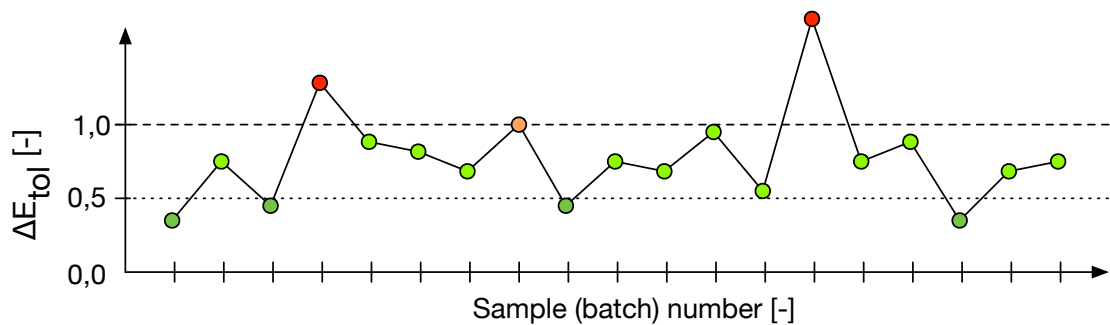
If there is a customer request to change the tolerance limits, this could be approached in two ways. The first is often referred to as a graphic and a second statistic. Remember when establishing color tolerances, subjective visual evaluations are not enough. The seller may check a production batch against the buyer's standard and feel it is acceptable, only to submit it to the buyer and have it rejected. What is acceptable to one person may not be to another. Some objective method of arbitration must be developed in order to carefully evaluate the product for color.

A graphic way adjustment equation for calculation of color differences is used for rough estimate whether the requirement of the customer feasible and based on the trend graphs of manufactured products. If we have data for a particular shade or close, which

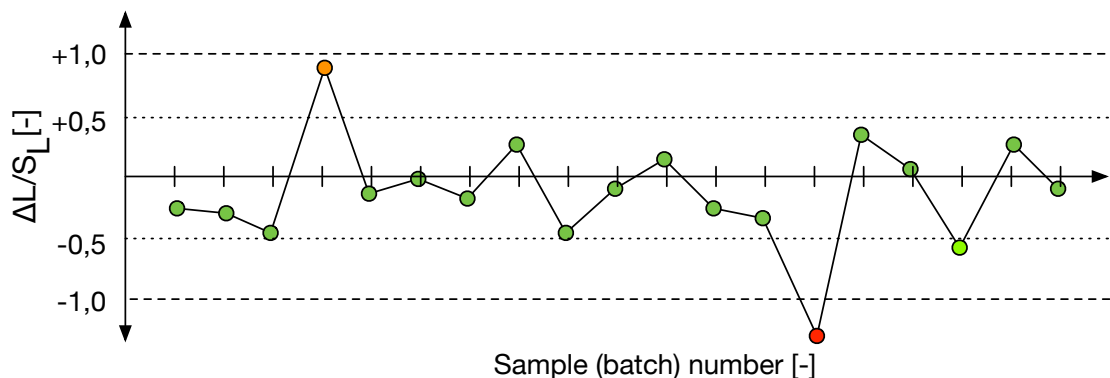
was produced by a certain period, so most commercial software allows you to view trending for both the overall color deviation, and are used in various colorimetric system, most CIELAB. In the event that are displayed data for the selected formula as CMC ( $l:c$ ), DIN99 and CIE2000, it is obviously used presentation of the weighted values of differences in cylindrical CIELCH system.

In the graph in Figure 7.38 shows the data of the color difference equation CMC ( $l:c$ ), which was adjusted to the basic setting, a 2:1 ratio and tolerated overall color difference equal to 1. In the event that the customer would like to raise the level of P / F opinions (PASS / FAIL - pass / fail) the average of the critical, therefore, that the value of the commercial factor  $cf$  decreased from 1.0 to 0.5; then it can almost certainly say **that such a requirement is impossible for manufacturers.**

The idea that a company that has not yet fulfilled their contracts, especially in the upper part of the permitted tolerance, will be from day to day, so unable to change their technology, production and quality management to be able to compress your existing tolerance in half is simply beyond reality. Conversely, in the event that the same production was assessed the possibility of reducing the ratio of the adjustment coefficients measurement lightness and cleanliness of the current 2 : 1 to 1.5 : 1 or about 1 : 1, it is obvious that such a treatment has been for manufacturers acceptable because with the exception of two outlier all remaining lots were within the limit of half of the existing weighted tolerance.



**Figure 7.38** Trend plot of total color differences of individual batches in order as was produced by using of CMC( $l:c$ ) 2:1,  $cf=1$



**Figure 7.39** Trend plot of weighted lightness differences of individual batches in order as was produced by using of CMC( $l:c$ ) 2:1,  $cf=1$

### 7.3.1 Statistical Tolerance Limits

The above graphical method for determining the user tolerance is a rough estimate typically applicable for calculation equations color differences. In other cases, determined by statistical tolerance limits to us with a given probability interval, which will cover some of the basic data set.

In other cases, it is necessary to estimate statistical tolerance limits, which allows define the range of data that fall within a specified percentage with a specified level of confidence. A tolerance interval can be seen as a statistical version of a probability interval. In the parameters-known case, a 95% tolerance interval and a 95% prediction interval are the same. If we knew a population's exact parameters, we would be able to compute a range within which a certain proportion of the population falls. For example, if we know a population is normally distributed with population mean  $\mu$  and variance  $\sigma^2$  of size  $N(\mu, \sigma^2)$ , the two-sided limits can be given as follows  $\mu \pm Q_p \cdot \sigma$ , where  $Q_p$  is a quantile of normalized normal distribution. Key quantiles are present on Fig. 7.25, in case of 95% of the population is key quantile 1.96. Because in many cases we don't know size of parameters  $\mu$  a  $\sigma^2$ , it is necessary to use sample mean  $\bar{x}$  and standard deviation  $s$  [158]. Statistical limits are then rewritten in following form:  $\bar{x} \pm k \cdot s$ , where  $k$  is the statistical tolerance factor taken in table 7.7:

**Table 7.7 Two-sided tolerance factors**

Sample size $n$	Proportion $P$ (statistical tolerance factor $k$ )			
	<b>0.75</b>	<b>0.90</b>	<b>0.95</b>	<b>0.99</b>
5	3.002	4.275	5.079	6.634
6	2.604	3.712	4.414	5.775
7	2.361	3.369	4.007	5.248
8	2.197	3.139	3.732	4.991
9	2.078	2.967	3.532	4.631
10	1.987	2.836	3.379	4.433
17	1.679	2.400	2.858	3.754
37	1.450	2.073	2.470	3.246
145	1.280	1.829	2.179	2.864
$\infty$	1.150	1.645	1.960	2.576

From table 7.7 it is visible that statistical tolerance factor  $k$  is equal to quantiles only if we will evaluate infinite number of samples. Tolerance intervals are calculated using a variable multiple of sample standard deviations determined based not only on the desired confidence level and proportion of the population to be covered, but also the sample size available. Thus, tolerance intervals yield reasonable estimations of process capability even with small data sets. Also, because tolerance intervals specify a region covering a proportion of the population, not just the uncertainty associated with a population parameter, tolerance intervals are the widest of the intervals. Tolerance intervals should be used when the capability of a process, that is, the ratio of a process specification to the population spread is the primary goal. That means it is important to understand that statistical tolerance limits (ST) are dependent on number of measured samples  $n$ .

So, consider a test scenario, in which several batches  $y_1, y_2, \dots, y_n$  of particular color are tested to produce final length of ordered fabric. The final number of measured batches was  $n = 17$ .

Whole analysis we can describe by following steps:

- First step in establishing metric color difference standards is to select a difference calculation method (color space or color difference formula).
- Next step is preparation of color difference charts, where will be presented following differences  $(\Delta a^* \Delta b^*, \Delta C^* \Delta H^*), (\Delta a^* \Delta L^*, \Delta b^* \Delta L^*, \Delta C^* \Delta L^*, \Delta H^* \Delta L^*)$ .
- On each chart, it is necessary to check outliers, which can affect analysis
- Then we will calculate estimation of sample mean for every axis of used color space by following formula:

$$\Delta \bar{t} = \frac{1}{n} \sum_{i=1}^n \Delta t_i \quad (7.31)$$

where  $\Delta t$  are differences in following directions  $\Delta L^*, \Delta a^*, \Delta b^*, \Delta C^*$  or  $\Delta H^*$ . Be careful, such estimation is obviously deflected from 0 because we have limited number of batches (higher deflection than 1 is obviously caused by outlier data).

- As expected, now it is necessary to calculate standard deviation  $s$ :

$$s(\Delta t) = \sqrt{\frac{\sum_{i=1}^n (\Delta t_i - \Delta \bar{t})^2}{n-1}} \quad (7.32)$$

- The tolerance interval is calculated as:

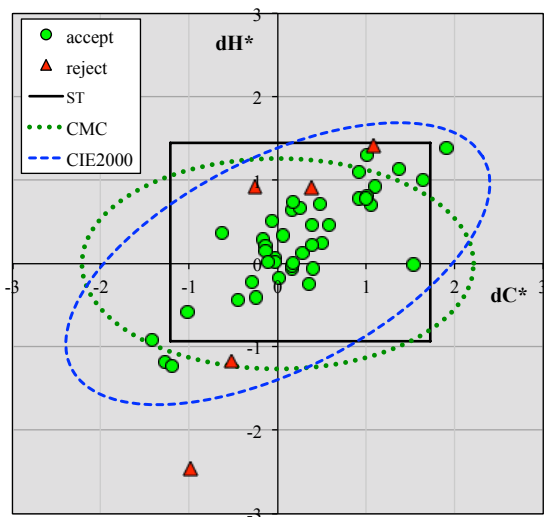
$n$	Lower limit	Upper limit
17	$\Delta \bar{t} - 2.858 \cdot s(\Delta t)$	$\Delta \bar{t} + 2.858 \cdot s(\Delta t)$

- As result in our example we received these limits:

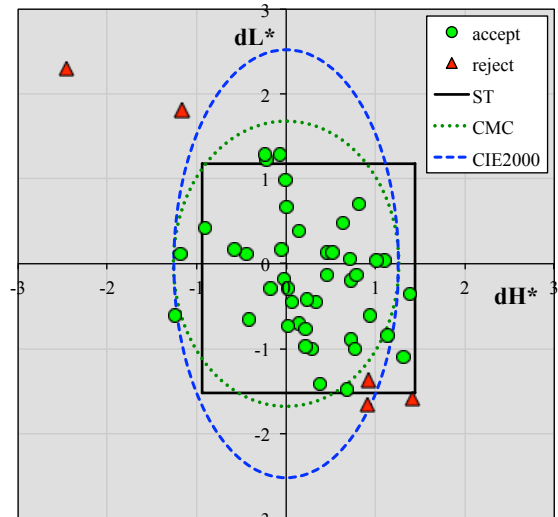
Color difference	$\Delta L^*$	$\Delta a^*$	$\Delta b^*$
Lower limit	-0,65	-0,20	-0,15
Upper limit	+0,35	+0,40	+0,40

- On the end these statistical limits we will represent on mentioned color difference charts as we can see on Figs. 7.40 and 7.41.

The graphs of Figs. 7.40 and 7.41, we can see that the graphic interpretation of the statistical limits (ST) is the tolerance block. As already mentioned, since the occurrence of the colorimetric data of the individual batches in colorimetric systems is not usually due to the relatively small number ideally uniform, so the center of gravity of the block is not in the center differential graph as would result from the properties of a standard normal distribution, but his position is skewed. In other words, tolerance is asymmetrical.



**Figure 7.40** Projection of statistical tolerance (ST) together with color difference formula CMC( $l:c$ ) and CIE2000 on  $\Delta C^* \Delta H^*$  plane



**Figure 7.41** Projection of statistical tolerance (ST) together with color difference formula CMC( $l:c$ ) and CIE2000 on  $\Delta H^* \Delta L^*$  plane

That's not the only problem of statistical tolerance limits in colorimetry. Returning back to the graph in Figure 7.40 we can see that the deployment of colorimetric data for the batch, which met in the visual assessment panel observers (assessors 5) has more or less ellipsoid character. Given that it is a navy-blue shade is rotated against the main ellipsoid coordinate axes colorimetric system CIELCH. It is also shown that equation CIE2000 unlike equation CMC ( $l : c$ ), which form concentric ellipsoid responds to this fact thanks to the rotation RT. In the case of other hues are more or less aligned character of tolerance, as noted in section 3.4 From the viewpoint of statistical tolerance limits it is however the problem of occurrence of large marginal areas in which there would be a batch evaluation is satisfactory, although the panel is highly likely observers assessed as unsatisfactory. This problem is evaluated using the wrong decision criterion **WDC**<sup>11</sup>, which indicates the percentage of opinions different from visual evaluation:

$$WDC = \frac{100.(P_x + F_x)}{N} \quad (7.33)$$

Where values  $P_x$  and  $F_x$  are based on result summarized in  $2 \times 2$  contingency table, which allows evaluation of association and independence between two categorical factors, is a classic topic of interest in statistical inference.

Method of this evaluation is a simple: Let  $N$  is number of batches, of which  $P$  is number of batches visually passed and  $F$  is number of batches visually failed. At any given total color difference  $\Delta E_{tol}$  from standard, let  $P_C$  is number of visually passed batches with a

<sup>11</sup> In CIE Colorimetry is present day preferred the standardized residual sum of squares (STRESS) [173]. Nevertheless, WDC due to its simplicity as single number express agreement between visual assessment and calculated PASS/FAIL evaluation in form of percentage is frequently used in industry.

color difference smaller than  $\Delta E_{tol}$ ,  $P_X$  is number of visually passed batches with a color difference equal or greater than  $\Delta E_{tol}$ ,  $F_X$  is number of visually failed batches with a color difference smaller than  $\Delta E_{tol}$  and  $F_C$  is number of visually failed batches with a color difference equal or greater than  $\Delta E_{tol}$ .

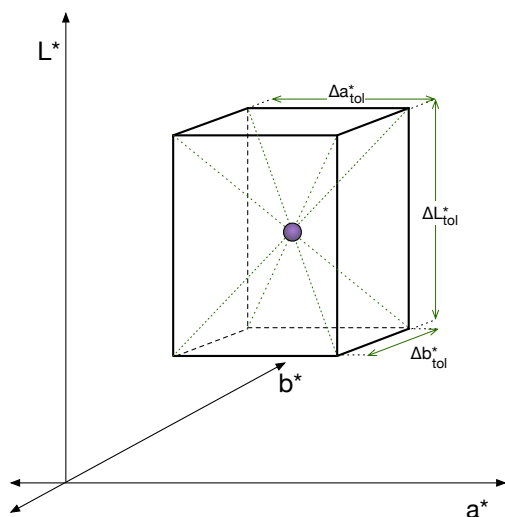
**Table 7.8 Contingency table of samples and failed**

	Formula PASS	Formula FAIL	Total
Visual PASS	$P_C$	$P_X$	$P$
Visual FAIL	$F_X$	$F_C$	$F$
Total	$P_C + F_X$	$P_X + F_C$	$N$

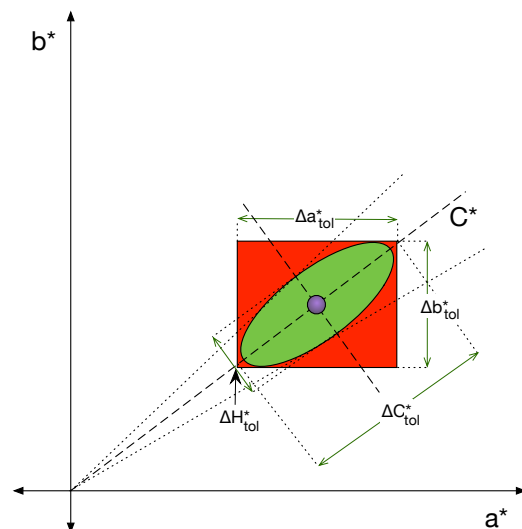
If the value  $\Delta E$  was used as the limit for passing using the formula, then  $P_C$  batches would be agreed with the visual pass assessment and  $F_C$  batches would agree with the visual assessed fail assessments.

The wrong decisions are then  $P_X$  and  $F_X$  i.e. the formula is giving a different evaluation to the visual assessment. Thus  $P_X + F_X$  can be calculated at various values of  $\Delta E$  and the minimum found to give one measure of the agreement between visual and calculated PASS/FAIL assessment as visible on Eq. (7.33). The minimum value shows also possible set up of commercial factor  $cf$ .

In the schematic representation of statistical tolerances in Figs 7.42 and 7.43 we can see the ideal case when the mean value  $\Delta t$  equal to 0. Marginal zone corresponding poor assessments are shown in red and fill the corners of the tolerance box. The disadvantage determination of statistical tolerance limits ST CIELAB colorimetric system is a variation of the size of the marginal areas, hence the WDC depending on the evaluation shade as visible on Fig. 7.44.



**Figure 7.42** A plus/minus delta  $L^*a^*b^*$  tolerance represents box a “box” shaped volume in color difference space

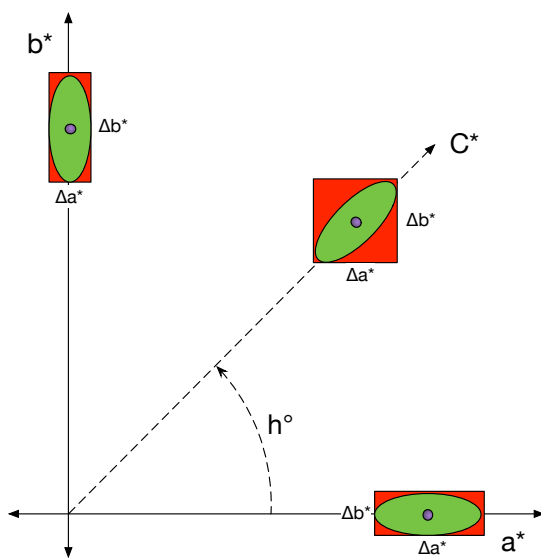


**Figure 7.43** Problem of rectangular tolerance limits - samples within the box and not in the ellipsoid are numerically correct but visually unacceptable

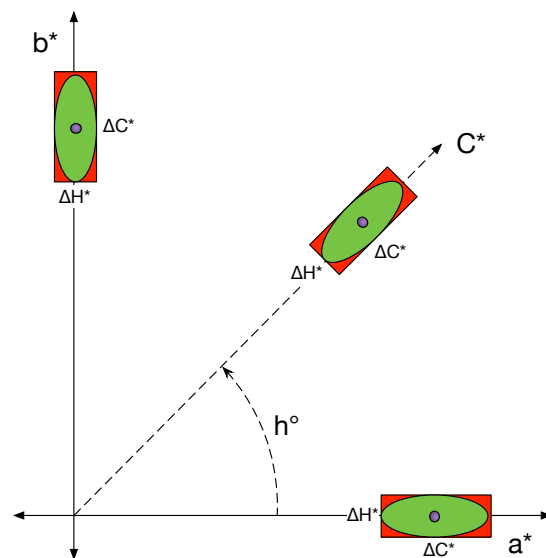


The largest uncertainties right expertise is achieved in shades of mid hue angles defining quadrants colorimetric system, that is the orange (brown); yellow-green (khaki), cyan and purple (purple) color shades where the hypothetical distribution ellipsoid oriented acceptable color differences in terms of the diagonal rectangle (square) formed projections tolerance to chromatic block area. As shown in the schematic representation of tolerances in figure 4.21, with the exception blues tolerance ellipsoid is oriented in the sense of principal axes colorimetric system CIELCH. From Figures 7.44 and 7.45, it is apparent that more sensible approach is to set tolerances in terms  $\Delta L^*$ ,  $\Delta C^*$ ,  $\Delta H^*$ . Remember CIELAB system allows for an alternate but equivalent definition of total color difference  $\Delta E^*$  in these terms. If we want to reduce the size of areas of uncertainty correct evaluation of color differences must use a comprehensive approach to statistical tolerances. Calculation of statistical tolerance limits based on equations (7.31) and (7.32) neglects the interaction between differences in colorimetric coordinate system. As shown, the distribution of color differences acceptable forms an ellipsoid in the three-dimensional color space. This means that when visual evaluation panel observer takes into account not only the difference in a given direction but also the size differences in the remaining directions. In other words, if the batch exhibits a difference in the specific brightness approaching a tolerance limit, then the watcher is already too tolerated differences in specific purity and luminous efficacy hue.

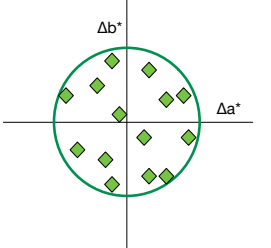
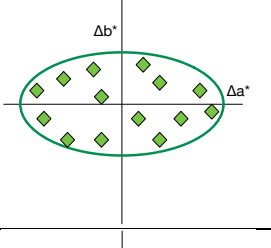
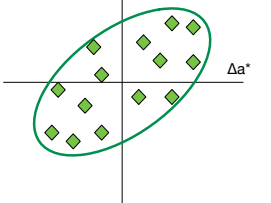
This problem can be solved if instead of a simple analysis of variance (ANOVA) was used in determining the tolerance limits ANOVA (MANOVA). The resulting covariance matrix defines the spatial variance ellipsoid in which a given confidence level of 95% occur samples which visual evaluators evaluated as acceptable in terms of color variation. Since the individual coefficients of the covariance matrix can be rewritten metric coefficients. The following table shows the three-basic geometric representation of the covariance matrix if the amount of data available and their character allow correct calculation of colorimetric tolerances.



**Figure 7.44** Corresponding tolerance boxes in terms of  $da^* db^*$



**Figure 7.45** Corresponding tolerance boxes in terms of  $dC^* dH^*$

Geometric representation	Verbal description	Mathematical description
	Random scattering of data – tolerancing body is a sphere	$\frac{(\Delta L^*)^2}{r^2} + \frac{(\Delta a^*)^2}{r^2} + \frac{(\Delta b^*)^2}{r^2} = 1$ $q_{11} \cdot (\Delta a^*)^2 + q_{22} \cdot (\Delta b^*)^2 + q_{33} \cdot (\Delta L^*)^2 = 1$ $q_{11} = q_{22} = q_{33}$
	Scattering of data is associated with main axis of used color space – tolerancing body is a triaxial ellipsoid	$\frac{(\Delta L^*)^2}{m^2} + \frac{(\Delta a^*)^2}{n^2} + \frac{(\Delta b^*)^2}{o^2} = 1$ $q_{11} \cdot (\Delta a^*)^2 + q_{22} \cdot (\Delta b^*)^2 + q_{33} \cdot (\Delta L^*)^2 = 1$ $q_{11} \neq q_{22} \neq q_{33}$
	Scattering of data is rotated from main axis of used color space – tolerancing body is an uniaxial ellipsoid	$q_{11} \cdot (\Delta a^*)^2 + q_{22} \cdot (\Delta b^*)^2 + q_{33} \cdot (\Delta L^*)^2$ $+ 2q_{12} \cdot \Delta a^* \Delta b^* + 2q_{13} \cdot \Delta a^* \Delta L^* +$ $+ 2q_{23} \cdot \Delta b^* \Delta L^* = 1$

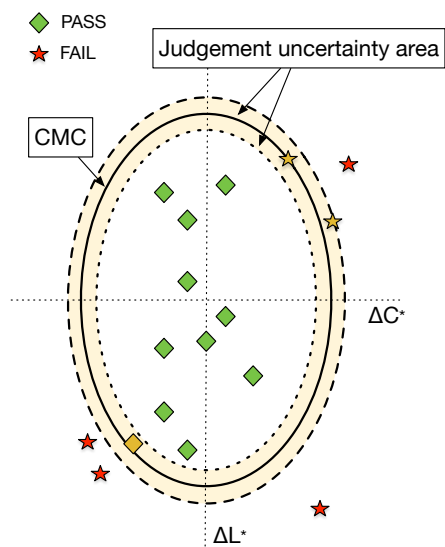
Although it has been stated that the most frequent case in the visual evaluation of color differences is the variance associated with the axes and thus the result coaxial ellipsoid, this is the case generally for the controlled data, which in the context of visual experiments in various research laboratories, data is organized so as to monitor the assumption of normal distribution. It should also be point out that in case of multi-factor analysis of variance without adequate statistical software package (software such as SPSS, Statistica QC Expert, GraphPad Prism, etc.) cannot be ignored because the real colorimetric data of the individual batches are affected by the addition of random, also non-random factors [162]. In other words, the setting of statistical tolerance limits using multifactor analysis to monitor deviations from the normal distribution, etc.

### 7.3.2 Tolerance and uncertainty

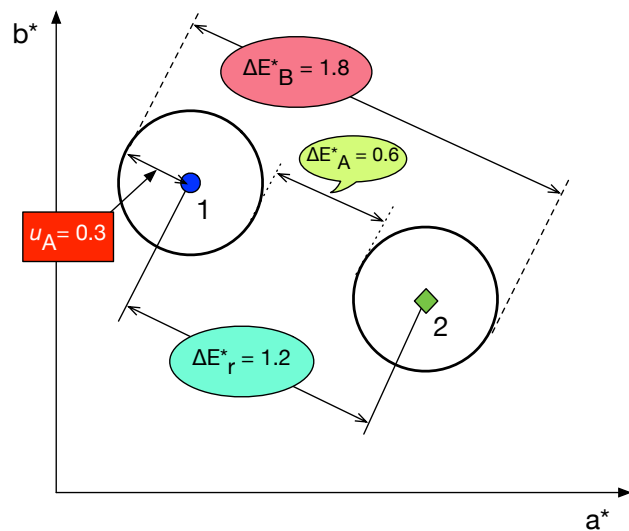
Besides the aspects mentioned above set the tolerance limits, it is necessary to reports PASS / FAIL (pass / fail) to include measurement uncertainty. In the event that we judge two batches at  $\Delta E_{tol} \leq 1$ , the product will be a color difference  $\Delta E = 0.99$  compliant product and a color difference  $\Delta E = 1.01$  unsatisfactory? In this extreme case, about every hesitated. It follows that the application of methods sharp cut can lead to questionable judgments. The example of the colorimetric measurement in section 7.2.7, it was shown that the four-fold repeating the measurement uncertainty is due to the coefficient of expansion  $k_A$  at **1.7 times the standard deviation of the mean** from individual measurements. A number of control programs used in spectrophotometers colorimetry use the default settings bands uncertainty assessment PASS/FAIL within  $\pm 0.1 \Delta E^*$ . Ignoring the fact that the colorimetric system CIELAB is about evenly graded

and therefore the size range should be constant, resulting in reports PWF (PASS/WARN/FAIL). This means that all batches have a total color difference is less than 0.9 ( $\Delta E^* < 0.9$ ) are satisfactory (PASS), samples, which is in the range of values from 0.9 to 1.1 are to be considered (WARN) and samples to which the total color difference is greater than 1.1 ( $\Delta E^* > 1.1$ ) are unsatisfactory (FAIL). Schematic representation of the default settings uncertainty band's report is shown in Figure 7.46. Although defaults zone of uncertainty assessment of the color difference helps in controlling the quality of production, it is necessary to realize that assumes a priori measurements with repetition. This means that for typically used quadruple repetition using a measuring aperture of 30 mm diameter it is necessary that the standard deviation of the arithmetic mean is less than 0.06  $\Delta E^*$ . Otherwise you must reckon with the fact that the size of bandwidth measurement uncertainty of  $\pm u_A$  affects the PASS/FAIL evaluation of color differences as shown in the schematic representation in Figure 7.47. Where is visible that increasing of uncertainty of measurement caused problems with PASS/FAIL evaluation. One or two readings can be surly accepted ( $\Delta E^* = 0.6$ ) or rejected ( $\Delta E^* = 1.8$ ) with the same probability.

Measurement uncertainty  $u$  is therefore extremely important, and in general they are more critical evaluation of color differences, the greater demands are imposed on the reproducibility of measurements. It should therefore happen that someone called down the tolerance limits away from the table without having to have conducted an analysis of measurement uncertainties. The result is an absurd situation where so specified tolerance limits, not only that you cannot keep, but not to measure. Typical examples are the colored areas with multiple textures (such as plastic parts used in car interiors), mélange, nonwoven fabrics, and carpets, and so on, where, thanks to visual inhomogeneity in these products, the uncertainty of measurement is higher than usual. In such cases, it often happens that the data measured by the manufacturer and the customer varies considerably. Remember statistics is a tool that can be used in manufacturing to monitor both precision and reproducibility.



**Figure 7.46** Example of common setup of uncertainty area if  $u_A \leq 0,1$  – some of samples it is necessary to re-measure



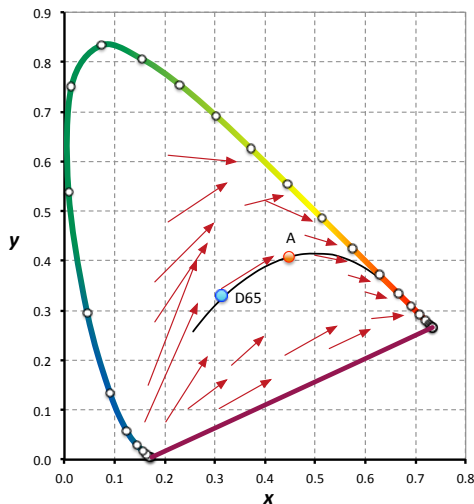
**Figure 7.47** Effect of high uncertainty on PASS/FAIL evaluation - batch can be accepted or rejected with the same probability and the number of such batches increases with  $u_A$

## 7.4 Metamerism

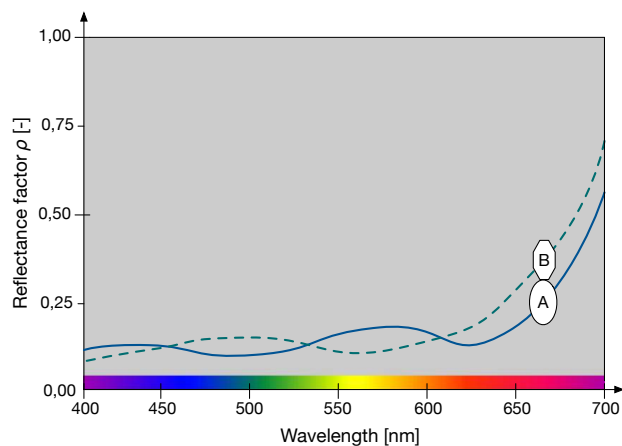
At one time or another, nearly everyone has carefully chosen and purchased a colored article from a store only to find that in another location the color was not exactly what had been expected. The disappointment may have been due either to poor color constancy or to metamerism. Both phenomena are related to a change in the spectral energy distribution of the light reflected back to the eye from the article in question in moving from one light source to another.

Color constancy is the property of human vision by which the colors of an object under different light sources with widely varying intensity levels and spectral distributions are perceived as the same or remain constant. It is common practice to change light sources quickly while continuing to stare at the standard. Resulting change in color is known as *flare* in textile industry. Position change of individual color samples caused by change from D65 simulator to illuminant A inside of CIE xy diagram is shown on Fig. 7.46.

More often than common people will be comparing a colored sample against a standard, rather than looking at an individual sample. When the samples match the standard less than one illuminant, but fails to match when the illuminant is changed, the phenomenon is called *metamerism*, and we speak about *metameric pair*. This is the obvious situation when the batch is of different material to the standard, or when the colorants used to color batch are differ to colorants used to color the standard (frequently we don't know, which colorants were used to color the standard). In this case reflectance curves of the standard and batch will differ. The opposite situation, when the batch matches standard under all illuminant would be non-metameric match, a state of affairs that every colorist dreams, thus we speak about *isomeric pair*.



**Figure 7.46** Chromaticity shift obtained for observer – each vector shows the change in chromaticity which was required to maintain a visual match between two halves of visual colorimeter



**Figure 7.47** Example of wavelength intersections of metameric pair of samples – Thornton in 1973 proposed that the wavelengths of the intersections are  $448 \pm 4$ ,  $537 \pm 3$  and  $612 \pm 8$  nm, then for textiles crossover wavelengths were readjusted into: 458, 541 and 611 nm.

Such situation is likely to be achieved when the batch is made of the same material as the standard, and is of the same color, and when the same colorants are used. In this case reflectance curves of the standard and the batch will be identical. For an object pair to be metameric, the reflectance curves of its members must be intersecting at multiple wavelengths throughout the visible range. It was verified on a theoretical basis that two stimuli to be metameric, must cross at least three times [164].

Geometric Metamerism – phenomenon exhibited by a pair of colors that appear to be a color match at one angle of illumination and viewing but that no longer match when the angle of illumination or viewing is changed; caused by gloss and/or texture differences.

Metamerism is a visual effect on at least two objects. This is important because in addition metamerism caused by changing lighting yet known color change of one sample in connection with the change of lighting. This phenomenon is also called color stability. As documented in the graph in Figure 7.46 the position of each shade is in the CIE colorimetric triangle constant, but is tied to the used light, which affects the position of the white point.

Returning back to metamerism, then we mark as metameric those samples that appear during certain conditions of illumination and observation as the same and after the change of these conditions appear to be differently colored. If we were to describe mathematically this phenomenon, the characteristics of the system XYZ CIE follows that two objects appear to the human eye as well colored when the consensus in tristimulus XYZ ingredients:

$$\begin{aligned} X_1^{D65} &= X_2^{D65} \\ Y_1^{D65} &= Y_2^{D65} \\ Z_1^{D65} &= Z_2^{D65} \end{aligned} \tag{7.34}$$

From equation (3.11) to (3.13) suggest that to meet the equations (7.34) no consensus reflectance curves of both samples  $R_i(\lambda)$  ( $i = 1,2$ ). It turned out that these curves must cross at least three points. As shown in the graph in Figure 7.47 the place where most often intersect spectral curves were established in about 458, 541 and 611 nanometers.

### 7.4.1 Special Indices of Metamerism

Two specimens having identical tristimulus values for a given reference illuminant and reference observer are metameric if their spectral radiance distributions differ within the visible spectrum. The procedures concerned with a special metamerism index for a change from a reference illuminant to a test illuminant of different spectral composition, or for a change from a reference observer to a test observer having different color-matching functions are called the determination of special metamerism indices. A measure of the metamerism for the two specimens is the color-difference between the two metameric specimens caused by substituting an illuminant, *special metamerism index: change in illuminant*, or caused by substituting an observer, *special*

*metamerism index: change in observer.* The color-difference is evaluated using a color-difference formula and it must be clearly stated which formula has been used.

**1. Metamerism for change in illuminant  $M_{ilm}$ :**

$$\begin{aligned} X_1^{A,F,LED\dots} &\neq X_2^{A,F,LED} \\ Y_1^{A,F,LED\dots} &\neq Y_2^{A,F,LED} \\ Z_1^{A,F,LED\dots} &\neq Z_2^{A,F,LED} \end{aligned} \quad (7.35)$$

**2. Metamerism for change in observer  $M_{obs}$ ,** a method for evaluating the degree of color mismatch for a metameric color pair (object color or illuminant color) when an actual observer with normal color vision is substituted for the standard colorimetric observer:

$$\begin{aligned} \bar{x}_d(\lambda) &= \bar{x}(\lambda) + \Delta\bar{x}(\lambda) \\ \bar{y}_d(\lambda) &= \bar{y}(\lambda) + \Delta\bar{y}(\lambda) \\ \bar{z}_d(\lambda) &= \bar{z}(\lambda) + \Delta\bar{z}(\lambda) \end{aligned} \quad (7.36)$$

Values  $\Delta\bar{x}(\lambda)$ ,  $\Delta\bar{y}(\lambda)$ ,  $\Delta\bar{z}(\lambda)$  are called as „first deviation function“, CIE *Standard Deviate Observer* values respectively [28][166], see in Appendix C2.

Observer metamerism refers to differences in metameric matches when made by different observers. Identical spectral matches will match in color for all observers. However, when the spectral power distributions of the two stimuli differ, and only metameric matching is possible, a match made by one observer will typically not match for other observers. This is caused by differences in the color matching functions of the various observers. Among color-normal observers, these differences are caused by variation in macular pigment density, pre-retinal filtering in the optical media (cornea, lens, and humors), and differences in cone spectral responsivity and photo pigment density. Higher-level mechanisms of chromatic adaptation and color appearance do not impact metameric matching. On the end two sets of tristimulus values of the members of the metameric pair with respect to the Standard Deviate Observer are calculated and resulting color difference (recommended is CIELAB or CIELUV).

## 7.4.2 General Indices of Metamerism

The CIE Special Index of Metamerism is illuminant specific. It needs one reference and at least one test illuminant. The test illuminant can be varied and a number of indices may be calculated. To make the index illuminant independent and to specify the degree of metamerism of a pair of specimens by a single number, a number of general indices of metamerism have been proposed. They are based on the spectral difference between standard and trial, which is inevitable for metamers. Accordingly, Bridgeman [167] developed following index:

$$MI = \sqrt{\sum_{\lambda} (R_1(\lambda) - R_2(\lambda))^2} \quad (7.37)$$

where  $R_i(\lambda)$  represents the reflectance of the color samples investigated at each reported wavelength, subscript  $i$  means 1 or 2 and denote two samples of a pair.

Index described by equation (7.37) does not take into account the variation of the eyes' sensitivity to different spectral lights. Nimeroff a Yurow [168] weighted the spectral differences with color matching functions, and they proposed an index as bellow:

$$MI = \sqrt{\sum_{\lambda} [\bar{x}(\lambda)(\Delta R(\lambda))]^2 + \sum_{\lambda} [\bar{y}(\lambda)(\Delta R(\lambda))]^2 + \sum_{\lambda} [\bar{z}(\lambda)(\Delta R(\lambda))]^2} \quad (7.38)$$

Nevertheless, such correction is not fully accepted and present day is used as comparison method only [169][170].

### 7.4.3 Color-difference and metamerism index

The coloristic practice, the most commonly encountered assessment using metameric difference  $ME$ .  $ME$  calculation is based on a calculation of the color variations in different lighting than has been achieved color conformity in CIELAB space:

$$ME_{D65-A} = \sqrt{(\Delta L_{D65}^* - \Delta L_A^*)^2 + (\Delta a_{D65}^* - \Delta a_A^*)^2 + (\Delta b_{D65}^* - \Delta b_A^*)^2} \quad (7.39)$$

where  $\Delta L_{D65}^*$ ,  $\Delta a_{D65}^*$ ,  $\Delta b_{D65}^*$  are color differences under D65 and  $\Delta L_A^*$ ,  $\Delta a_A^*$ ,  $\Delta b_A^*$  are color differences under illuminant A.

It is recommended to use such quantification of metamerism minimally for two pairs of light source. Obviously is used change from D65 – A and D65 – F11 (TL84):

$$ME_{D65-F11} = \sqrt{(\Delta L_{D65}^* - \Delta L_{F11}^*)^2 + (\Delta a_{D65}^* - \Delta a_{F11}^*)^2 + (\Delta b_{D65}^* - \Delta b_{F11}^*)^2} \quad (7.40)$$

This equation allows following evaluation of metamerism:

- $ME^* \leq 0,5$  – target and batch are non-metameric
- $0,5 < ME^* \leq 1,0$  - target and batch are less metameric (MARGINAL)
- $ME^* > 1,0$  - target and batch are metameric (FAIL).

Due to nonuniformity of CIELAB color space is frequently metameric difference recalculated by using color difference formula such as  $CMC(l:c)$ :

$$\Delta ME_{CMC(l:c)D65-A} = \left[ \begin{aligned} & \left( \Delta L_{D65}^* / SI_{D65} - \Delta L_A^* / SI_A \right)^2 + \\ & \left( \Delta C_{D65}^* / cSc_{D65} - \Delta C_A^* / cSc_A \right)^2 + \\ & \left( \Delta H_{D65}^* / Sh_{D65} - \Delta H_A^* / Sh_A \right)^2 \end{aligned} \right]^{1/2} \quad (7.41)$$

where  $Sl_{D65}$ ,  $Sc_{D65}$ ,  $Sh_{D65}$  are weighting functions dependent on target under standard daylight D65,  $Sl_A$ ,  $Sc_A$ ,  $Sh_A$  are weighting functions dependent on target under standard illuminant A.

The present measures of metamerism demand perfect matching under at least one selected illuminant, in the absence of which the measures are unreliable or unpredictable. Moreover, when metamerism exists between a pair or is created purposely to generate *flare* effects, the reliability of present measures should be studied more intensively. When the illuminant is changed or its intensity varied, the eye's sensitivity changes to some degree to compensate for the change of illuminance. Here it is necessary to point out influence of daylight simulators, which are used in industry. Wide range of lighting cabinets is equipped fluorescent tube F7 and visual assessment of metameric pairs gives almost similar results. If is used another kind of daylight simulator such as filtered tungsten or incoming multispectral LED system, situation, results respectively can be much differ. Of course, we have different measures how to evaluate daylight simulators; nevertheless, at customer it is obviously difficult to analyze real SPDs of used cabinet<sup>12</sup>. Possible solution of this problem is also assessment under north sky, but here we are limited in time period, which is dependent on season and general recommendation for visual assessment under daylight is to do it from 10 a.m. to 3 p.m. (during winter season from 11 a.m. to 2 p.m.).

## 7.5 On-line measurement

Inspection system for evaluation of fabric represents the optimal quality control system of the textile product. At present, it is usually divided into two substantially independent parts consisting of the evaluation of appearance characteristics of the fabrics, the number of weaving or other manufacturing defects. These systems are implemented either as part of the drying and fixation frames, or as an additional device for browsing tables. Irrespective of this assessment is offered on-line color measurement. Color and flexibility are requisite requirements. You're also expected to achieve exceptional results quickly, efficiently and cost-effectively. The on-line measurement system enables you to do it all:

- **Consistent, predictable results.** With the ability to measure color throughout the entire roll, you're assured of accurate, repeatable color quality.
- **Fast, accurate color.** Smart spectrophotometer technology enables the system to quickly detect and analyze colorimetric and density variations from targets located *anywhere within the product* while the press is running.
- **Improved productivity.** Significant time is wasted when your operators have to stop the press and remove a section of the web to measure color. On-line measurements eliminate that time-consuming process.
- **Reduced waste.** Less stopping and starting the presses combined with faster make-readies equals' decreased waste.

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<sup>12</sup> *Simple method how to check quality of daylight simulator is based on metameric strips such as PANTONE Lighting Indicator. For more precise evaluation is possible to use portable spectroradiometer such as LightDrop Smart Spectrometer.*



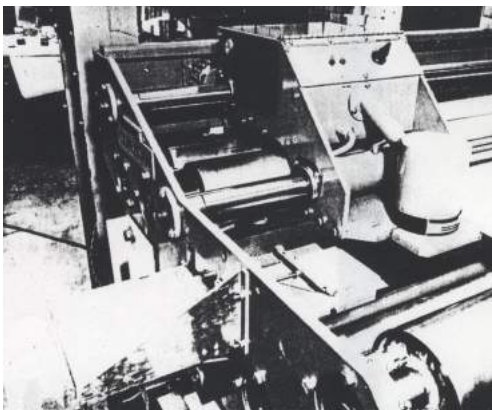
Due to these advantages, it is possible to continuously improve the quality of technological processes and final products. Although he was the first system of online color measurement installed in 1978 in the company of Ford Aerospace & Communications Corp. Fig. 7.48, we can say that the first wave of the presentation of these measuring systems dating back to the period 1987-1995 at international exhibitions ITMA. Then on-line measuring systems called. First generation was based on a principle called. In tele colorimetric systems was the distance from the measured fabrics ranged from 0.4 m to 6.5 m. The main reason was the expected deployment of measurement systems, for example for drying and fixation frame respectively for continuous steamers. There was thus concern about the potential impact of heat radiation on the goods and increased humidity too close to the measurement sensor from the fabric to the measured values and the service life of the measuring head, therefore, a number of systems fitted pyrometers for measuring the temperature of the goods. Other reasons for these extreme distances was an effort to minimize the impact of variability in the thickness of the fabric and its vibration during movement on the measured colorimetric parameters as documented in the chart in Fig. 7.49.

Devices like Optronik TeleFlash or EagleEye made by Macbeth were equipped with high-capacity flash-based system xenon lamps (up to 100kW), the spectral range of 400-700 nm and 20 nm spectral steps. Despite the great interest of the industry, the production of these systems gradually stopped. The reason was the **high price** of the device itself, so regular servicing, it was further discomfort operator dazzling flashes, respectively ballast light source from the platen and finally **incompatibility** measured data with measurements carried out on an off-line measurement systems in laboratories.

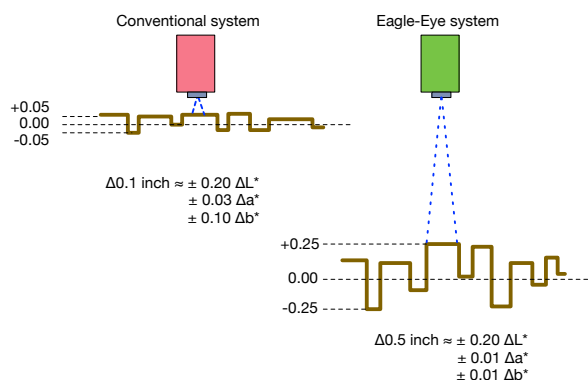
This starting damp squib caused focus of many producers on simple on-line systems, which were installed in food, pulp and paper industry. In most cases, such systems were adopted version of tristimulus colorimeters without necessity to catch top level of accuracy.

Generally, we can divide on-line measuring systems into two groups:

- One or more measuring heads placed in fixed position
- One movable measuring head, which scan whole width of fabric



**Figure 7.48** One of first On-line measuring system in Ford Aerospace company



**Figure 7.49** Description of differences between conventional and Eagle-Eye system by Macbeth company – less sensitivity on differences in sample positioning



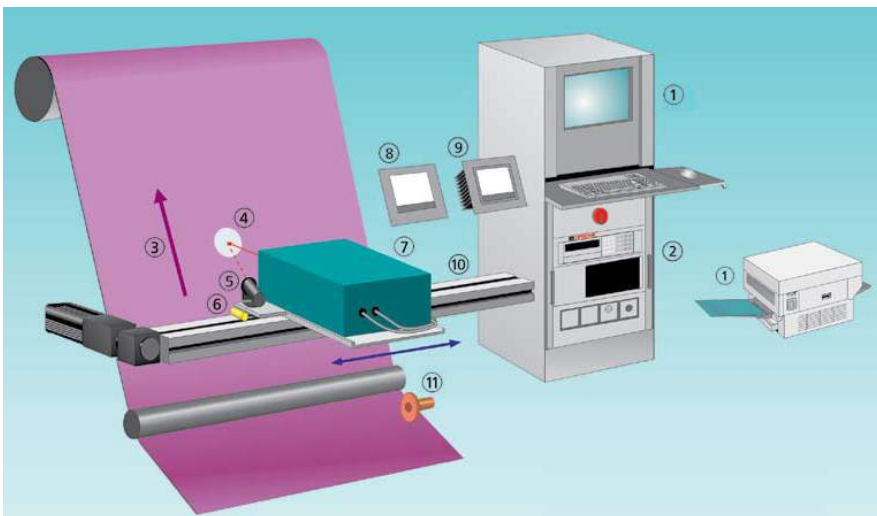
**Figure 7.50** c-tex COLOUR® (Nixtex, GB)



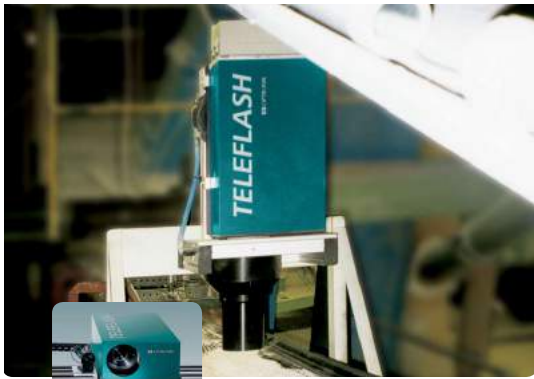
**Figure 7.51** SpectraTrend® HT (HunterLab, USA)

In the first category include, for example systems as c-tex Colour Nixtex Company, which consists of three sensor heads positioned at the center and both edges of the measured regions, as documented in Fig. 7.50. Measuring System c-tex is built based colorimeters and is therefore only used for quality control of assessed colored belts, whether it be a fabric, paper, film, or the like. A similar design can of course be used with other systems such as SpectraTrend HT firm HunterLab, Fig. 7.51.

Currently, the measuring head connected only through the industrial data buses, but also via Ethernet. The measurement data can then be sent directly to the company network and information from individual measuring points can be processed either centrally or locally, according to customer requirements. The second solution is, of course, can apply to previous systems. As shown in the diagram in Fig. 7.52 the measuring head can be continuously traverse across the width of the fabric, or at higher distances from the fabric can be used in a combined manner when the measuring head is stopped for a certain period at a defined position, typically at the center of the scanned fabric strip.



**Figure 7.52** Typical scheme of scanning system



**Figure 7.53** TELEFLASH device  
(X-Rite, USA)



**Figure 7.54** COLORSCAN CIS 12  
(MAHLO, Germany)

Traversing measuring systems can either be conceived as a "mere" color measurement, respectively quality control achieved shades, such as measurement systems Teleflash firm X-Rite (Fig. 7.53) and ColorScan CIS 12 Mahlo - Fig. 7.54, or is a combined evaluation of color and appearance characteristics of the fabric as is the case with the measuring system SpectroEdge of Techkon company, Fig. 7.55. Spectral range of measurement is in the range from 380 to 760 nm, or in a shortened range 400-700 nm spectral steps 3-10 nm. As the light sources used are halogen lamps, xenon lamps and LED light sources.

Quality control software is designed in different concepts, nevertheless it must be understood that an on-line measuring system can collect vast amounts of data. Without a clear idea of how these data can be condensed into useful information, the system is likely to only confuse users. List of some of the important things (questions) to consider in deciding on or designing an on-line system software is follow:

- At what point(s) in the process would the collection of data be most beneficial?
- How must these data compare with other instruments inside or outside of the company?
- What frequency of measurement and how much averaging is required for a fabric?
- What additional information must be collected other than color (appearance, speed, yardage, temperature, pH, humidity, etc.)?
- From where (physical place) will the instrument be controlled? What limits will impose on operators?
- What type of data will be most beneficial and where should it be provided?
- What other systems/terminals/users can or should be interfaced into the facility?
- Will there be a need (now or later) for multiple instruments in the facility?
- What in house computer hardware and expertise are already available, which could be made a part of the system?
- What type of requirements on communication lines are important in point of view of stability against high voltage discharge (technology such as USB, Ethernet)?

**SPECTRO  
EDGE**



**Figure 7.55** Spectrophotometer a densitometer SpectroEdge (Techkon, USA)

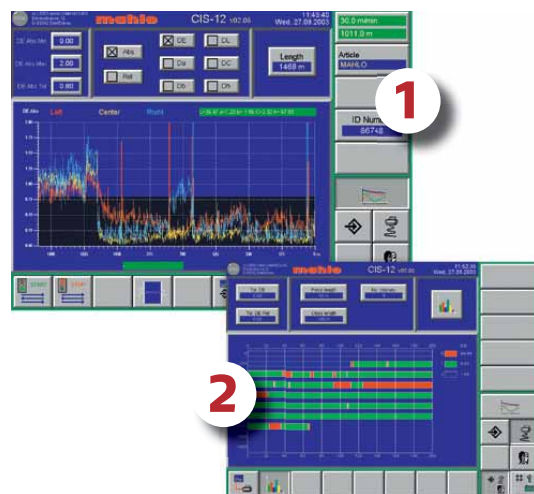
Obviously designed is therefore focused on trend data representation by bars or curves such as examples in Figs. 7.56 and 7.57.

If we look at it what are the advantages and disadvantages of current solutions for on-line measurement systems than first generation presented in the late 90s of the 20th century. Generally, in the case of benefits is primarily a greater ease of operation and integration into existing information systems used in companies such as SAP, and the like. A further advantage can be considered narrower spectral measuring step, which is usually 10 nm, but in some cases 3 nm or less. In practice, however, they say that they are meaningful only spectral steps 1 and 5 nm, respectively 10 nm, for which there is a standard methodology for calculating the CIE colorimetric coordinates.

All other spectral steps are transferred to the above, and therefore the information narrower spectral steps as e.g. 3 nm if Mahlo misleading, because this distinction is only at the level of hardware data processed in the device firmware. The data are then transferred to a broader spectrum step 5 or 10 nm, it cannot determine from the information available. However, this procedure is common for a number of manufacturers. The main disadvantages include possible incompatibility with the values measured by using off-line systems and usually poorer reproducibility of the measured data than the declared values.

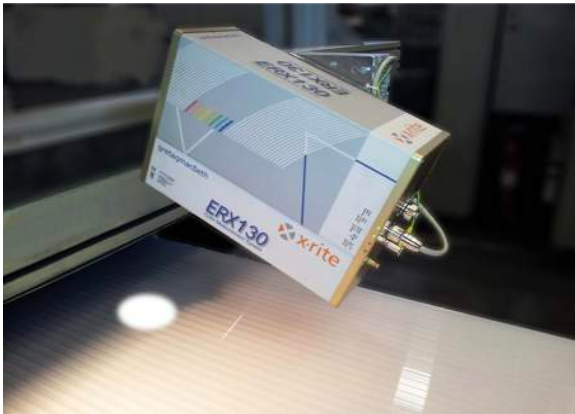


**Figure 7.56** Screen of Shade View software (Nixtex, GB)

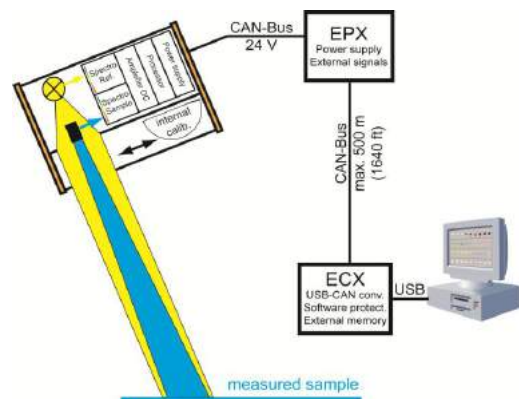


**Figure 7.57** Screens of CIS-12 software (MAHLO, Germany)





**Figure 7.58** ERX130  
(X-Rite, USA)

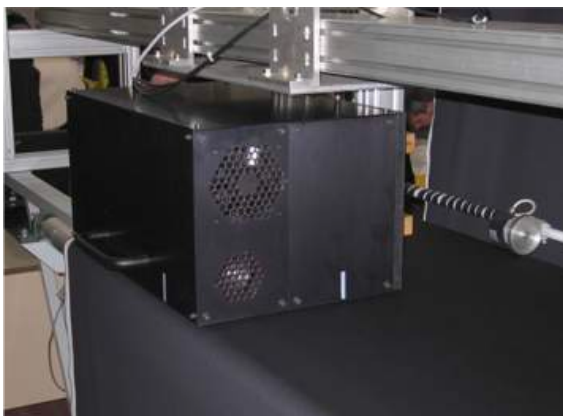


**Figure 7.59** Scheme of ERX130  
(X-Rite, USA)

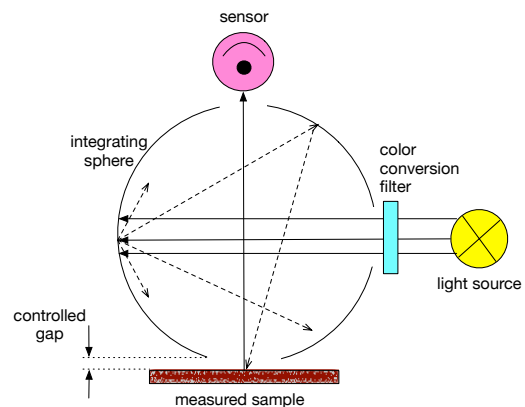
A certain exception is the two on-line measurement systems, which were developed to enhance the traceability of data between online and off-line systems. The first is a measurement system X-Rite ERX130 (Fig. 7.58). This system utilizes a retro reflecting arrangement, when the beam is rotated by  $22.5^\circ$ , as shown in the diagram in Fig. 7.59. Such an arrangement has two advantages [170]. Firstly, it is not so sensitive to vibrations measured waist goods during passage through the measuring point, which is the main cause higher variance data for standard online systems equipped with measuring geometry arrangement  $0 : 45^\circ$  alternatively  $0 : 30^\circ$ . The second advantage is the higher traceability of data to the off-line systems with integration spheres.

The second measuring system aiming at compatibility with the off-line measuring systems is a flow measuring system VÚTS that allows native measuring total spectral reflectance. Results from tests conducted in the company Mosilana, Inc. Brno, Czech Republic showed very good agreement with experiments on laboratory equipment. It was also demonstrated high repeatability of this system.

The technologies available on the market today vary widely. Using the lower technically specified systems still requires a considerable amount of set up and manual interaction. At the higher end of technical sophistication, the vision systems have self-learning and the ability to run and re-run webs or cloth in a simulated fashion thus reducing the need for manual interaction and set up times.



**Figure 7.60** On-line spectrophotometer  
VÚTS FM (Czech Rep.)



**Figure 7.61** Simplified optical scheme of  
On-line spectrophotometer VÚTS FM

## 7.6 Final reminder

Remember that there are many more sources of potential troubles in colorimetry and measurement generally. As was mentioned previously, the common wisdom is that systematic uncertainties are repeatable and do not vary. However, this is not true. Systematic uncertainties can vary significantly from measurement to measurement. The systematic uncertainty will be the same if all measurement conditions are identical, but for different measured values or under different measuring conditions, the uncertainty can be different. What is given here is not the full story. Special cases have not been dealt with in this book. Extra rules apply:

- if you use statistics on very small sets of data (less than about 10)
- if one component of uncertainty is much bigger than all the others involved
- if some inputs to the calculation are correlated
- if the spread or distribution is unusual in shape
- if the uncertainty is not for a single result, but for fitting a curve or line to a number of points

These cases are covered by some of the texts listed below in REFERENCES. Other thing is integration of colorimetry in production, system of quality management respectively. To realize maximum benefit from color measurement, the user must be aware both of the factors, which could cause shade changes and potential magnitude of the changes, which can occur between the goods exiting the dry cans and their final color evaluation as finished goods. The numerical interpretation of colors, gathered at the end of the range, must be readily understood by the quality control manager, the dyer, etc. so that any appropriate corrective action can be taken for goods still to be dyed and so the color of finished product can be accurately projected. Based on that the following suggestions are offered to company management as a guide in establishing a program of color quality control. These suggestions are rewritten from old DIANO CORPORATION book Color Technology and its Application in Industry from 1970, nevertheless by my opinion still valid.

### 1. Select a Project Leader

Perhaps the most important decision management must make is selecting the right motivated person to head up the project. This person should be one who has the respect of both management and production personnel. He should have sufficient education and experience to be able to learn color technology and to recognize the practical aspects of implementing new ideas and procedures into an existing business. Most important of all, he must have an open mind and want the program to succeed but be realistic. If people are sure that such a program

### 2. Training of Personnel

The project leader for your color instrumentation program and his staff must be trained in color technology. Management and supervisory personnel in other activities who will be affected by or who can affect the successful overcome of such a program should also be included in this training program. This training program should consist of attendance at schools in color technology, making available texts and publications on the subject, and on the job experience.

### **3. Selecting Hardware**

Before purchase hardware, decide what you want to accomplish and how you plan to implement the program. Once these decisions have been made, you can make a much better decision regarding the hardware. The buyer should be careful of buying expensive, special purpose instruments and computers that are limited in their capability, unless he has proven that his business warrants such equipment.

### **4. Sell your Ideas**

For a successful program, management and the project personnel responsible for implementing the plan must make sure that everyone who will be involved in the program understands what the program consists of and how it affects them. The colorist and color matchers should know that this equipment does not eliminate the need for people but is only a tool that will help them do a better job if it is properly used.

### **5. Allow Time for Implementation**

Don't expect miracles overnight. It takes time to properly implement an instrumental color matching and control program, but once established it can pay handsome rewards in both profits and higher quality products.

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# APPENDIX CONTENTS

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## A TABLES REPRESENTING COLORIMETRIC OBSERVERS

*Appendix A. 1 Photopic spectral luminous efficiency function  $V(\lambda)$ . Scotopic spectral luminous efficiency function  $V'(\lambda)$*

$\lambda$ [nm]	$V(\lambda)$	$V'(\lambda)$	nm	$V(\lambda)$	$V'(\lambda)$
380	0.00004	0.00059	585	0.81630	0.08990
385	0.00006	0.00111	590	0.75700	0.06550
390	0.00012	0.00221	595	0.69490	0.04690
395	0.00022	0.00453	600	0.63100	0.03315
400	0.00040	0.00929	605	0.56680	0.02312
405	0.00064	0.01852	610	0.50300	0.01593
410	0.00121	0.03484	615	0.44120	0.01088
415	0.00218	0.06040	620	0.38100	0.00737
420	0.00400	0.09660	625	0.32100	0.00497
425	0.00730	0.14360	630	0.26500	0.00334
430	0.01160	0.19980	635	0.21700	0.00224
435	0.01684	0.26250	640	0.17500	0.00150
440	0.02300	0.32810	645	0.13820	0.00101
445	0.02980	0.39310	650	0.10700	0.00068
450	0.03800	0.45500	655	0.08160	0.00046
455	0.04800	0.51300	660	0.06100	0.00031
460	0.06000	0.56700	665	0.04458	0.00021
465	0.07390	0.62000	670	0.03200	0.00015
470	0.09098	0.67600	675	0.02320	0.00010
475	0.11260	0.73400	680	0.01700	0.00007
480	0.13902	0.79300	685	0.01192	0.00005
485	0.16930	0.85100	690	0.00821	0.00004
490	0.20802	0.90400	695	0.00572	0.00003
495	0.25860	0.94900	700	0.00410	0.00002
500	0.32300	0.98200	705	0.00293	0.00001
505	0.40730	0.99800	710	0.00209	0.00001
510	0.50300	0.99700	715	0.00148	0.00001
515	0.60820	0.97500	720	0.00105	0.00000
520	0.71000	0.93500	725	0.00074	0.00000
525	0.79320	0.88000	730	0.00052	0.00000
530	0.86200	0.81100	735	0.00036	0.00000
535	0.91485	0.73300	740	0.00025	0.00000
540	0.95400	0.65000	745	0.00017	0.00000
545	0.98030	0.56400	750	0.00012	0.00000
550	0.99495	0.48100	755	0.00008	0.00000
555	1.00000	0.40200	760	0.00006	0.00000
560	0.99500	0.32880	765	0.00004	0.00000
565	0.97860	0.26390	770	0.00003	0.00000
570	0.95200	0.20760	775	0.00002	0.00000
575	0.91540	0.16020	780	0.00001	0.00000
580	0.87000	0.12120	-	-	-

**Appendix A.2: CIE 1931 standard colorimetric observer**

$\lambda$ [nm]	$\bar{x}(\lambda)$	$\bar{y}(\lambda)$	$\bar{z}(\lambda)$	$x(\lambda)$	$y(\lambda)$
380	0.001 368	0.000 039	0.006 450	0.174 11	0.004 96
385	0.002 236	0.000 064	0.010 550	0.174 01	0.004 98
390	0.004 243	0.000 120	0.020 050	0.173 80	0.004 92
395	0.007 650	0.000 217	0.036 210	0.173 56	0.004 92
400	0.014 310	0.000 396	0.067 850	0.173 34	0.004 80
405	0.023 190	0.000 640	0.110 200	0.173 02	0.004 78
410	0.043 510	0.001 210	0.207 400	0.172 58	0.004 80
415	0.077 630	0.002 180	0.371 300	0.172 09	0.004 83
420	0.134 380	0.004 000	0.645 600	0.171 41	0.005 10
425	0.214 770	0.007 300	1.039 050	0.170 30	0.005 79
430	0.283 900	0.011 600	1.385 600	0.168 88	0.006 90
435	0.328 500	0.016 840	1.622 960	0.166 90	0.008 56
440	0.348 280	0.023 000	1.747 060	0.164 41	0.010 86
445	0.348 060	0.029 800	1.782 600	0.161 10	0.013 79
450	0.336 200	0.038 000	1.772 110	0.156 64	0.017 70
455	0.318 700	0.048 000	1.744 100	0.150 99	0.022 74
460	0.290 800	0.060 000	1.669 200	0.143 96	0.029 70
465	0.251 100	0.073 900	1.528 100	0.135 50	0.039 88
470	0.195 360	0.090 980	1.287 640	0.124 12	0.057 80
475	0.142 100	0.112 600	1.041 900	0.109 59	0.086 84
480	0.095 640	0.139 020	0.812 950	0.091 29	0.132 70
485	0.057 950	0.169 300	0.616 200	0.068 71	0.200 72
490	0.032 010	0.208 020	0.465 180	0.045 39	0.294 98
495	0.014 700	0.258 600	0.353 300	0.023 46	0.412 70
500	0.004 900	0.323 000	0.272 000	0.008 17	0.538 42
505	0.002 400	0.407 300	0.212 300	0.003 86	0.654 82
510	0.009 300	0.503 000	0.158 200	0.013 87	0.750 19
515	0.029 100	0.608 200	0.111 700	0.038 85	0.812 02
520	0.063 270	0.710 000	0.078 250	0.074 30	0.833 80
525	0.109 600	0.793 200	0.057 250	0.114 16	0.826 21
530	0.165 500	0.862 000	0.042 160	0.154 72	0.805 86
535	0.225 750	0.914 850	0.029 840	0.192 88	0.781 63
540	0.290 400	0.954 000	0.020 300	0.229 62	0.754 33
545	0.359 700	0.980 300	0.013 400	0.265 78	0.724 32
550	0.433 450	0.994 950	0.008 750	0.301 60	0.692 31
555	0.512 050	1.000 000	0.005 750	0.337 36	0.658 85
560	0.594 500	0.995 000	0.003 900	0.373 10	0.624 45
565	0.678 400	0.978 600	0.002 750	0.408 74	0.589 61
570	0.762 100	0.952 000	0.002 100	0.444 06	0.554 71
575	0.842 500	0.915 400	0.001 800	0.478 77	0.520 20
580	0.916 300	0.870 000	0.001 650	0.512 49	0.486 59
585	0.978 600	0.816 300	0.001 400	0.544 79	0.454 43
590	1.026 300	0.757 000	0.001 100	0.575 15	0.424 23
595	1.056 700	0.694 900	0.001 000	0.602 93	0.396 50
600	1.062 200	0.631 000	0.000 800	0.627 04	0.372 49



$\lambda$ [nm]	$\bar{x}(\lambda)$	$\bar{y}(\lambda)$	$\bar{z}(\lambda)$	$x(\lambda)$	$y(\lambda)$
605	1.045 600	0.566 800	0.000 600	0.648 23	0.351 39
610	1.002 600	0.503 000	0.000 340	0.665 76	0.334 01
615	0.938 400	0.441 200	0.000 240	0.680 08	0.319 75
620	0.854 450	0.381 000	0.000 190	0.691 50	0.308 34
625	0.751 400	0.321 000	0.000 100	0.700 61	0.299 30
630	0.642 400	0.265 000	0.000 050	0.707 92	0.292 03
635	0.541 900	0.217 000	0.000 030	0.714 03	0.285 93
640	0.447 900	0.175 000	0.000 020	0.719 03	0.280 93
645	0.360 800	0.138 200	0.000 010	0.723 03	0.276 95
650	0.283 500	0.107 000	0.000 000	0.725 99	0.274 01
655	0.218 700	0.081 600	0.000 000	0.728 27	0.271 73
660	0.164 900	0.061 000	0.000 000	0.729 97	0.270 03
665	0.121 200	0.044 580	0.000 000	0.731 09	0.268 91
670	0.087 400	0.032 000	0.000 000	0.731 99	0.268 01
675	0.063 600	0.023 200	0.000 000	0.732 72	0.267 28
680	0.046 770	0.017 000	0.000 000	0.733 42	0.266 58
685	0.032 900	0.011 920	0.000 000	0.734 05	0.265 95
690	0.022 700	0.008 210	0.000 000	0.734 39	0.265 61
695	0.015 840	0.005 723	0.000 000	0.734 59	0.265 41
700	0.011 359	0.004 102	0.000 000	0.734 69	0.265 31
705	0.008 111	0.002 929	0.000 000	0.734 69	0.265 31
710	0.005 790	0.002 091	0.000 000	0.734 69	0.265 31
715	0.004 109	0.001 484	0.000 000	0.734 69	0.265 31
720	0.002 899	0.001 047	0.000 000	0.734 69	0.265 31
725	0.002 049	0.000 740	0.000 000	0.734 69	0.265 31
730	0.001 440	0.000 520	0.000 000	0.734 69	0.265 31
735	0.001 000	0.000 361	0.000 000	0.734 69	0.265 31
740	0.000 690	0.000 249	0.000 000	0.734 69	0.265 31
745	0.000 476	0.000 172	0.000 000	0.734 69	0.265 31
750	0.000 332	0.000 120	0.000 000	0.734 69	0.265 31
755	0.000 235	0.000 085	0.000 000	0.734 69	0.265 31
760	0.000 166	0.000 060	0.000 000	0.734 69	0.265 31
765	0.000 117	0.000 042	0.000 000	0.734 69	0.265 31
770	0.000 083	0.000 030	0.000 000	0.734 69	0.265 31
775	0.000 059	0.000 021	0.000 000	0.734 69	0.265 31
780	0.000 042	0.000 015	0.000 000	0.734 69	0.265 31

Summation at 5 nm intervals:

$$\sum \bar{x}(\lambda) = 21,371\,524 \quad \sum \bar{y}(\lambda) = 21,371\,327 \quad \sum \bar{z}(\lambda) = 21,371\,540$$

**Appendix A.3: CIE 1964 standard colorimetric observer**

$\lambda$ [nm]	$\bar{x}_{10}(\lambda)$	$\bar{y}_{10}(\lambda)$	$\bar{z}_{10}(\lambda)$	$x_{10}(\lambda)$	$y_{10}(\lambda)$
380	0.000 160	0.000 017	0.000 705	0.181 33	0.019 69
385	0.000 662	0.000 072	0.002 928	0.180 91	0.019 54
390	0.002 362	0.000 253	0.010 482	0.180 31	0.019 35
395	0.007 242	0.000 769	0.032 344	0.179 47	0.019 04
400	0.019 110	0.002 004	0.086 011	0.178 39	0.018 71
405	0.043 400	0.004 509	0.197 120	0.177 12	0.018 40
410	0.084 736	0.008 756	0.389 366	0.175 49	0.018 13
415	0.140 638	0.014 456	0.656 760	0.173 23	0.017 81
420	0.204 492	0.021 391	0.972 542	0.170 63	0.017 85
425	0.264 737	0.029 497	1.282 500	0.167 90	0.018 71
430	0.314 679	0.038 676	1.553 480	0.165 03	0.020 28
435	0.357 719	0.049 602	1.798 500	0.162 17	0.022 49
440	0.383 734	0.062 077	1.967 280	0.159 02	0.025 73
445	0.386 726	0.074 704	2.027 300	0.155 39	0.030 02
450	0.370 702	0.089 456	1.994 800	0.151 00	0.036 44
455	0.342 957	0.106 256	1.900 700	0.145 94	0.045 22
460	0.302 273	0.128 201	1.745 370	0.138 92	0.058 92
465	0.254 085	0.152 761	1.554 900	0.129 52	0.077 87
470	0.195 618	0.185 190	1.317 560	0.115 18	0.109 04
475	0.132 349	0.219 940	1.030 200	0.095 73	0.159 09
480	0.080 507	0.253 589	0.772 125	0.072 78	0.229 24
485	0.041 072	0.297 665	0.570 060	0.045 19	0.327 54
490	0.016 172	0.339 133	0.415 254	0.020 99	0.440 11
495	0.005 132	0.395 379	0.302 356	0.007 30	0.562 52
500	0.003 816	0.460 777	0.218 502	0.005 59	0.674 54
505	0.015 444	0.531 360	0.159 249	0.021 87	0.752 58
510	0.037 465	0.606 741	0.112 044	0.049 54	0.802 30
515	0.071 358	0.685 660	0.082 248	0.085 02	0.816 98
520	0.117 749	0.761 757	0.060 709	0.125 24	0.810 19
525	0.172 953	0.823 330	0.043 050	0.166 41	0.792 17
530	0.236 491	0.875 211	0.030 451	0.207 06	0.766 28
535	0.304 213	0.923 810	0.020 584	0.243 64	0.739 87
540	0.376 772	0.961 988	0.013 676	0.278 59	0.711 30
545	0.451 584	0.982 200	0.007 918	0.313 23	0.681 28
550	0.529 826	0.991 761	0.003 988	0.347 30	0.650 09
555	0.616 053	0.999 110	0.001 091	0.381 16	0.618 16
560	0.705 224	0.997 340	0.000 000	0.414 21	0.585 79
565	0.793 832	0.982 380	0.000 000	0.446 92	0.553 08
570	0.878 655	0.955 552	0.000 000	0.479 04	0.520 96
575	0.951 162	0.915 175	0.000 000	0.509 64	0.490 36
580	1.014 160	0.868 934	0.000 000	0.538 56	0.461 44
585	1.074 300	0.825 623	0.000 000	0.565 44	0.434 56
590	1.118 520	0.777 405	0.000 000	0.589 96	0.410 04
595	1.134 300	0.720 353	0.000 000	0.611 60	0.388 40

$\lambda$ [nm]	$\bar{x}_{10}(\lambda)$	$\bar{y}_{10}(\lambda)$	$\bar{z}_{10}(\lambda)$	$x_{10}(\lambda)$	$y_{10}(\lambda)$
600	1.123 990	0.658 341	0.000 000	0.630 63	0.369 37
605	1.089 100	0.593 878	0.000 000	0.647 13	0.352 87
610	1.030 480	0.527 963	0.000 000	0.661 22	0.338 78
615	0.950 740	0.461 834	0.000 000	0.673 06	0.326 94
620	0.856 297	0.398 057	0.000 000	0.682 66	0.317 34
625	0.754 930	0.339 554	0.000 000	0.689 76	0.310 24
630	0.647 467	0.283 493	0.000 000	0.695 48	0.304 52
635	0.535 110	0.228 254	0.000 000	0.700 99	0.299 01
640	0.431 567	0.179 828	0.000 000	0.705 87	0.294 13
645	0.343 690	0.140 211	0.000 000	0.710 25	0.289 75
650	0.268 329	0.107 633	0.000 000	0.713 71	0.286 29
655	0.204 300	0.081 187	0.000 000	0.715 62	0.284 38
660	0.152 568	0.060 281	0.000 000	0.716 79	0.283 21
665	0.112 210	0.044 096	0.000 000	0.717 89	0.282 11
670	0.081 261	0.031 800	0.000 000	0.718 73	0.281 27
675	0.057 930	0.022 602	0.000 000	0.719 34	0.280 66
680	0.040 851	0.015 905	0.000 000	0.719 76	0.280 24
685	0.028 623	0.011 130	0.000 000	0.720 02	0.279 98
690	0.019 941	0.007 749	0.000 000	0.720 16	0.279 84
695	0.013 842	0.005 375	0.000 000	0.720 30	0.279 70
700	0.009 577	0.003 718	0.000 000	0.720 36	0.279 64
705	0.006 605	0.002 565	0.000 000	0.720 32	0.279 68
710	0.004 553	0.001 768	0.000 000	0.720 23	0.279 77
715	0.003 145	0.001 222	0.000 000	0.720 09	0.279 91
720	0.002 175	0.000 846	0.000 000	0.719 91	0.280 09
725	0.001 506	0.000 586	0.000 000	0.719 69	0.280 31
730	0.001 045	0.000 407	0.000 000	0.719 45	0.280 55
735	0.000 727	0.000 284	0.000 000	0.719 19	0.280 81
740	0.000 508	0.000 199	0.000 000	0.718 91	0.281 09
745	0.000 356	0.000 140	0.000 000	0.718 61	0.281 39
750	0.000 251	0.000 098	0.000 000	0.718 29	0.281 71
755	0.000 178	0.000 070	0.000 000	0.717 96	0.282 04
760	0.000 126	0.000 050	0.000 000	0.717 61	0.282 39
765	0.000 090	0.000 036	0.000 000	0.717 24	0.282 76
770	0.000 065	0.000 025	0.000 000	0.716 86	0.283 14
775	0.000 046	0.000 018	0.000 000	0.716 46	0.283 54
780	0.000 033	0.000 013	0.000 000	0.716 06	0.283 94

Summation at 5 nm intervals:

$$\sum \bar{x}_{10}(\lambda) = 23,329\,353 \quad \sum \bar{y}_{10}(\lambda) = 23,332\,036 \quad \sum \bar{z}_{10}(\lambda) = 23,334\,153$$

## B TABLES OF COLORIMETRIC ILLUMINANTS

**Appendix B.1: Relative spectral power distributions  $[S(\lambda)]$  of CIE standard illuminants A and D65, as well as CIE illuminants C, D50, D55 and D75**

$\lambda$ [nm]	Standard Illuminant A	Standard Illuminant D65	Illuminant C	Illuminant D50	Illuminant D55	Illuminant D75
300	0.930 483	0.034 100 0	0.00	0.019	0.024	0.043
305	1.128 21	1.664 30	0.00	1.035	1.048	2.588
310	1.357 69	3.294 50	0.00	2.051	2.072	5.133
315	1.622 19	11.765 2	0.00	4.914	6.648	17.470
320	1.925 08	20.236 0	0.01	7.778	11.224	29.808
325	2.269 80	28.644 7	0.20	11.263	15.936	42.369
330	2.659 81	37.053 5	0.40	14.748	20.647	54.930
335	3.098 61	38.501 1	1.55	16.348	22.266	56.095
340	3.589 68	39.948 8	2.70	17.948	23.885	57.259
345	4.136 48	42.430 2	4.85	19.479	25.851	60.000
350	4.742 38	44.911 7	7.00	21.010	27.817	62.740
355	5.410 70	45.775 0	9.95	22.476	29.219	62.861
360	6.144 62	46.638 3	12.90	23.942	30.621	62.982
365	6.947 20	49.363 7	17.20	25.451	32.464	66.647
370	7.821 35	52.089 1	21.40	26.961	34.308	70.312
375	8.769 80	51.032 3	27.50	25.724	33.446	68.507
380	9.795 10	49.975 5	33.00	24.488	32.584	66.703
385	10.899 6	52.311 8	39.92	27.179	35.335	68.333
390	12.085 3	54.648 2	47.40	29.871	38.087	69.963
395	13.354 3	68.701 5	55.17	39.589	49.518	85.946
400	14.708 0	82.754 9	63.30	49.308	60.949	101.929
405	16.148 0	87.120 4	71.81	52.910	64.751	106.911
410	17.675 3	91.486 0	80.60	56.513	68.554	111.894
415	19.290 7	92.458 9	89.53	58.273	70.065	112.346
420	20.995 0	93.431 8	98.10	60.034	71.577	112.798
425	22.788 3	90.057 0	105.80	58.926	69.746	107.945
430	24.670 9	86.682 3	112.40	57.818	67.914	103.092
435	26.642 5	95.773 6	117.75	66.321	76.760	112.145
440	28.702 7	104.865	121.50	74.825	85.605	121.198
445	30.850 8	110.936	123.45	81.036	91.799	127.104
450	33.085 9	117.008	124.00	87.247	97.993	133.010
455	35.406 8	117.410	123.60	88.930	99.228	132.682
460	37.812 1	117.812	123.10	90.612	100.463	132.355
465	40.300 2	116.336	123.30	90.990	100.188	129.838
470	42.869 3	114.861	123.80	91.368	99.913	127.322
475	45.517 4	115.392	124.09	93.238	101.326	127.061
480	48.242 3	115.923	123.90	95.109	102.739	126.800
485	51.041 8	112.367	122.92	93.536	100.409	122.291
490	53.913 2	108.811	120.70	91.963	98.078	117.783
495	56.853 9	109.082	116.90	93.843	99.379	117.186
500	59.861 1	109.354	112.10	95.724	100.680	116.589
505	62.932 0	108.578	106.98	96.169	100.688	115.146
510	66.063 5	107.802	102.30	96.613	100.695	113.702
515	69.252 5	106.296	98.81	96.871	100.341	111.181
520	72.495 9	104.790	96.90	97.129	99.987	108.659
525	75.790 3	106.239	96.78	99.614	102.098	109.552

$\lambda$ [nm]	Standard Illuminant A	Standard Illuminant D65	Illuminant C	Illuminant D50	Illuminant D55	Illuminant D75
530	79.132 6	107.689	98.00	102.099	104.210	110.445
535	82.519 3	106.047	99.94	101.427	103.156	108.367
540	85.947 0	104.405	102.10	100.755	102.102	106.289
545	89.412 4	104.225	103.95	101.536	102.535	105.596
550	92.912 0	104.046	105.20	102.317	102.968	104.904
555	96.442 3	102.023	105.67	101.159	101.484	102.452
560	100.000	100.000	105.30	100.000	100.000	100.000
565	103.582	98.167 1	104.11	98.868	98.608	97.808
570	107.184	96.334 2	102.30	97.735	97.216	95.616
575	110.803	96.061 1	100.15	98.327	97.482	94.914
580	114.436	95.788 0	97.80	98.918	97.749	94.213
585	118.080	92.236 8	95.43	96.208	94.590	90.605
590	121.731	88.685 6	93.20	93.499	91.432	86.997
595	125.386	89.345 9	91.22	95.593	92.926	87.112
600	129.043	90.006 2	89.70	97.688	94.419	87.227
605	132.697	89.802 6	88.83	98.478	94.780	86.684
610	136.346	89.599 1	88.40	99.269	95.140	86.140
615	139.988	88.648 9	88.19	99.155	94.680	84.861
620	143.618	87.698 7	88.10	99.042	94.220	83.581
625	147.235	85.493 6	88.06	97.382	92.334	81.164
630	150.836	83.288 6	88.00	95.722	90.448	78.747
635	154.418	83.493 9	87.86	97.290	91.389	78.587
640	157.979	83.699 2	87.80	98.857	92.330	78.428
645	161.516	81.863 0	87.99	97.262	90.592	76.614
650	165.028	80.026 8	88.20	95.667	88.854	74.801
655	168.510	80.120 7	88.20	96.929	89.586	74.562
660	171.963	80.214 6	87.90	98.190	90.317	74.324
665	175.383	81.246 2	87.22	100.597	92.133	74.873
670	178.769	82.277 8	86.30	103.003	93.950	75.422
675	182.118	80.281 0	85.30	101.068	91.953	73.499
680	185.429	78.284 2	84.00	99.133	89.956	71.576
685	188.701	74.002 7	82.21	93.257	84.817	67.714
690	191.931	69.721 3	80.20	87.381	79.677	63.852
695	195.118	70.665 2	78.24	89.492	81.258	64.464
700	198.261	71.609 1	76.30	91.604	82.840	65.076
705	201.359	72.979 0	74.36	92.246	83.842	66.573
710	204.409	74.349 0	72.40	92.889	84.844	68.070
715	207.411	67.976 5	70.40	84.872	77.539	62.256
720	210.365	61.604 0	68.30	76.854	70.235	56.443
725	213.268	65.744 8	66.30	81.683	74.768	60.343
730	216.120	69.885 6	64.40	86.511	79.301	64.242
735	218.920	72.486 3	62.80	89.546	82.147	66.697
740	221.667	75.087 0	61.50	92.580	84.993	69.151
745	224.361	69.339 8	60.20	85.405	78.437	63.890
750	227.000	63.592 7	59.20	78.230	71.880	58.629
755	229.585	55.005 4	58.50	67.961	62.337	50.623
760	232.115	46.418 2	58.10	57.692	52.793	42.617
765	234.589	56.611 8	58.00	70.307	64.360	51.985
770	237.008	66.805 4	58.20	82.923	75.927	61.352
775	239.370	65.094 1	58.50	80.599	73.872	59.838
780	241.675	63.382 8	59.10	78.274	71.818	58.324

**Appendix B.2: Components  $S_0(\lambda)$ ,  $S_1(\lambda)$ ,  $S_2(\lambda)$  of daylight used in the calculation of relative spectral power distributions of CIE daylight illuminants of different correlated color temperatures**

$\lambda$ [nm]	$S_0(\lambda)$	$S_1(\lambda)$	$S_2(\lambda)$	$\lambda$ . nm	$S_0(\lambda)$	$S_1(\lambda)$	$S_2(\lambda)$
300	0.04	0.02	0.00	515	108.65	10.90	-1.25
305	3.02	2.26	1.00	520	106.50	8.60	-1.20
310	6.00	4.50	2.00	525	107.65	7.35	-1.10
315	17.80	13.45	3.00	530	108.80	6.10	-1.00
320	29.60	22.40	4.00	535	107.05	5.15	-0.75
325	42.45	32.20	6.25	540	105.30	4.20	-0.50
330	55.30	42.00	8.50	545	104.85	3.05	-0.40
335	56.30	41.30	8.15	550	104.40	1.90	-0.30
340	57.30	40.60	7.80	555	102.20	0.95	-0.15
345	59.55	41.10	7.25	560	100.00	0.00	0.00
350	61.80	41.60	6.70	565	98.00	-0.80	0.10
355	61.65	39.80	6.00	570	96.00	-1.60	0.20
360	61.50	38.00	5.30	575	95.55	-2.55	0.35
365	65.15	40.20	5.70	580	95.10	-3.50	0.50
370	68.80	42.40	6.10	585	92.10	-3.50	1.30
375	66.10	40.45	4.55	590	89.10	-3.50	2.10
380	63.40	38.50	3.00	595	89.80	-4.65	2.65
385	64.60	36.75	2.10	600	90.50	-5.80	3.20
390	65.80	35.00	1.20	605	90.40	-6.50	3.65
395	80.30	39.20	0.05	610	90.30	-7.20	4.10
400	94.80	43.40	-1.10	615	89.35	-7.90	4.40
405	99.80	44.85	-0.80	620	88.40	-8.60	4.70
410	104.80	46.30	-0.50	625	86.20	-9.05	4.90
415	105.35	45.10	-0.60	630	84.00	-9.50	5.10
420	105.90	43.90	-0.70	635	84.55	-10.20	5.90
425	101.35	40.50	-0.95	640	85.10	-10.90	6.70
430	96.80	37.10	-1.20	645	83.50	-10.80	7.00
435	105.35	36.90	-1.90	650	81.90	-10.70	7.30
440	113.90	36.70	-2.60	655	82.25	-11.35	7.95
445	119.75	36.30	-2.75	660	82.60	-12.00	8.60
450	125.60	35.90	-2.90	665	83.75	-13.00	9.20
455	125.55	34.25	-2.85	670	84.90	-14.00	9.80
460	125.50	32.60	-2.80	675	83.10	-13.80	10.00
465	123.40	30.25	-2.70	680	81.30	-13.60	10.20
470	121.30	27.90	-2.60	685	76.60	-12.80	9.25
475	121.30	26.10	-2.60	690	71.90	-12.00	8.30
480	121.30	24.30	-2.60	695	73.10	-12.65	8.95
485	117.40	22.20	-2.20	700	74.30	-13.30	9.60
490	113.50	20.10	-1.80	705	75.35	-13.10	9.05
495	113.30	18.15	-1.65	710	76.40	-12.90	8.50
500	113.10	16.20	-1.50	715	69.85	-11.75	7.75
505	111.95	14.70	-1.40	720	63.30	-10.60	7.00
510	110.80	13.20	-1.30	725	67.50	-11.10	7.30

$\lambda$ [nm]	$S_0(\lambda)$	$S_1(\lambda)$	$S_2(\lambda)$	$\lambda$ . nm	$S_0(\lambda)$	$S_1(\lambda)$	$S_2(\lambda)$
730	71.70	-11.60	7.60	785	65.50	-10.50	6.90
735	74.35	-11.90	7.80	790	66.00	-10.60	7.00
740	77.00	-12.20	8.00	795	63.50	-10.15	6.70
745	71.10	-11.20	7.35	800	61.00	-9.70	6.40
750	65.20	-10.20	6.70	805	57.15	-9.00	5.95
755	56.45	-9.00	5.95	810	53.30	-8.30	5.50
760	47.70	-7.80	5.20	815	56.10	-8.80	5.80
765	58.15	-9.50	6.30	820	58.90	-9.30	6.10
770	68.60	-11.20	7.40	825	60.40	-9.55	6.30
775	66.80	-10.80	7.10	830	61.90	-9.80	6.50
780	65.00	-10.40	6.80	-	-	-	-

**Appendix B.3: Relative SPDs of recommended indoor illuminants ID65 and ID50**

$\lambda$ [nm]	<i>ID65</i> ( $\lambda$ )	<i>ID50</i> ( $\lambda$ )	$\lambda$ [nm]	<i>ID65</i> ( $\lambda$ )	<i>ID50</i> ( $\lambda$ )
380	40.99	20.08	585	81.23	84.73
385	43.82	22.77	590	77.89	82.12
390	46.88	25.63	595	78.25	83.72
395	59.78	34.45	600	78.63	85.34
400	72.56	43.23	605	78.26	85.82
405	76.58	46.51	610	77.87	86.27
410	80.35	49.63	615	76.75	85.85
415	81.03	51.07	620	75.63	85.41
420	81.73	52.51	625	73.49	83.71
425	78.75	51.52	630	71.38	82.03
430	75.79	50.55	635	71.31	83.09
435	83.72	57.97	640	71.24	84.14
440	91.70	65.43	645	69.45	82.52
445	97.22	71.02	650	67.68	80.90
450	102.88	76.71	655	67.55	81.72
455	103.60	78.47	660	67.42	82.53
460	104.30	80.22	665	68.09	84.31
465	103.23	80.74	670	68.72	86.03
470	102.10	81.22	675	66.76	84.04
475	102.71	82.99	680	64.82	82.08
480	103.30	84.75	685	61.09	76.98
485	100.26	83.46	690	57.39	71.92
490	97.21	82.16	695	57.94	73.37
495	97.52	83.90	700	58.45	74.77
500	97.83	85.64	705	59.32	74.99
505	97.20	86.09	710	60.19	75.20
510	96.57	86.55	715	54.79	68.41
515	95.25	86.80	720	49.44	61.68
520	93.90	87.04	725	52.56	65.30
525	95.17	89.24	730	55.64	68.88
530	96.43	91.42	735	57.45	70.98
535	94.91	90.77	740	59.22	73.02
540	93.38	90.11	745	54.46	67.08
545	93.15	90.74	750	49.74	61.18
550	92.90	91.36	755	42.84	52.93
555	91.00	90.23	760	36.00	44.75
560	89.08	89.08	765	43.73	54.31
565	87.32	87.95	770	51.40	63.80
570	85.53	86.77	775	49.88	61.76
575	85.07	87.08	780	48.37	59.73
580	84.60	87.36	-	-	-



**Appendix B.4: Tristimulus values, chromaticity coordinates of CIE standard illuminants A, D65 and CIE illuminants C, D50, D55, D75**

1. For the CIE 1931 standard colorimetric observer

	Standard Illuminant A	Standard Illuminant D65	Illuminant C	Illuminant D50	Illuminant D55	Illuminant D75
X	109.85	95.04	98.07	96.42	95.68	94.97
Y	100.00	100.00	100.00	100.00	100.00	100.00
Z	35.58	108.88	118.22	82.51	92.14	122.61
x	0.447 58	0.312 72	0.310 06	0.345 67	0.332 43	0.299 03
y	0.407 45	0.329 03	0.316 16	0.358 51	0.347 44	0.314 88
u'	0.255 97	0.197 83	0.200 89	0.209 16	0.204 43	0.193 53
v'	0.524 29	0.468 34	0.460 89	0.488 08	0.480 75	0.458 53

2. For the CIE 1964 standard colorimetric observer

	Standard Illuminant A	Standard Illuminant D65	Illuminant C	Illuminant D50	Illuminant D55	Illuminant D75
X <sub>10</sub>	111.14	94.81	97.29	96.72	95.80	94.42
Y <sub>10</sub>	100.00	100.00	100.00	100.00	100.00	100.00
Z <sub>10</sub>	35.20	107.32	116.14	81.43	90.93	120.64
x <sub>10</sub>	0.451 17	0.313 81	0.310 39	0.347 73	0.334 12	0.299 68
y <sub>10</sub>	0.405 94	0.330 98	0.319 05	0.359 52	0.348 77	0.317 40
u' <sub>10</sub>	0.258 96	0.197 86	0.200 00	0.210 15	0.205 07	0.193 05
v' <sub>10</sub>	0.524 25	0.469 54	0.462 55	0.488 86	0.481 65	0.460 04

Tristimulus values X, Y, Z and chromaticity coordinates x, y and u', v' for CIE standard illuminants A and D65 as well as for CIE illuminants C, D50, D55 and D75 computed for the 1931 and 1964 standard colorimetric observers.

**Appendix B.5: Relative SPDs of illuminants representing typical fluorescent lamps**

$\lambda$ [nm]	FL1	FL2*	FL3	FL4	FL5	FL6	FL7*	FL8	FL9	FL10	FL11*	FL12
380	1.87	1.18	0.82	0.57	1.87	1.05	2.56	1.21	0.90	1.11	0.91	0.96
385	2.36	1.48	1.02	0.70	2.35	1.31	3.18	1.50	1.12	0.80	0.63	0.64
390	2.94	1.84	1.26	0.87	2.92	1.63	3.84	1.81	1.36	0.62	0.46	0.40
395	3.47	2.15	1.44	0.98	3.45	1.90	4.53	2.13	1.60	0.57	0.37	0.33
400	5.17	3.44	2.57	2.01	5.10	3.11	6.15	3.17	2.59	1.48	1.29	1.19
405	19.49	15.69	14.36	13.75	18.91	14.80	19.37	13.08	12.80	12.16	12.68	12.48
410	6.13	3.85	2.70	1.95	6.00	3.43	7.37	3.83	3.05	2.12	1.59	1.12
415	6.24	3.74	2.45	1.59	6.11	3.30	7.05	3.45	2.56	2.70	1.79	0.94
420	7.01	4.19	2.73	1.76	6.85	3.68	7.71	3.86	2.86	3.74	2.46	1.08
425	7.79	4.62	3.00	1.93	7.58	4.07	8.41	4.42	3.30	5.14	3.33	1.37
430	8.56	5.06	3.28	2.10	8.31	4.45	9.15	5.09	3.82	6.75	4.49	1.78
435	43.67	34.98	31.85	30.28	40.76	32.61	44.14	34.10	32.62	34.39	33.94	29.05
440	16.94	11.81	9.47	8.03	16.06	10.74	17.52	12.42	10.77	14.86	12.13	7.90
445	10.72	6.27	4.02	2.55	10.32	5.48	11.35	7.68	5.84	10.40	6.95	2.65
450	11.35	6.63	4.25	2.70	10.91	5.78	12.00	8.60	6.57	10.76	7.19	2.71
455	11.89	6.93	4.44	2.82	11.40	6.03	12.58	9.46	7.25	10.67	7.12	2.65
460	12.37	7.19	4.59	2.91	11.83	6.25	13.08	10.24	7.86	10.11	6.72	2.49
465	12.75	7.40	4.72	2.99	12.17	6.41	13.45	10.84	8.35	9.27	6.13	2.33
470	13.00	7.54	4.80	3.04	12.40	6.52	13.71	11.33	8.75	8.29	5.46	2.10
475	13.15	7.62	4.86	3.08	12.54	6.58	13.88	11.71	9.06	7.29	4.79	1.91
480	13.23	7.65	4.87	3.09	12.58	6.59	13.95	11.98	9.31	7.91	5.66	3.01
485	13.17	7.62	4.85	3.09	12.52	6.56	13.93	12.17	9.48	16.64	14.29	10.83
490	13.13	7.62	4.88	3.14	12.47	6.56	13.82	12.28	9.61	16.73	14.96	11.88
495	12.85	7.45	4.77	3.06	12.20	6.42	13.64	12.32	9.68	10.44	8.97	6.88
500	12.52	7.28	4.67	3.00	11.89	6.28	13.43	12.35	9.74	5.94	4.72	3.43
505	12.20	7.15	4.62	2.98	11.61	6.20	13.25	12.44	9.88	3.34	2.33	1.49
510	11.83	7.05	4.62	3.01	11.33	6.19	13.08	12.55	10.04	2.35	1.47	0.92
515	11.50	7.04	4.73	3.14	11.10	6.30	12.93	12.68	10.26	1.88	1.10	0.71
520	11.22	7.16	4.99	3.41	10.96	6.60	12.78	12.77	10.48	1.59	0.89	0.60
525	11.05	7.47	5.48	3.90	10.97	7.12	12.60	12.72	10.63	1.47	0.83	0.63
530	11.03	8.04	6.25	4.69	11.16	7.94	12.44	12.60	10.78	1.80	1.18	1.10
535	11.18	8.88	7.34	5.81	11.54	9.07	12.33	12.43	10.96	5.71	4.90	4.56
540	11.53	10.01	8.78	7.32	12.12	10.49	12.26	12.22	11.18	40.98	39.59	34.40
545	27.74	24.88	23.82	22.59	27.78	25.22	29.52	28.96	27.71	73.69	72.84	65.40
550	17.05	16.64	16.14	15.11	17.73	17.46	17.05	16.51	16.29	33.61	32.61	29.48
555	13.55	14.59	14.59	13.88	14.47	15.63	12.44	11.79	12.28	8.24	7.52	7.16
560	14.33	16.16	16.63	16.33	15.20	17.22	12.58	11.76	12.74	3.38	2.83	3.08
565	15.01	17.56	18.49	18.68	15.77	18.53	12.72	11.77	13.21	2.47	1.96	2.47
570	15.52	18.62	19.95	20.64	16.10	19.43	12.83	11.84	13.65	2.14	1.67	2.27
575	18.29	21.47	23.11	24.28	18.54	21.97	15.46	14.61	16.57	4.86	4.43	5.09

$\lambda$ [nm]	<b>FL1</b>	<b>FL2*</b>	<b>FL3</b>	<b>FL4</b>	<b>FL5</b>	<b>FL6</b>	<b>FL7*</b>	<b>FL8</b>	<b>FL9</b>	<b>FL10</b>	<b>FL11*</b>	<b>FL12</b>
580	19.55	22.79	24.69	26.26	19.50	23.01	16.75	16.11	18.14	11.45	11.28	11.96
585	15.48	19.29	21.41	23.28	15.39	19.41	12.83	12.34	14.55	14.79	14.76	15.32
590	14.91	18.66	20.85	22.94	14.64	18.56	12.67	12.53	14.65	12.16	12.73	14.27
595	14.15	17.73	19.93	22.14	13.72	17.42	12.45	12.72	14.66	8.97	9.74	11.86
600	13.22	16.54	18.67	20.91	12.69	16.09	12.19	12.92	14.61	6.52	7.33	9.28
605	12.19	15.21	17.22	19.43	11.57	14.64	11.89	13.12	14.50	8.31	9.72	12.31
610	11.12	13.80	15.65	17.74	10.45	13.15	11.60	13.34	14.39	44.12	55.27	68.53
615	10.03	12.36	14.04	16.00	9.35	11.68	11.35	13.61	14.40	34.55	42.58	53.02
620	8.95	10.95	12.45	14.42	8.29	10.25	11.12	13.87	14.47	12.09	13.18	14.67
625	7.96	9.65	10.95	12.56	7.32	8.95	10.95	14.07	14.62	12.15	13.16	14.38
630	7.02	8.40	9.51	10.93	6.41	7.74	10.76	14.20	14.72	10.52	12.26	14.71
635	6.20	7.32	8.27	9.52	5.63	6.69	10.42	14.16	14.55	4.43	5.11	6.46
640	5.42	6.31	7.11	8.18	4.90	5.71	10.11	14.13	14.40	1.95	2.07	2.57
645	4.73	5.43	6.09	7.01	4.26	4.87	10.04	14.34	14.58	2.19	2.34	2.75
650	4.15	4.68	5.22	6.00	3.72	4.16	10.02	14.50	14.88	3.19	3.58	4.18
655	3.64	4.02	4.45	5.11	3.25	3.55	10.11	14.46	15.51	2.77	3.01	3.44
660	3.20	3.45	3.80	4.36	2.83	3.02	9.87	14.00	15.47	2.29	2.48	2.81
665	2.81	2.96	3.23	3.69	2.49	2.57	8.65	12.58	13.20	2.00	2.14	2.42
670	2.47	2.55	2.75	3.13	2.19	2.20	7.27	10.99	10.57	1.52	1.54	1.64
675	2.18	2.19	2.33	2.64	1.93	1.87	6.44	9.98	9.18	1.35	1.33	1.36
680	1.93	1.89	1.99	2.24	1.71	1.60	5.83	9.22	8.25	1.47	1.46	1.49
685	1.72	1.64	1.70	1.91	1.52	1.37	5.41	8.62	7.57	1.79	1.94	2.14
690	1.67	1.53	1.55	1.70	1.48	1.29	5.04	8.07	7.03	1.74	2.00	2.34
695	1.43	1.27	1.27	1.39	1.26	1.05	4.57	7.39	6.35	1.02	1.20	1.42
700	1.29	1.10	1.09	1.18	1.13	0.91	4.12	6.71	5.72	1.14	1.35	1.61
705	1.19	0.99	0.96	1.03	1.05	0.81	3.77	6.16	5.25	3.32	4.10	5.04
710	1.08	0.88	0.83	0.88	0.96	0.71	3.46	5.63	4.80	4.49	5.58	6.98
715	0.96	0.76	0.71	0.74	0.85	0.61	3.08	5.03	4.29	2.05	2.51	3.19
720	0.88	0.68	0.62	0.64	0.78	0.54	2.73	4.46	3.80	0.49	0.57	0.71
725	0.81	0.61	0.54	0.54	0.72	0.48	2.47	4.02	3.43	0.24	0.27	0.30
730	0.77	0.56	0.49	0.49	0.68	0.44	2.25	3.66	3.12	0.21	0.23	0.26
735	0.75	0.54	0.46	0.46	0.67	0.43	2.06	3.36	2.86	0.21	0.21	0.23
740	0.73	0.51	0.43	0.42	0.65	0.40	1.90	3.09	2.64	0.24	0.24	0.28
745	0.68	0.47	0.39	0.37	0.61	0.37	1.75	2.85	2.43	0.24	0.24	0.28
750	0.69	0.47	0.39	0.37	0.62	0.38	1.62	2.65	2.26	0.21	0.20	0.21
755	0.64	0.43	0.35	0.33	0.59	0.35	1.54	2.51	2.14	0.17	0.24	0.17
760	0.68	0.46	0.38	0.35	0.62	0.39	1.45	2.37	2.02	0.21	0.32	0.21
765	0.69	0.47	0.39	0.36	0.64	0.41	1.32	2.15	1.83	0.22	0.26	0.19
770	0.61	0.40	0.33	0.31	0.55	0.33	1.17	1.89	1.61	0.17	0.16	0.15
775	0.52	0.33	0.28	0.26	0.47	0.26	0.99	1.61	1.38	0.12	0.12	0.10
780	0.43	0.27	0.21	0.19	0.40	0.21	0.81	1.32	1.12	0.09	0.09	0.05

**Appendix B.6: High-pressure discharge lamps, HP1: Standard high-pressure sodium lamp; HP2: Color enhanced high-pressure sodium lamp; HP3-5: Three types of high-pressure metal halide lamps**

$\lambda$ [nm]	HP1	HP2	HP3	HP4	HP5
380	1.90	2.64	3.15	9.80	0.34
385	2.20	2.77	7.49	13.30	7.11
390	2.50	3.42	10.87	19.97	11.49
395	2.70	3.68	12.57	25.81	14.97
400	3.10	4.33	12.97	24.69	14.95
405	4.30	5.50	21.29	47.66	29.14
410	3.80	5.94	26.29	54.44	38.08
415	4.20	7.20	30.18	63.82	51.56
420	4.80	9.02	43.06	85.52	62.56
425	5.19	10.27	29.58	60.54	55.61
430	5.89	12.48	23.18	38.37	41.98
435	7.39	16.82	35.28	88.20	50.02
440	7.89	16.04	26.29	44.94	42.14
445	5.69	15.26	24.29	35.64	39.04
450	12.89	22.58	22.91	30.75	40.52
455	6.69	20.07	26.20	33.77	45.29
460	4.30	15.13	29.31	40.81	51.01
465	20.78	25.27	25.30	33.77	49.18
470	12.99	28.04	28.14	35.28	49.05
475	6.69	15.99	24.05	32.55	46.12
480	1.40	10.40	21.82	29.44	45.73
485	1.50	11.10	20.51	26.16	39.46
490	3.20	13.44	23.05	29.96	44.39
495	18.18	22.62	26.98	32.83	46.14
500	56.24	49.71	30.96	33.58	49.54
505	2.90	17.21	30.72	41.16	59.76
510	2.10	17.12	27.13	32.93	48.47
515	13.39	27.26	29.55	32.13	48.38
520	2.10	20.02	34.22	34.45	48.70
525	2.00	21.54	29.98	30.12	44.25
530	2.20	23.36	41.21	41.13	54.42
535	2.30	25.66	173.14	187.10	128.93
540	2.60	29.69	141.37	101.37	81.26
545	5.10	43.12	64.98	123.96	67.36
550	11.39	98.30	33.83	42.47	48.48
555	15.48	125.60	34.26	34.73	51.41
560	20.78	134.57	33.32	31.82	48.88
565	55.64	149.70	52.80	54.67	68.52
570	254.03	166.12	74.29	57.45	80.85
575	56.14	98.77	47.97	70.43	65.96

$\lambda$ [nm]	<b>HP1</b>	<b>HP2</b>	<b>HP3</b>	<b>HP4</b>	<b>HP5</b>
580	111.78	30.47	49.20	69.50	59.43
585	297.98	1.17	96.07	49.37	67.57
590	142.55	0.39	85.41	183.35	128.34
595	334.84	1.65	175.18	162.15	131.85
600	189.40	21.41	153.73	109.35	101.70
605	117.78	76.11	120.22	72.38	77.05
610	79.92	126.16	98.90	70.60	66.27
615	108.09	161.96	90.22	58.08	77.09
620	46.85	160.06	70.07	44.13	60.51
625	38.16	158.19	66.84	50.20	65.23
630	32.47	153.69	57.61	40.80	57.86
635	28.37	147.40	53.03	37.91	56.20
640	25.37	140.60	49.85	36.71	54.32
645	22.98	134.92	48.16	38.30	56.34
650	20.38	127.59	42.76	31.24	45.74
655	19.78	124.65	50.64	35.31	50.79
660	17.78	118.02	48.42	45.62	56.66
665	16.78	113.94	41.27	35.82	51.99
670	19.18	118.10	43.44	89.91	84.31
675	17.98	115.16	40.48	36.01	47.48
680	13.69	102.85	35.16	32.57	47.46
685	9.99	90.54	34.94	39.26	61.78
690	8.19	83.34	24.68	23.27	34.51
695	7.59	79.44	24.70	25.30	38.74
700	6.99	76.97	21.49	20.02	30.98
705	6.79	74.85	19.49	17.54	25.45
710	6.49	73.12	18.48	16.25	22.88
715	6.39	71.51	17.55	15.20	20.82
720	6.09	70.13	17.36	15.15	21.05
725	5.99	69.04	17.09	15.22	20.81
730	5.79	67.48	16.32	14.26	18.69
735	5.79	66.70	16.07	12.63	17.54
740	5.79	66.31	16.58	14.75	19.58
745	5.79	65.14	15.78	13.19	16.42
750	6.39	65.70	17.66	17.63	23.77
755	5.99	64.79	20.46	23.38	35.39
760	5.59	64.10	16.59	16.02	21.37
765	31.97	83.04	17.81	24.46	34.58
770	27.87	86.25	16.07	22.05	30.21
775	5.89	63.93	14.83	16.11	19.71
780	6.69	64.92	14.61	12.91	15.61

**Appendix B.7: Colorimetric data for the fluorescent lamp illuminants**

<b>Lamp</b>	<b>Chromaticity coordinates</b>		<b>Correlated color temperature (<math>T_{cp}</math>) (kelvins)</b>	<b>General color rendering index <math>R_a</math></b>
	<b>x</b>	<b>y</b>		
FL 1	0.3131	0.3371	6430	76
FL 2	0.3721	0.3751	4220	64
FL 3	0.4091	0.3941	3450	57
FL 4	0.4402	0.4031	2940	51
FL 5	0.3138	0.3452	6350	72
FL 6	0.3779	0.3882	4150	59
FL 7	0.3129	0.3292	6500	90
FL 8	0.3458	0.3586	5000	96
FL 9	0.3741	0.3727	4150	90
FL 10	0.3458	0.3588	5000	81
FL 11	0.3805	0.3769	4000	83
FL 12	0.4370	0.4042	3000	83

**Appendix B.8: Colorimetric data for the high pressure illuminants**

	<b>HP1</b>	<b>HP2</b>	<b>HP3</b>	<b>HP4</b>	<b>HP5</b>
$x =$	0.533	0.4778	0.4302	0.3812	0.3776
$y =$	0.415	0.4158	0.4075	0.3797	0.3713
$T_{cp} =$	1959 K	2506 K	3144 K	4002 K	4040 K
Special Rendering Indices					
No. 1 =	-3	97	86	77	89
No. 2 =	61	88	92	86	95
No. 3 =	40	73	87	84	97
No. 4 =	-27	89	89	80	91
No. 5 =	-4	88	84	77	90
No. 6 =	52	71	90	80	95
No. 7 =	21	81	82	79	87
No. 8 =	-76	73	49	46	68
No. 9 =	-261	53	-29	-51	19
No. 10 =	43	66	71	58	87
No. 11 =	-52	65	89	79	92
No. 12 =	27	55	72	65	91
No. 13 =	7	90	90	81	92
No. 14 =	60	82	91	90	99
General Color Rendering Index. $R_a$					
$R_a =$	8	83	82	76	89

## C TABLES OF INDICES

**Appendix C.1: Values of efficiency function  $F_\lambda$  of  $R_{457}$  Brightness**

Wavelength nm	$F(\lambda)$	Weighted values 5 nm	$F(\lambda)$	Weighted values 10 nm	$F(\lambda)$	Weighted values 20 nm
400	1.0	0.107	1.0	0.213	1.0	0.425
405	2.9	0.309				
410	6.7	0.715	6.7	1.430		
415	12.1	1.291				
420	18.2	1.942	18.2	3.885	18.2	7.728
425	25.8	2.752				
430	34.5	3.680	34.5	7.364		
435	44.9	4.790				
440	57.6	6.145	57.6	12.295	57.6	24.459
445	70.0	7.467				
450	82.5	8.801	82.5	17.609		
455	94.1	10.038				
460	100.0	10.668	100.0	21.345	100.0	42.463
465	99.3	10.593				
470	88.7	9.462	88.7	18.933		
475	72.5	7.734				
480	53.1	5.665	53.1	11.334	53.1	22.548
485	34.0	3.627				
490	20.3	2.166	20.3	4.333		
495	11.1	1.184				
500	5.6	0.597	5.6	1.195	5.6	2.378
505	2.2	0.235				
510	0.3	0.032	0.3	0.064		
<b>Summation</b>	<b>937.4</b>	<b>100.000</b>	<b>468.5</b>	<b>100.000</b>	<b>235.5</b>	<b>100.000</b>



**Appendix C.2: Values of the first deviation function used in the calculation of the observer metamerism index**

$\lambda$ . nm	$\Delta \bar{x}(\lambda)$	$\Delta \bar{y}(\lambda)$	$\Delta \bar{z}(\lambda)$	$\lambda$ . nm	$\Delta \bar{x}(\lambda)$	$\Delta \bar{y}(\lambda)$	$\Delta \bar{z}(\lambda)$
380	-0.0001	0.0000	-0.0002	585	-0.0637	-0.0162	-0.0011
385	-0.0003	0.0000	-0.0010	590	-0.0656	-0.0196	-0.0009
390	-0.0009	-0.0001	-0.0036	595	-0.0638	-0.0199	-0.0008
395	-0.0026	-0.0004	-0.0110	600	-0.0595	-0.0187	-0.0006
400	-0.0069	-0.0009	-0.0294	605	-0.0530	-0.0170	-0.0005
405	-0.0134	-0.0015	-0.0558	610	-0.0448	-0.0145	-0.0004
410	-0.0197	-0.0019	-0.0820	615	-0.0346	-0.0112	0.0000
415	-0.0248	-0.0022	-0.1030	620	-0.0242	-0.0077	0.0002
420	-0.0276	-0.0021	-0.1140	625	-0.0155	-0.0048	0.0000
425	-0.0263	-0.0017	-0.1079	630	-0.0085	-0.0025	-0.0002
430	-0.0216	-0.0009	-0.0872	635	-0.0044	-0.0012	-0.0002
435	-0.0122	0.0005	-0.0455	640	-0.0019	-0.0006	0.0000
440	-0.0021	0.0015	-0.0027	645	-0.0001	0.0000	0.0000
445	0.0036	0.0008	0.0171	650	0.0010	0.0003	0.0000
450	0.0092	-0.0003	0.0342	655	0.0016	0.0005	0.0000
455	0.0186	-0.0005	0.0703	660	0.0019	0.0006	0.0000
460	0.0263	-0.0011	0.0976	665	0.0019	0.0006	0.0000
465	0.0256	-0.0036	0.0859	670	0.0017	0.0006	0.0000
470	0.0225	-0.0060	0.0641	675	0.0013	0.0005	0.0000
475	0.0214	-0.0065	0.0547	680	0.0009	0.0003	0.0000
480	0.0205	-0.0060	0.0475	685	0.0006	0.0002	0.0000
485	0.0197	-0.0045	0.0397	690	0.0004	0.0001	0.0000
490	0.0187	-0.0031	0.0319	695	0.0003	0.0001	0.0000
495	0.0167	-0.0037	0.0228	700	0.0002	0.0001	0.0000
500	0.0146	-0.0047	0.0150	705	0.0001	0.0000	0.0000
505	0.0133	-0.0059	0.0117	710	0.0001	0.0000	0.0000
510	0.0118	-0.0060	0.0096	715	0.0001	0.0000	0.0000
515	0.0094	-0.0025	0.0062	720	0.0000	0.0000	0.0000
520	0.0061	0.0010	0.0029	725	0.0000	0.0000	0.0000
525	0.0017	0.0005	0.0005	730	0.0000	0.0000	0.0000
530	-0.0033	-0.0011	-0.0012	735	0.0000	0.0000	0.0000
535	-0.0085	-0.0020	-0.0020	740	0.0000	0.0000	0.0000
540	-0.0139	-0.0028	-0.0022	745	0.0000	0.0000	0.0000
545	-0.0194	-0.0039	-0.0024	750	0.0000	0.0000	0.0000
550	-0.0247	-0.0044	-0.0024	755	0.0000	0.0000	0.0000
555	-0.0286	-0.0027	-0.0021	760	0.0000	0.0000	0.0000
560	-0.0334	-0.0022	-0.0017	765	0.0000	0.0000	0.0000
565	-0.0426	-0.0073	-0.0015	770	0.0000	0.0000	0.0000
570	-0.0517	-0.0127	-0.0014	775	0.0000	0.0000	0.0000
575	-0.0566	-0.0129	-0.0013	780	0.0000	0.0000	0.0000
580	-0.0600	-0.0126	-0.0013	-	-	-	-

## D SUPPLEMENTARY COLORIMETRIC CALCULATIONS

D.1: Reverse transformation from values  $L^*$ ,  $a^*$ ,  $b^*$  to tristimulus values  $X$ ,  $Y$ ,  $Z$

*Reverse transformation:*

1) Calculate from the values  $L^*$ ,  $a^*$ ,  $b^*$ :

$$f(Y/Y_n) = (L^* + 16) / 116 \quad (D.1)$$

$$f(X/X_n) = a^* / 500 + f(Y/Y_n) \quad (D.2)$$

$$f(Z/Z_n) = f(Y/Y_n) - b^* / 200 \quad (D.3)$$

2) Calculate then the tristimulus values  $X$ ,  $Y$ ,  $Z$  from:

$$X = X_n [f(X/X_n)]^3 \quad \text{if } f(X/X_n) > 24/116 \quad (D.4)$$

$$X = X_n [f(X/X_n) - 16/116] \cdot (108/841) \quad \text{if } f(X/X_n) \leq 24/116 \quad (D.5)$$

$$Y = Y_n [f(Y/Y_n)]^3 \quad \text{if } f(Y/Y_n) > 24/116 \text{ or } L^* > 8 \quad (D.6)$$

$$Y = Y_n [f(Y/Y_n) - 16/116] \cdot (108/841) \quad \text{if } f(Y/Y_n) \leq 24/116 \text{ or } L^* \leq 8 \quad (D.7)$$

$$Z = Z_n [f(Z/Z_n)]^3 \quad \text{if } f(Z/Z_n) > 24/116 \quad (D.8)$$

$$Z = Z_n [f(Z/Z_n) - 16/116] \cdot (108/841) \quad \text{if } f(Z/Z_n) \leq 24/116 \quad (D.9)$$

**Appendix D.2: Reflectance of unpolarized light at a plane boundary between two media as a function of their refractive index**

Refractive index	Reflectance for perpendicular incidence	Reflectance for diffuse incidence		Refractive index	Reflectance for perpendicular incidence	Reflectance for diffuse incidence	
		External reflection	Internal reflection			External reflection	Internal reflection
1.00	0.000000	0.0000	0.0000	1.46	0.034966	0.0859	0.5711
1.01	0.000025	0.0031	0.0228	1.47	0.036208	0.0873	0.5777
1.02	0.000098	0.0061	0.0446	1.48	0.037461	0.0888	0.5840
1.03	0.000218	0.0088	0.0657	1.49	0.038725	0.0903	0.5902
1.04	0.000384	0.0114	0.0860	1.50	0.040000	0.0918	0.5963
1.05	0.000595	0.0139	0.1056	1.51	0.041285	0.0932	0.6023
1.06	0.000848	0.0163	0.1245	1.52	0.042580	0.0947	0.6082
1.07	0.001144	0.0186	0.1428	1.53	0.043884	0.0962	0.6139
1.08	0.001479	0.0208	0.1605	1.54	0.045198	0.0976	0.6195
1.09	0.001854	0.0230	0.1777	1.55	0.046521	0.0991	0.6250
1.10	0.002268	0.0252	0.1943	1.56	0.047852	0.1005	0.6304
1.11	0.002718	0.0272	0.2105	1.57	0.049191	0.1020	0.6357
1.12	0.003204	0.0293	0.2261	1.58	0.050538	0.1034	0.6408
1.13	0.003725	0.0313	0.2413	1.59	0.051892	0.1048	0.6459
1.14	0.004280	0.0332	0.2561	1.60	0.053254	0.1062	0.6509
1.15	0.004867	0.0351	0.2704	1.61	0.054623	0.1077	0.6557
1.16	0.005487	0.0370	0.2843	1.62	0.055999	0.1091	0.6605
1.17	0.006137	0.0389	0.2979	1.63	0.057381	0.1105	0.6652
1.18	0.006818	0.0407	0.3110	1.64	0.058770	0.1119	0.6698
1.19	0.007527	0.0425	0.3238	1.65	0.060164	0.1133	0.6743
1.20	0.008264	0.0443	0.3363	1.66	0.061564	0.1147	0.6787
1.21	0.009029	0.0460	0.3484	1.67	0.062969	0.1161	0.6831
1.22	0.009821	0.0478	0.3602	1.68	0.064380	0.1175	0.6873
1.23	0.010638	0.0495	0.3717	1.69	0.065795	0.1189	0.6915
1.24	0.011480	0.0512	0.3829	1.70	0.067215	0.1203	0.6956
1.25	0.012346	0.0529	0.3939	1.71	0.068640	0.1217	0.6996
1.26	0.013235	0.0546	0.4045	1.72	0.070069	0.1231	0.7036
1.27	0.014147	0.0562	0.4149	1.73	0.071502	0.1245	0.7075
1.28	0.015082	0.0579	0.4250	1.74	0.072939	0.1259	0.7113
1.29	0.016037	0.0595	0.4348	1.75	0.074380	0.1272	0.7150
1.30	0.017013	0.0611	0.4445	1.76	0.075824	0.1286	0.7187
1.31	0.018009	0.0627	0.4538	1.77	0.077272	0.1300	0.7223
1.32	0.019025	0.0643	0.4630	1.78	0.078723	0.1313	0.7258
1.33	0.020059	0.0659	0.4719	1.79	0.080176	0.1327	0.7293
1.34	0.021112	0.0675	0.4807	1.80	0.081633	0.1341	0.7327
1.35	0.022182	0.0691	0.4892	1.81	0.083092	0.1354	0.7361
1.36	0.023269	0.0706	0.4975	1.82	0.084553	0.1368	0.7394
1.37	0.024373	0.0722	0.5057	1.83	0.086017	0.1381	0.7426
1.38	0.025493	0.0737	0.5136	1.84	0.087483	0.1395	0.7458
1.39	0.026628	0.0753	0.5214	1.85	0.088950	0.1408	0.7490
1.40	0.027778	0.0768	0.5290	1.86	0.090420	0.1421	0.7520
1.41	0.028942	0.0783	0.5364	1.87	0.091891	0.1435	0.7551
1.42	0.030121	0.0799	0.5437	1.88	0.093364	0.1448	0.7580
1.43	0.031313	0.0814	0.5508	1.89	0.094838	0.1461	0.7610
1.44	0.032518	0.0829	0.5577	1.90	0.096314	0.1475	0.7638
1.45	0.033736	0.0844	0.5645	-	-	-	-

## E ILLUMINANT-OBSERVER WEIGHTS FOR CALCULATING TRISTIMULUS VALUES

This appendix gives illuminant-observer weights for calculating tristimulus values from data of spectral reflectance factor or spectral transmittance factor. These weights were published as Table 6 in ASTM Document E 308–2006. These values should ideally be used only for data uncorrected for band pass errors, but they have been found to be beneficial for general use. It is common industrial practice to carry out the summation to tristimulus values in two steps. In the first of these, a set of normalized tristimulus weighting factors  $W_x$ ,  $W_y$ ,  $W_z$  is calculated as follows:

$$W_x(\lambda) = k \cdot S(\lambda) \cdot \bar{x}(\lambda) \Delta\lambda$$

$$W_y(\lambda) = k \cdot S(\lambda) \cdot \bar{y}(\lambda) \Delta\lambda$$

$$W_z(\lambda) = k \cdot S(\lambda) \cdot \bar{z}(\lambda) \Delta\lambda$$

$$\text{for } \lambda = 380 \dots 780 \text{ nm and where } k = 100 / \sum_{380}^{780} S(\lambda) \cdot \bar{y}(\lambda) \Delta\lambda$$

For a given selection of illuminant, observer, measurement interval  $\Delta\lambda$ , and measurement band pass, this calculation needs to be done only once, since the spectral reflectance (or transmittance or radiance) factor  $R(\lambda)$  is not included in the weighting factors  $W$ . In the second step, tristimulus values  $X$ ,  $Y$ ,  $Z$  (or  $X_{10}$ ,  $Y_{10}$ ,  $Z_{10}$ ) are calculated using the values of  $W$  and  $R(\lambda)$  in the following equations:

$$X = \sum_{380}^{780} W_x(\lambda) \cdot R(\lambda) \Delta\lambda$$

$$Y = \sum_{380}^{780} W_y(\lambda) \cdot R(\lambda) \Delta\lambda$$

$$Z = \sum_{380}^{780} W_z(\lambda) \cdot R(\lambda) \Delta\lambda$$

**Appendix E.1: Illuminant A and D65, 1931 Observer – 10 nm interval**

$\Delta\lambda=10$ nm	Illuminant A, 1931 Observer			Illuminant D65, 1931 Observer		
	$W_x$	$W_y$	$W_z$	$W_x$	$W_y$	$W_z$
360	0.000	0.000	0.000	0.000	0.000	0.000
370	0.000	0.000	0.001	0.002	0.000	0.009
380	0.001	0.000	0.005	0.006	0.000	0.029
390	0.004	0.000	0.018	0.016	0.000	0.077
400	0.017	0.000	0.081	0.097	0.003	0.460
410	0.057	0.002	0.272	0.311	0.009	1.477
420	0.246	0.007	1.178	1.164	0.033	5.581
430	0.660	0.025	3.214	2.400	0.092	11.684
440	0.942	0.059	4.710	3.506	0.221	17.532
450	1.039	0.113	5.454	3.755	0.413	19.729
460	1.043	0.205	5.969	3.298	0.662	18.921
470	0.790	0.353	5.209	2.141	0.973	14.161
480	0.416	0.608	3.602	1.001	1.509	8.730
490	0.148	1.012	2.277	0.293	2.107	4.623
500	0.016	1.749	1.493	0.028	3.288	2.769
510	0.028	3.047	0.963	0.054	5.122	1.584
520	0.388	4.778	0.505	0.581	7.082	0.736
530	1.187	6.345	0.305	1.668	8.833	0.421
540	2.288	7.625	0.157	2.860	9.472	0.191
550	3.702	8.594	0.071	4.257	9.830	0.081
560	5.484	9.255	0.034	5.632	9.446	0.034
570	7.562	9.496	0.020	6.960	8.709	0.018
580	9.739	9.265	0.018	8.344	7.901	0.015
590	11.644	8.567	0.013	8.676	6.357	0.009
600	12.811	7.563	0.010	9.120	5.379	0.007
610	12.782	6.365	0.004	8.568	4.259	0.003
620	11.460	5.076	0.002	7.119	3.149	0.001
630	8.991	3.689	0.001	5.049	2.070	0.000
640	6.536	2.543	0.000	3.522	1.370	0.000
650	4.296	1.616	0.000	2.112	0.794	0.000
660	2.583	0.954	0.000	1.229	0.454	0.000
670	1.405	0.514	0.000	0.658	0.240	0.000
680	0.780	0.283	0.000	0.331	0.120	0.000
690	0.388	0.140	0.000	0.142	0.051	0.000
700	0.200	0.072	0.000	0.074	0.027	0.000
710	0.106	0.038	0.000	0.039	0.014	0.000
720	0.054	0.020	0.000	0.016	0.006	0.000
730	0.028	0.010	0.000	0.009	0.003	0.000
740	0.014	0.005	0.000	0.005	0.002	0.000
750	0.007	0.002	0.000	0.002	0.001	0.000
760	0.003	0.001	0.000	0.001	0.000	0.000
770	0.002	0.001	0.000	0.001	0.000	0.000
780	0.001	0.000	0.000	0.000	0.000	0.000

Check Sum    109.848    99.997    35.586    95.047    100.001    108.882  
White Point    109.850    100.000    35.585    95.047    100.000    108.883

**Appendix E.2: Illuminant A and D65, 1931 Observer – 20 nm interval**

$\Delta\lambda=20$ nm	Illuminant A, 1931 Observer			Illuminant D65, 1931 Observer		
	$W_x$	$W_y$	$W_z$	$W_x$	$W_y$	$W_z$
360	0.000	0.000	0.000	0.000	0.000	0.000
380	0.013	0.000	0.060	0.040	0.000	0.187
400	-0.026	0.000	-0.123	-0.026	0.004	-0.120
420	0.483	0.009	2.306	2.114	0.041	10.065
440	1.955	0.106	9.637	7.323	0.411	36.235
460	2.145	0.385	12.257	6.815	1.281	39.090
480	0.848	1.119	7.301	1.843	2.797	16.753
500	-0.112	3.247	2.727	-0.219	6.291	4.727
520	0.611	9.517	1.035	1.003	14.463	1.532
540	4.407	15.434	0.274	5.723	19.509	0.314
560	10.804	18.703	0.055	11.284	19.106	0.058
580	19.601	18.746	0.034	16.548	15.600	0.027
600	26.256	15.233	0.018	18.528	10.607	0.013
620	23.295	10.105	0.003	14.397	6.240	0.002
640	12.853	4.939	0.000	6.646	2.540	0.000
660	4.863	1.784	0.000	2.290	0.842	0.000
680	1.363	0.495	0.000	0.574	0.208	0.000
700	0.359	0.129	0.000	0.120	0.043	0.000
720	0.100	0.036	0.000	0.034	0.012	0.000
740	0.023	0.008	0.000	0.007	0.003	0.000
760	0.006	0.002	0.000	0.001	0.000	0.000
780	0.002	0.001	0.000	0.001	0.000	0.000

Check Sum	109.849	99.998	35.584	95.046	99.998	108.883
White Point	109.850	100.000	35.585	95.047	100.000	108.883

**Appendix E.3: Illuminant A and D65, 1964 Observer – 10 nm interval**

$\Delta\lambda=10$ nm	Illuminant A, 1964 Observer			Illuminant D65, 1964 Observer		
	$W_{X10}$	$W_{Y10}$	$W_{Z10}$	$W_{X10}$	$W_{Y10}$	$W_{Z10}$
360	0.000	0.000	0.000	0.000	0.000	0.000
370	0.000	0.000	0.000	0.000	0.000	-0.001
380	0.000	0.000	0.000	0.001	0.000	0.004
390	0.002	0.000	0.007	0.005	0.000	0.020
400	0.018	0.002	0.078	0.097	0.010	0.436
410	0.118	0.012	0.540	0.616	0.064	2.808
420	0.372	0.038	1.760	1.660	0.171	7.868
430	0.686	0.082	3.374	2.377	0.283	11.703
440	0.982	0.154	5.024	3.512	0.549	17.958
450	1.094	0.255	5.876	3.789	0.888	20.358
460	1.024	0.414	5.882	3.103	1.277	17.861
470	0.747	0.688	5.023	1.937	1.817	13.085
480	0.326	1.073	3.236	0.747	2.545	7.510
490	0.061	1.589	1.926	0.110	3.164	3.743
500	0.003	2.397	1.129	0.007	4.309	2.003
510	0.189	3.503	0.638	0.314	5.631	1.004
520	0.717	4.857	0.377	1.027	6.896	0.529
530	1.617	6.096	0.205	2.174	8.136	0.271
540	2.823	7.290	0.100	3.380	8.684	0.116
550	4.296	8.116	0.028	4.735	8.903	0.030
560	6.177	8.799	-0.003	6.081	8.614	-0.003
570	8.285	9.039	0.001	7.310	7.950	0.001
580	10.218	8.758	0.000	8.393	7.164	0.000
590	12.041	8.350	0.000	8.603	5.945	0.000
600	12.850	7.492	0.000	8.771	5.110	0.000
610	12.441	6.337	0.000	7.996	4.067	0.000
620	10.872	5.025	0.000	6.476	2.990	0.000
630	8.604	3.753	0.000	4.635	2.020	0.000
640	5.951	2.469	0.000	3.074	1.275	0.000
650	3.846	1.537	0.000	1.814	0.724	0.000
660	2.259	0.891	0.000	1.031	0.407	0.000
670	1.242	0.485	0.000	0.557	0.218	0.000
680	0.643	0.250	0.000	0.261	0.102	0.000
690	0.324	0.126	0.000	0.114	0.044	0.000
700	0.160	0.062	0.000	0.057	0.022	0.000
710	0.078	0.030	0.000	0.028	0.011	0.000
720	0.039	0.015	0.000	0.011	0.004	0.000
730	0.019	0.007	0.000	0.006	0.002	0.000
740	0.010	0.004	0.000	0.003	0.001	0.000
750	0.005	0.002	0.000	0.001	0.000	0.000
760	0.002	0.001	0.000	0.000	0.000	0.000
770	0.001	0.001	0.000	0.000	0.000	0.000
780	0.001	0.000	0.000	0.000	0.000	0.000

Check Sum 111.143 99.999 35.201 94.813 99.997 107.304

White Point 111.144 100.000 35.200 94.811 100.000 107.304

**Appendix E.4: Illuminant A and D65, 1964 Observer – 20 nm interval**

$\Delta\lambda=20$ nm	Illuminant A, 1964 Observer			Illuminant D65, 1964 Observer		
	nm	$W_{X10}$	$W_{Y10}$	$W_{Z10}$	$W_{X10}$	$W_{Y10}$
360	0.000	0.000	0.000	0.000	0.000	0.000
380	0.007	0.000	0.037	0.003	-0.001	0.025
400	-0.016	0.000	-0.088	0.056	0.013	0.199
420	0.691	0.066	3.226	2.951	0.280	13.768
440	2.025	0.285	10.278	7.227	1.042	36.808
460	2.158	0.796	12.345	6.578	2.534	37.827
480	0.642	2.043	6.555	1.278	4.872	14.226
500	-0.160	4.630	1.966	-0.259	8.438	1.025
520	1.284	9.668	0.721	1.951	14.03	3.254
540	5.445	14.621	0.171	6.751	17.715	0.184
560	12.238	17.766	-0.013	12.223	17.407	-0.013
580	20.755	17.800	0.004	16.779	14.21	0.004
600	26.325	15.129	-0.001	17.793	10.121	-0.001
620	22.187	10.097	0.000	13.135	5.971	0.000
640	11.816	4.858	0.000	5.859	2.399	0.000
660	4.221	1.643	0.000	1.901	0.741	0.000
680	1.154	0.452	0.000	0.469	0.184	0.000
700	0.282	0.109	0.000	0.088	0.034	0.000
720	0.068	0.026	0.000	0.023	0.009	0.000
740	0.017	0.007	0.000	0.005	0.002	0.000
760	0.004	0.002	0.000	0.001	0.000	0.000
780	0.001	0.000	0.000	0.000	0.000	0.000

Check Sum 111.144 99.998 35.201 94.812 100.001 107.306  
 White Point 111.144 100.000 35.200 94.811 100.000 107.304



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