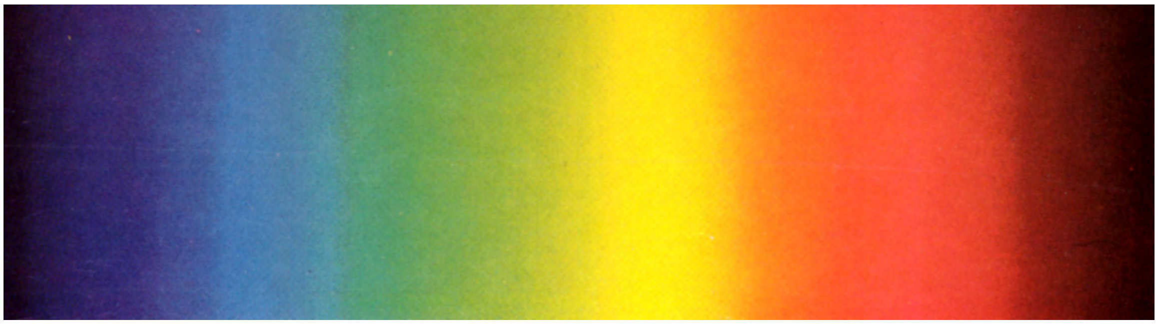
Color Vision and Technology

Rolf G. Kuehni



American Association of Textile Chemists and Colorists

Navigation Tips:

- To change format (e.g., two-page to single-page view), go to the “View” pull-down menu and select “Page Display.”

- Click once on any bookmark (on the left side of the screen) to go directly to the chapter or section indicated.

- Specific chapters or sections can also be reached by clicking once on the desired selection in the Table of Contents.

- A full-text search can be performed for any word or phrase by pressing CTRL + F. Enter the desired text in the pop-up box and click “Next” or “Previous.”

- Clicking once on a key word (*blue italic text*) within the text will bring you to the glossary definition of that word. From the glossary, press ALT + ← to return to the previously-viewed page.

TABLE OF CONTENTS

INTRODUCTION

Color, in addition to form and feel, is a major marketing tool for textile materials. Well-executed industrial management of color is an important task in the competitive, successful production and marketing of most textiles.

But colors are, first and foremost, human experiences. As such, they remain a scientific mystery. While much is known about the color vision apparatus in the human visual system, the nature of our color experiences, as that of other sensory experiences, remains a mystery. Thus, color is only to a certain degree subject to engineering science. Individual human color experiences from a certain colored material or the interpretation of differences in color experience from two or more different samples vary considerably among people with normal color vision. Reflectance properties of materials can be measured with considerable accuracy and repeatability but they do not relate closely to what a given individual experiences when looking at them. As a result, even today's best mathematical models of predicting color experiences, such as color difference formulas, predict the related experiences of an average observer only modestly well and of individual observers often poorly.

As a result, color science as a product-engineering science has limitations. For people involved in producing colored materials, it is important to understand the strengths and limitations of color science in regard to predicting the average or individual judgments of colors and color differences.

Color science and color engineering are complex because the world, the human mind, and its interpretation of color stimuli (lights bearing color messages from the surrounding world) are complex. In the following text, an effort has been made to describe the issues reasonably simply, with the help of many illustrations, but with up-to-date, scientific accuracy. It is likely that some readers will find it too simple and others too complicated. The former group is encouraged to work through it to gain an understanding of a viewpoint that is somewhat different from that of existing textbooks. The latter group is encouraged to attempt to work through it two or three times. What is not clear in the first reading may become clearer after repeated reading and discussion with colleagues having a more complete understanding of the issues.

The viewpoint presented here is that the human color vision system is not built according to conventional instrument performance standards. It is the result of natural adaptation to prevailing conditions over millions of years, with the goal of enhancing an individual's life prospects. Just as we do not have a universal language, but many different ones that serve the same basic purpose, a degree of flexibility has been built into the human color vision system to adapt itself to viewing conditions, surrounds, and needs encountered in life in a given place. Rather than being a precise, absolute color measuring instrument, our color vision system is built to determine where one object ends and another begins and to provide information to the brain that helps in interpreting what the object in the visual field may be. Much of the basic learning processes in this matter take place during the first three years of our life. What is important in this regard is to determine if two objects are the same or different and not the degree of difference. Even expert colorists tend to disagree reliably about how big the perceived difference between two similar samples is, or which sample represents a green that is neither bluish nor yellowish. To answer such questions accurately were not engineering requirements during the development of the human color vision system.

The problem of industrial color management is to find a useful compromise between the variability in how color-normal humans experience colors and color differences, and the control of production of colored goods to meaningful standards.

The purpose of this text is not to provide detailed guidance on how to apply international or national color standards but to provide general background information on the operation of the human color vision system and the relationship between physically measurable data of materials and the color experiences that can result from them. A companion work, a color management handbook under development by the American Association of Textile Chemists and Colorists (AATCC), will offer the former. Together, it is hoped, they will provide useful information for many kinds of job holders in a textile supply chain to gain a better understanding of the complexities of color as an "engineering entity."

Rolf Kuehni
Charlotte, N.C., USA

Mr. Kuehni generously donated his time and work on this publication. All proceeds from its sale go to AATCC to further the objects of the Association: to increase knowledge, encourage research, and establish channels of communication regarding the design, coloration, chemical processes, and materials of importance to the textile industry. Mr. Kuehni's efforts are greatly appreciated by the entire AATCC membership and staff.

John Y. Daniels
Executive Vice President, AATCC

Plan of the Book

This book is a general introduction to the subject of color, slanted in the direction of processing and quality control of textile products. It emphasizes, to a degree, the phenomenon of color and its subjective, perceptual experience, often somewhat neglected in highly technical texts. While it is best to read the complete text from beginning to end, this may not be in the interest of every reader. Readers should note that the book does not provide detailed information on how to implement a color management system, or how to use standard test methods. Its purpose is to provide necessary background information to such procedures or methods.

The book begins with general background material and proceeds to more specific issues. Below is a brief description of the contents of each chapter to help selective readers find particular areas of interest. Readers can click on each chapters or section listed in the Table of Contents to advance them quickly to that place.

In the main text, a number of terms appear in *blue italics*. These terms are defined in the Glossary at the end of the book and clicking on them will bring the reader to the definition in the Glossary. Clicking ALT + ← will return the reader to the text. The page number on which the word is first found is listed at the end of each definition.

A very brief list of other works a reader may want to consult for additional information is included at the end of Chapter 14.

Chapter 1, Light and Vision, is an introductory discussion where some key factors about light are introduced, including its position in the larger spectrum of electromagnetic radiation. The physical description of light in the form of its spectral power distribution is mentioned. The section on sources of light discusses sunlight and the resulting daylight on earth, as well as artificial light sources, and their description by color temperature or correlated color temperature. The properties of certain materials to exhibit fluorescence or phosphorescence are described together with lamps that take advantage of the process of fluorescence.

In the second half of the chapter, the importance of light for life is discussed. The process of vision, for humans and some animals, is introduced. The two human vision systems, sometimes named vision-for-action and vision-for-perception, are introduced. A few examples demonstrate that human vision is not always veridical: the conclusions we draw from seeing certain objects are not always truthful.

Light is shown to be an illuminator, providing information to many living beings about their surroundings. Illumination can be sharp or diffuse. Finally, the technical difference between a light source and an illuminant is explained.

Chapter 2, Color Stimuli: Lights and Objects, introduces the normal causes of our experiences of vision and color: light stimuli.

These come either directly to our eyes from a light source or indirectly after having been reflected from an object. The fact that light can contain much information is described and one aspect of our interpretation of the information, the hue of a color, is introduced. Nassau's 15 causes of color are listed and two of these, dispersion or refraction and scattering, are discussed in some detail because of their importance in generating color stimuli.

Chapter 3, Dyes, Pigments, and Fibers, introduces colorants (dyes and pigments) as modifiers of reflected light that result in perceived colors. Absorption and emission of photons, the units of light, are briefly explained.

This chapter includes a brief discussion about fibers and their optical properties that make them absorb, reflect, or scatter light. The technologies of spinning, weaving, and knitting are briefly mentioned as well as the surface properties of fabrics that result in differences in reflection and the scattering of light.

An introduction to the subject of dyes and the different classes that are applied to various fiber types to make them appear colored is included, as is a section on dye application methods and an introduction to pigments.

Absorption and scattering of light interacting with fibers is discussed in more detail, including the effect colorants have on the measurement of the transmittance of dye solutions and on the reflectance of dyeings. The Kubelka-Munk law that describes the absorption and scattering of light by objects is introduced. This chapter also contains a very short summary of application and fastness properties of dyes and pigments.

Chapter 4, Measuring Color Stimuli, is a more detailed discussion of transmittance and reflectance measurement of dyes in solution and on fabrics, respectively.

Absolute and relative spectral power distribution and the relative nature of transmittance and reflectance measurements are introduced. The direct measurement of light is discussed in some detail and the CIE photopic standard observer is introduced. The standard measuring geometries used in the spectrophotometers are covered, including inclusion or exclusion of the specular component of reflectance. Operation, calibration and sample presentation for spectrophotometirc measurement are discussed.

Chapter 5, Color and Color Vision, offers a more detailed discussion of the phenomena of color and how we come to experience them.

It begins with an introduction to the operation of the human eye and very briefly discusses the still-open question of what color is. The two basic kinds of light-sensitive cells in the retina, the rods and the cones are described. The question of how many different colors there are is addressed

The chapter is an introduction to placing our color experiences into some logical order and to sorting them by two basic sets of color attributes, hue, chroma, and lightness in one case, and hue, whiteness, and blackness in the other. A “fabric store” experiment demonstrates the value of such attributes. The terms color space and color solid, important for an understanding of color order are defined. A collection of important color perception phenomena are demonstrated and discussed. They all show that the relationship between color stimulus data such as reflection or spectral power distribution and the resulting color experiences is not a close one. It is shown that all people do not experience color stimuli the same way.

Color judgments are discussed along with the distinction between threshold (just perceptible) and supra-threshold (larger differences) color differences, as well as absolute and relative difference judgments. The concept of reliability of judgments is introduced. It is shown that judgments depend on the observer, the lighting, and the surround in which they are made.

Chapter 6, The Colorimetric System, is an introduction to the CIE colorimetric system and its importance and drawbacks for color control in manufacturing.

The difference between color measurement and color stimulus measurement is introduced. To gain a better understanding of the workings of the colorimetric system, the history of its development is briefly described. A description of the interaction of photons with cones in the retina at a level applicable to the colorimetric system is given. The CIE colorimetric system and some of its properties are described in Part 4. How CIE tristimulus values X, Y, and Z and chromaticity coordinates x and y are calculated is described. The shape of the object color solid in the CIE tristimulus space and its shape above the CIE chromaticity diagram are also described. All possible object color stimuli fit onto the surface or within the object color solid in either version. The second CIE standard observer, the 10° observer, is explained, and some comments about the practical value of the CIE colorimetric system are made.

Chapter 7, Color Order, is a very brief history of color order and a discussion of the relationship of geometric distances between color points in a color solid to perceptual distances. The arrangement of a color order system can be related to the color stimuli or to the perceived differences. Systems where the geometric distances represent stimulus differences are described. The RGB space of color monitors and the halftone printing process are given as examples.

Three well-known color order systems, the Munsell system, the Natural Color System, and the Optical Society of America Uniform Color Scales are described in detail.

Chapter 8, Addition of Lights and Colorants, addresses the problems of color mixture with an introduction to additive color mixture, or the mixture of lights, and to subtractive mixture, or mixture of colorants. A worked example of additive and subtractive color mixture is offered for a better understanding of the differences that have been a longstanding source of confusion for many color experts and continue to confuse most people even today.

Chapter 9, Color Reproduction, introduces two separate concepts, color and general appearance. Color reproduction can be done at different levels of reproductive accuracy and this chapter demonstrates and discusses four kinds along with visual and computer-supported matching. Color management in large organizations or supply chains is briefly explored.

Chapter 10, Strength of Colorants, introduces such concepts as coloring power, absolute and relative strength of colorants, and colorant standardization.

Included is a discussion of the determination of relative strength and shade of textile colorants, the measurement of dye strength in solution, a discussion of expressing strength as parts or percent, and determination of strength by reflectance measurement of dyeings. The chapter also shows that strength difference and color difference are interrelated and introduces the concept of residual color difference.

Chapter 11, Color Constancy and Metamerism, discusses the relationship and differences between the two concepts in some depth.

Chapter 12, Artificial Lights and Color Rendering, looks at some of the issues of Chapter 11 from the point of view of light sources, and defines the meaning of color rendering.

Natural and artificial light sources are briefly reviewed and the CIE color rendering index, its meaning, and its problems are briefly discussed.

Chapter 13, Color Difference Perception and Calculation, provides an overview of the subject and its importance to textile color control.

The chapter text indicates that color difference can be looked at from a top-down (large differences divided into smaller ones) or bottom-up (just noticeable differences added up to larger differences) perspective. Different kinds of color difference judgments are reintroduced and information is provided about intra- and inter-observer variability in color difference judgments. In the absence of a standard for describing visual color differences in a uniform manner, this chapter proposes a system of color difference terminology. In view of the considerable variability in color difference judgments, the desirability of an objective method of determining average perceived color difference is explained.

CIELAB and CMC (*l*:*c*) color difference formulas are both recommended by ISO and AATCC for use with textiles. Part 7 raises the question if significantly more accurate color difference formulas can be expected anytime soon. Part 8 discusses the place of color difference calculation in color quality control. Part 9 is an introduction to objective assessment of fastness testing involving staining or change of shade.

Chapter 14 summarizes important issues addressed throughout the book.

Chapter 1 LIGHT AND VISION

1 Light

1.1 Light is a specific type of energy—radiant energy—radiated from a source into the surrounding space. Since light is radiant energy, it can be projected through empty space (a vacuum) or through transparent matter (e.g., glass).

1.2 Radiant energy such as light is known as *electromagnetic energy*. Electromagnetism is the force responsible for the emission of tiny packets of energy from a source.

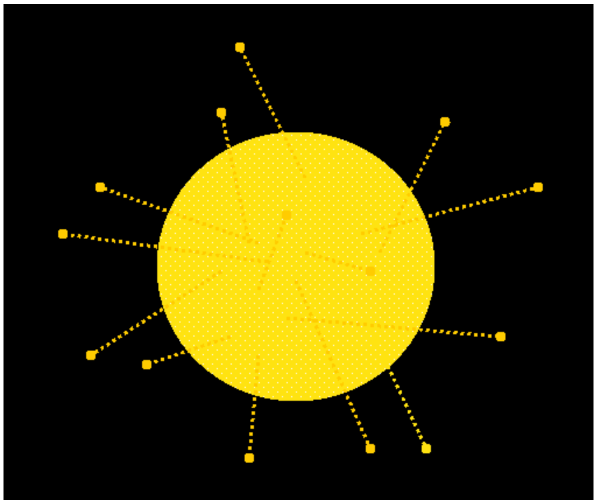


Fig. 1.1. Photons escaping the sun.

1.3 The packets of light energy are called *photons* (from the Greek "phot," meaning light). These packets of light are also called quanta (singular: *quantum*). A beam of light consists of billions of photons flowing from its source into the surrounding space (Fig. 1.1).

1.4 The energy of a single photon is expressed in units of electron volt and is very small.

1.5 Many photons together form wave-like streams. The waves are characterized by "hills and valleys" (Fig. 1.2).

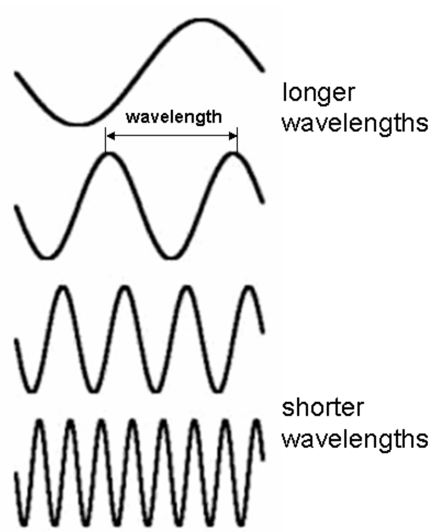


Fig. 1.2. Electromagnetic energy waves of different wavelengths.

The energy of photons can also be expressed in terms of *frequency*. Frequency refers to the number of hill and valley cycles in a unit length of distance.

In color science, the energy of light waves is typically expressed in terms of *wavelength*, the distance between one "hilltop" and the next. Increasing wavelength means decreasing frequency and decreasing energy content, and vice versa. Light wavelengths range from about 380 *nanometers* (nm) to about 750 nm (often rounded to 400-700 nm). This range is known as the *visible spectrum* since it includes the wavelengths visible to the human eye. One nanometer is one billionth, or 10^{-9} m (a meter is approximately 3 ft). Wavelengths of light are very short!

1.6 Light is a small portion of the complete range of electromagnetic energy (Fig.1.3). It runs from extremely short wavelengths (a billion times shorter than those of light) of cosmic rays to extremely long ones (a billion times longer than those of light) of electric power transmission. Electromagnetic radiation with wavelengths slightly shorter than visible light is known as *ultraviolet* (above violet), or UV. Radiation with slightly longer wavelengths than those of visible light is called *infrared* (below red) or IR.

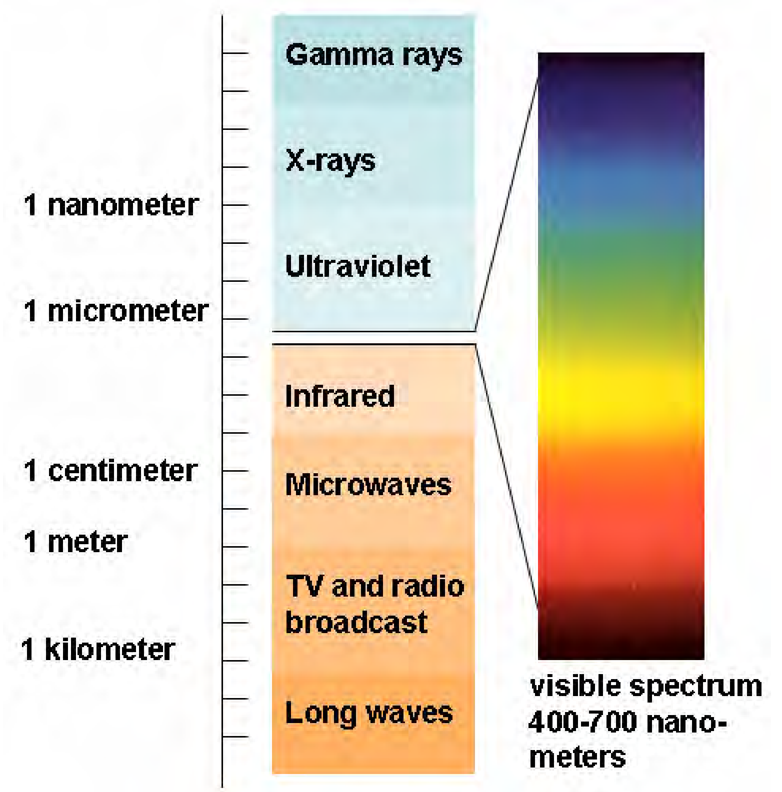


Fig. 1.3. Visible light only represents a small slice of the full spectrum.

1.7 In a given medium (e.g., air or glass), photons move very fast and in straight lines. Their speed and direction may change when they encounter an obstacle or a change in the medium.

The speed of light is approximately 300,000 km/sec in a vacuum. It is slightly less in denser media such as water or glass.

Over short distances movement of photons can be considered instantaneous, but a given photon takes about 8 min. to travel from the sun to the earth. Albert Einstein has shown that in the universe, the path of light can be bent by the effect of gravity.

1.8 In a beam of light, all photons can have the same energy level (wavelength). In this case the light is called *monochromatic*. A laser light may have a wavelength of 610 nm only.

The photons in a beam of light may have a variety of wavelengths. This is called *polychromatic* light. Daylight, for example has photons at all wavelengths from 380 to 740 nm.

1.9 A beam of light, whether monochromatic or polychromatic, can differ from another beam by the intensity of the photon flow, its *radiant power* (expressed in absolute terms as watts/sec) (Fig. 1.4). Instruments that can measure the radiant power of lights are called *radiometers*.

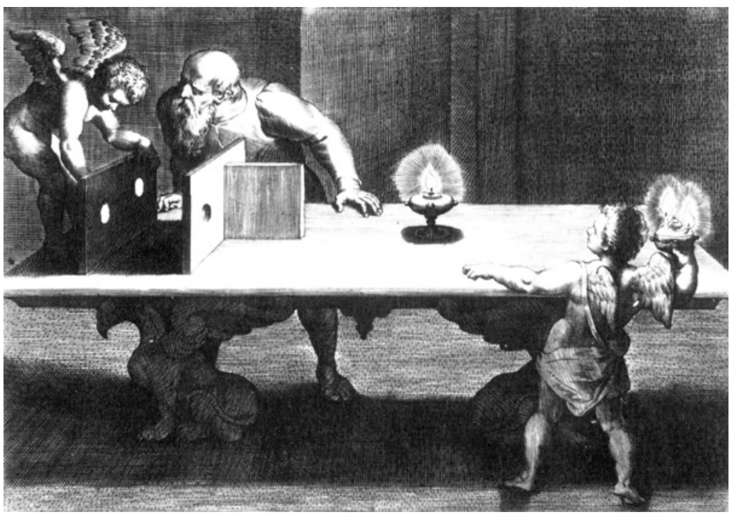


Fig. 1.4. A double lamp (right) gives off twice the radiant power of a single lamp (left), but because of the longer distance to the double lamp, the perceived brightness of the two lamps is the same. *Aguilonius, F., Opticorum libri sex, 1613.*

In color science, the absolute radiant power of a light source is often disregarded unless it is very high or very low; only the relative power of the source is considered. Relative power means that at a particular wavelength (usually 555 nm) the power is given a value of 1 (or 100), regardless of the actual power, and the power at all other wavelengths is expressed relative to that.

1.10 In science and technology, the spectral nature of a light source—its relative power at different wavelengths—is expressed as a *spectral power distribution* graph or table of numbers.

A spectral power distribution graph normally has wavelength on the horizontal axis and absolute or relative power on the vertical axis. (Fig. 1.5).

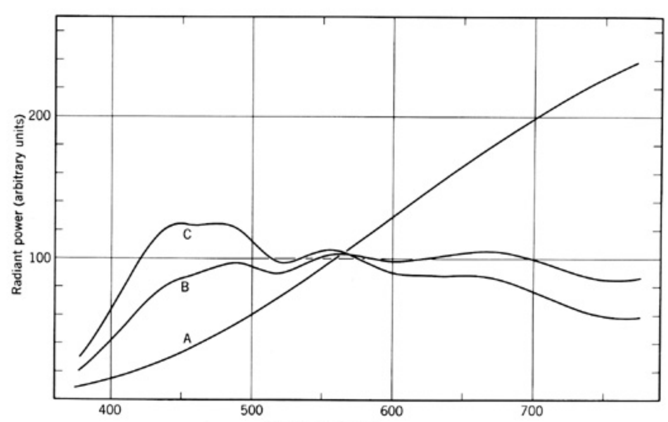


Fig. 1.5. The relative spectral power distribution curves of three kinds of lights. (Intensity units are arbitrary.) *Courtesy of John Wiley & Sons Inc. (Judd, D. B. and G. Wyszecki, Color in Business, Science and Industry, 1975). Used with permission.*

2 Light Sources

2.1 The most important source of light on Earth is the sun. Electromagnetic radiation of the complete power spectrum is generated by thermonuclear reactions and projected in all directions from the sun into space (Fig. 1.6). How much arrives on the surface of a planet depends on the distance from the sun and on the nature of its atmosphere (if it has one, as Earth does). Approximately half of the sun's energy arriving at Earth's atmosphere is absorbed or scattered away.

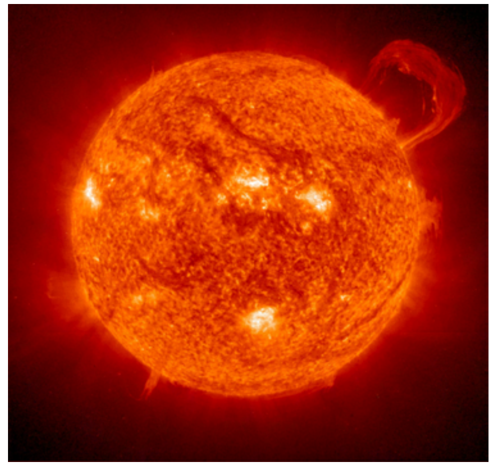


Fig. 1.6. The sun. *Courtesy of NASA Jet Propulsion Laboratory.*

2.2 The spectral power distribution of natural daylight varies with the time of day and weather. Daylight is not measured pointing the instrument at the sun but away from it. Fig. 1.7 shows ten typical kinds (*phases*) of daylight, in slightly idealized form. Actual measurements are more jagged, especially in the UV region from 300 to 400 nm.

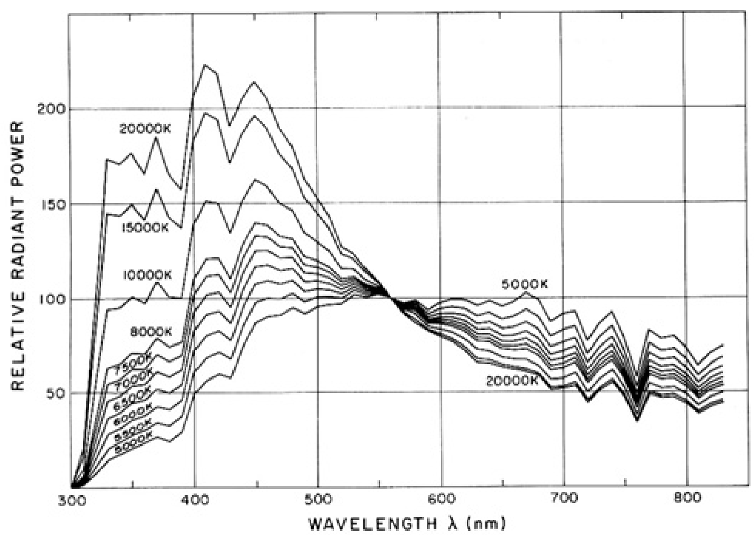


Fig. 1.7. The spectral power distributions of 10 phases of daylight, identified by their correlated color temperature (see Section 3 below). *Courtesy of John Wiley & Sons Inc. (Wyszecki, G. and W. S. Stiles, Color Science, 1982). Used with permission.*

2.3 Daylight varies in the amount of UV radiation (300-400 nm) and in the relative amounts of short wavelength (400-500 nm) and long wavelength radiation (600-700 nm) (see Fig. 1.7).

The amount of UV radiation is important for the measurement and appearance of optically-brightened white fabrics and fabrics dyed with fluorescent yellow and orange dyes. More short wavelength power gives the light a bluish appearance; more long wavelength power gives a yellowish appearance.

2.4. In Fig. 1.7 the different phases of daylight are identified by their blackbody temperature. *Blackbody temperature* is a measure that expresses what kind of light a theoretical, non-existent material (a blackbody) would give off when heated to a certain temperature as measured on the *Kelvin (K) temperature scale*. The Kelvin scale begins at "absolute zero" (the temperature in outer space). A temperature of 6000K is equivalent to approximately 5700C or 10,300F. (Think of a white-hot piece of metal giving off such light, Fig. 1.8). A blackbody temperature of 6000K means the blackbody material would need to be heated to 6000K to give off a light with approximately the same spectral power distribution as the daylight phase with the same designation (Fig. 1.9).

Fig. 1.8 Hot molten metal radiates photons of wavelengths that depend on the temperature of the metal.

The temperature of real materials, which do not behave exactly like blackbodies, is known as the *correlated color temperature*.

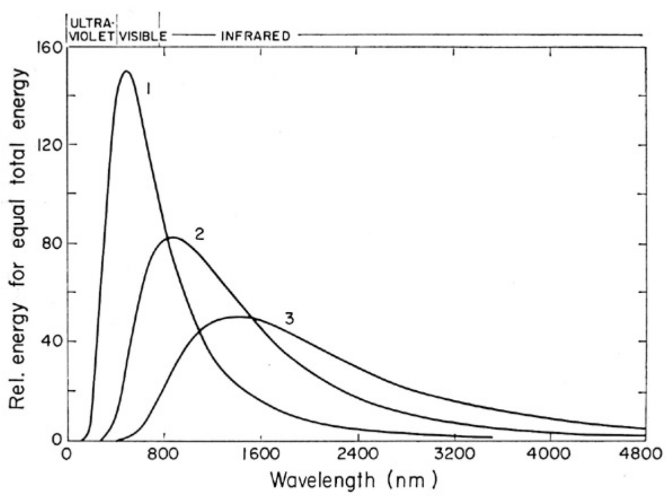


Fig. 1.9. The spectral power distributions of:
1. A blackbody at 6000K
2. A tungsten lamp at approximately 3200K
3. A carbon filament at approximately 2900K.
(Wavelength scale extends far into the infrared.) *Courtesy of John Wiley & Sons Inc. (Grum, F. R., Physical Methods in Chemistry, Vol. I, Part 3B, 1972). Used with permission.*

2.5 Some glowing metals or hot gases give off light approximating blackbody radiation by a process called *incandescence*. Fig. 1.10 illustrates the spectral power curves of blackbodies at different temperatures. At 1000K, only long wavelength light is given off, appearing reddish (think of red-hot metal). As the temperature increases, the distribution shifts from long wavelength light to short wavelength light. A regular light bulb (tungsten metal wire made to glow by resistance to electrical current) gives off light at a blackbody temperature of about 3000K (that is, a light that appears yellowish when compared to a balanced light. A *xenon lamp* gives off light of the spectral power distribution shown in Fig. 1.11. It reasonably resembles that of daylight at 6500K except that it has more UV radiation (see Fig. 1.7). On the other hand, light from the tungsten lamp at 3200K (Fig. 1.9) has hardly any UV radiation.

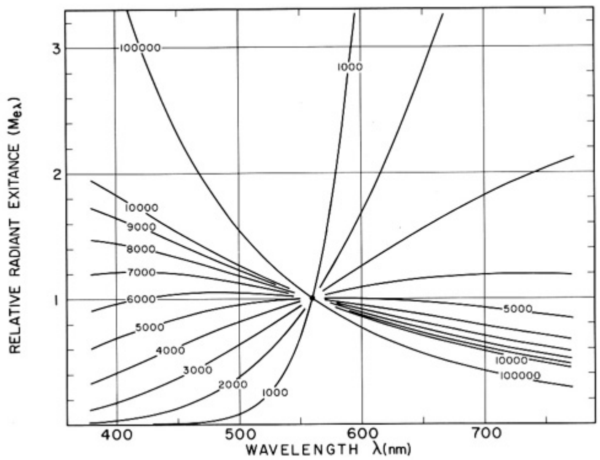


Fig. 1.10. Spectral power distributions in the visible range of a blackbody at 11 different Kelvin temperatures. *Courtesy of John Wiley & Sons Inc. (Wyszecki, G. and W. S. Stiles, Color Science, 1982). Used with permission.*

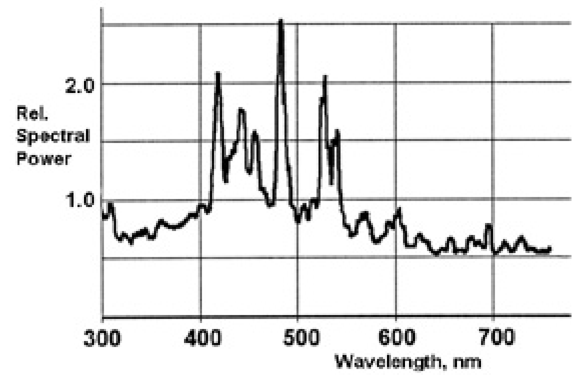


Fig. 1.11. The spectral power distribution of a xenon lamp.

2.6 When excited, some vaporized metals, such as mercury, give off light at sharp peaks. Figure 1.12 shows the spectral power distribution of a mercury vapor lamp. The mercury is converted to the vapor form by electrical current. It emits sharp peaks in the short wavelength region and even larger peaks in the middle wavelength region (500-600 nm). There is also a strong peak in the ultraviolet region near 250 nm, not shown in the graph.

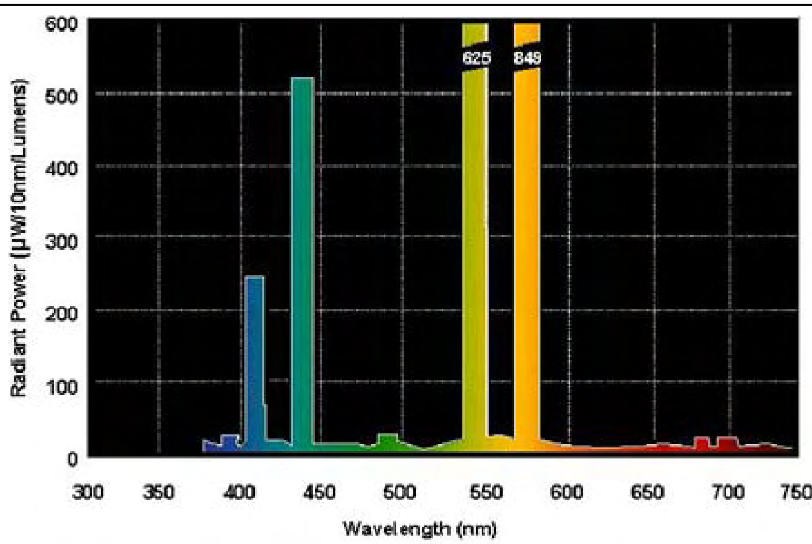


Fig. 1.12. The absolute spectral power distribution of the light of a mercury vapor lamp, showing 4 strong peaks. In addition, there is a high peak in the UV region near 250 nm. *Courtesy of General Electric Corp. Used with permission.*

Sodium vapor light is obtained from excited atoms of sodium metal. Sodium light is nearly monochromatic, with a yellowish appearance. Because they are inexpensive, sodium lamps are often used for parking lot or street lighting. Materials of known color in daylight look very different under this type of light.

Mercury and sodium vapor lamps are relatively inexpensive to operate because much or all of the lamps' output is in the visible range. Consider the curve of a tungsten lamp of 3000K (Fig. 1.9) and note that the curve rises far into the infrared region (longer than 700 nm). This means that most of its energy is given off as heat. This makes tungsten incandescent light very inefficient and expensive for large area lighting.

2.7 Some chemical elements and their compounds, as well as some organic chemicals, have the properties of *phosphorescence* or *fluorescence*.

The chemical element phosphor and some of its compounds, such as calcium halophosphate, have the property of absorbing UV and short wavelength visible radiation and emitting it at longer wavelengths with a relatively smooth distribution.

Fluorescent compounds, such as calcium silicate, also absorb short wavelengths and emit long ones. However, the process is subtly different from that of phosphorescence (Fig. 1.13).

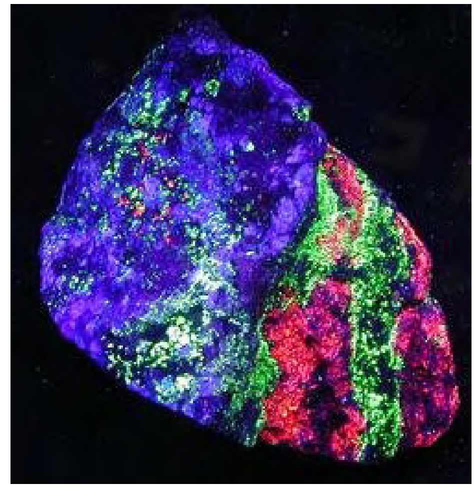


Fig. 1.13. A rock illuminated with UV radiation displays fluorescence. The appearance in daylight is that of a regular rock, nearly colorless. *Courtesy of Bruce H. Fine. Used with permission.*

Fluorescent light tubes use these properties to broaden and smooth out some of the undesirable sharp peaks of inexpensive mercury vapor light. The interior surface of the tube is coated with phosphorescent and fluorescent compounds. They absorb ultraviolet radiation and other short-wave light from the mercury vapor in the tube and, in proper mixtures, give off light of various broad spectral power distributions and blackbody temperatures. Fig. 1.14 shows spectral power distribution curves of a warm white fluorescent lamp and a cool white fluorescent lamp with correlated color temperatures of 3500K and 5500K, respectively.

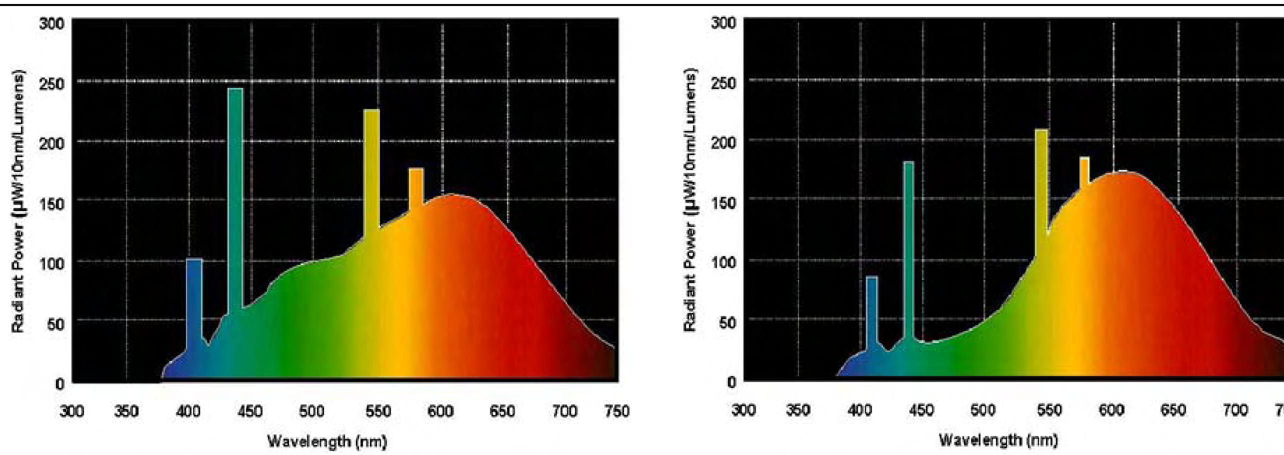


Fig. 1.14. The absolute spectral power distribution of cool white fluorescent light tubes (left) and warm white fluorescent light tubes (right). *Courtesy of General Electric Corp. Used with permission.*

2.8 Fluorescent lamps continue to be optimized to provide more accurate daylight simulation at lower cost. *Tri-band (fluorescent) lamps* attempt to achieve this balance by giving off much of their energy in three distinct bands (Fig. 1.15). The reasons for this and their advantages and disadvantages will be discussed in Chapter 12.

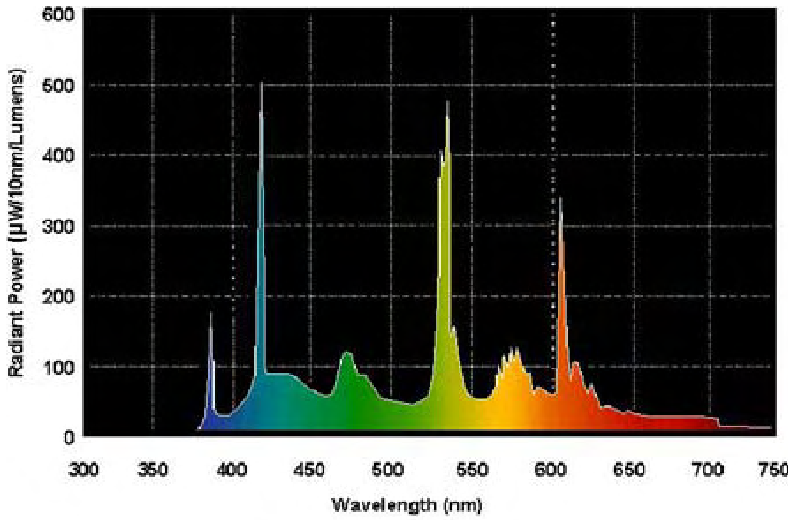


Fig. 1.15. The absolute spectral power distribution of a tri-band fluorescent light tube. *Courtesy of General Electric Corp. Used with permission.*

3 Light and Vision

3.1 Light is very important for most life on earth. (There are some living organisms that do not require light.) All living matter on the earth's surface and in lakes and oceans down to a certain depth uses light to initiate and help power internal chemical processes and possibly as a source of information about the surrounding world (Fig. 1.16).

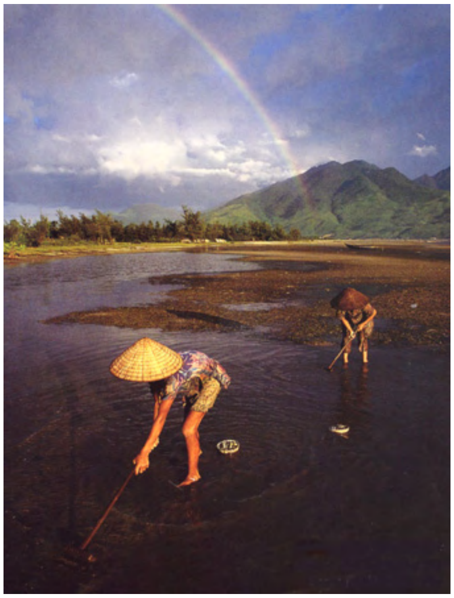


Fig. 1.16. Light in support of life.

3.2 Most living matter can sense light in some manner. Plants can sense light and orient themselves accordingly during growth. Animals have various sensory organs for light—eyes in most cases. Higher animals and humans have two eyes. Many simple animals have multiple eyes. Some spiders and ocean-dwelling animals have four or more. (Fig. 1.17)

Fig. 1.17. A jumping spider with multiple eyes.

3.3 For humans, vision is the most important sense. Higher animals and humans have five senses. In different species, these senses are developed to different degrees, presumably based on a species' need in its living environment. In the history of a species, sensory abilities can be strengthened or weakened, depending on changes in the environment in which they live. Think of bats that do not use light for their "vision" experiences, or dolphins that supplement theirs with sonar information. Humans have considerably better vision than dogs, but our sense of smell is much inferior. Some insects (e.g., bees) and birds can see in the near ultraviolet range (300-400 nm) where we are blind (Fig. 1.18).

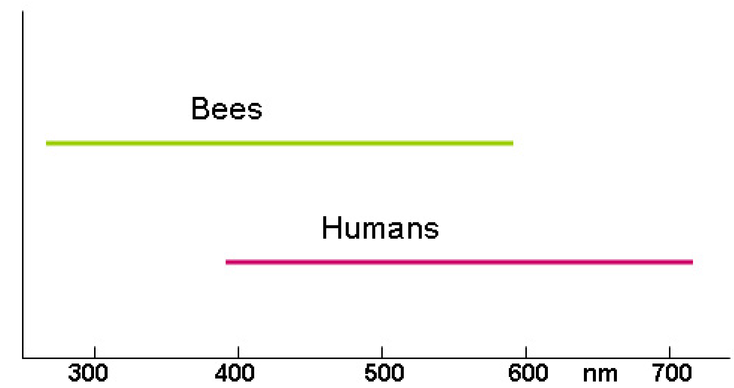


Fig. 1.18. A comparison of approximate spectral regions of visual sensitivity for bees and humans.

3.4 Electromagnetic radiation in the range of 300-800 nm is uniformly used for vision (except by bats). There is a "window" in the earth's atmosphere that lets these wavelengths reach the earth's surface and some distance into the water. Much of the radiation in the infrared and ultraviolet regions is absorbed by the atmosphere (Fig. 1.19). At wavelengths even shorter than ultraviolet, the energy content of the radiation can cause damage to living cells. (Think of the damage ultraviolet can already cause to skin in summer.) At considerably longer wavelengths, the radiation does not provide the very detailed information we can get from visible light because of a lack of resolution and image detail.

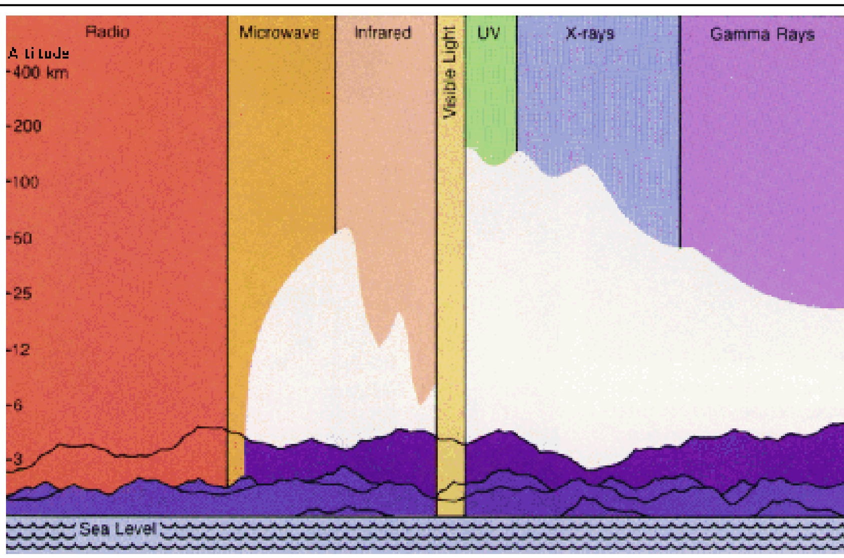


Fig. 1.19. Electromagnetic radiation with wavelengths used for radio communication and visible light reach the earth's surface while microwave, infrared, UV, and X-ray radiation coming from the sun is weakened below the altitude indicated by the upper edge of the white areas. *Courtesy of NASA's Goddard Space Flight Center (Imagine the Universe).*

3.5 For humans, vision is one of the most important senses. This can be concluded from the fact that our brains devote more resources (active brain cells) to vision than to any of the other four senses. Vision usually allows us to move safely around a complex world, recognize and react to situations we have seen before, and perform many other actions.

3.6 Vision is the general process of acquiring information from the world through photons streaming into the eyes. The vision process has four main steps (Fig. 1.20):

a) capturing a small stream of photons with our eyes;

b) converting the energy of the photons into *electrochemical signals* that proceed from the eyes to the brain;

c) interpreting the signals as representing information about the world in front of us; the interpretation is based on the knowledge about the world each of us has accumulated in the past;

d) if important or desirable, acting on the information, subconsciously or consciously. When fully awake, this process is a continuous one.

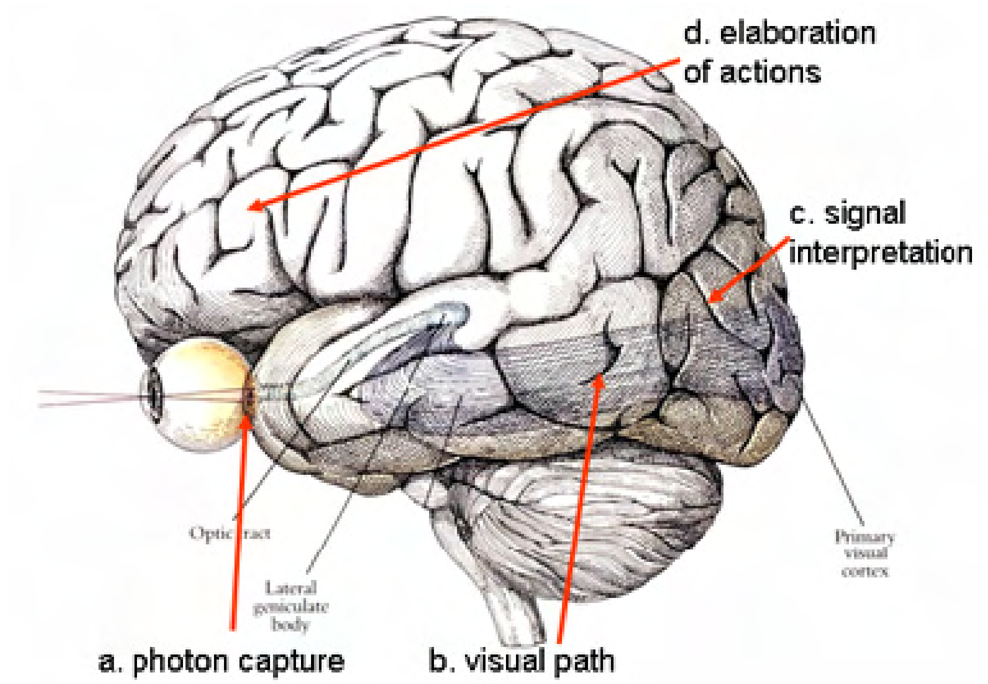


Fig. 1.20. Vision is a process for acquiring information from the world. *Courtesy of David Hubel (D. H. Hubel, Eye, Brain, and Vision, 1988.) Used with permission. Arrows added.*

3.7 We have two largely independent vision systems: *vision-for-action* and *vision-for-perception*. Both systems are fed by information coming from the eyes but are active in different regions of the brain. Vision-for-action operates mostly subconsciously. It provides information to the muscular systems so that we make sensible movements of body parts in walking in the world, grasping for things, hitting tennis balls coming at us, handing a full coffee cup to a friend, etc. We usually do not have time to consciously think about these activities without appearing impaired or klutzy, but the body, after some training, automatically performs them more or less flawlessly. Vision-for-perception is the vision we use to identify people or things, or to study new people or things that we see for the first time. We pay attention to them and store the information away more or less securely, depending on the importance of the new person or object. It is possible to be blind in either systems or both, with different outcomes (Fig. 1.21a and b).

Fig. 1.21a. Vision for action.

Fig. 1.21b. Vision for perception.

3.8 Visual perception is the name given to a particular activity of acquiring knowledge. Examples of visual perception at work are: being in a new city for the first time, reading a textbook, or comparing standard and batch samples of dyed textiles. Such activities require not only eyes, but a functioning brain that interprets the information received by the eyes. As a result of what the eyes capture, and based on past experiences stored in our brain, we interpret a given scene and act in a certain way. When we talk about vision in humans, we are usually referring to visual perception.

3.9 Veridical perception means truthful perception, perceiving what is really there. We usually assume that our vision is truthful, informing us about what is really there in the world. But is this really always so? When looking at Fig. 1.22 for the first time, it takes a second or two for it to become obvious that we are being fooled. The main clue is the fantastic subject matter. So-called visual illusions prove that our vision system can misinterpret information in many different ways (see Figs.1.23 and 1.24 for examples). Keep in mind that the brain has to interpret the world from the very limited information that enters the eyes. Our perception is veridical only to a limited extent and it is often not evident if a given perception is truthful or not.

Fig. 1.22. Sidewalk artist Kurt Wenner depicts the Chariot of Apollo leaping from a two-dimensional surface. *Courtesy of Kurt Wenner (www.kurtwenner.com). Chariot of Apollo, 1998, USA. Artwork and photo by Kurt Wenner. Used with permission.*

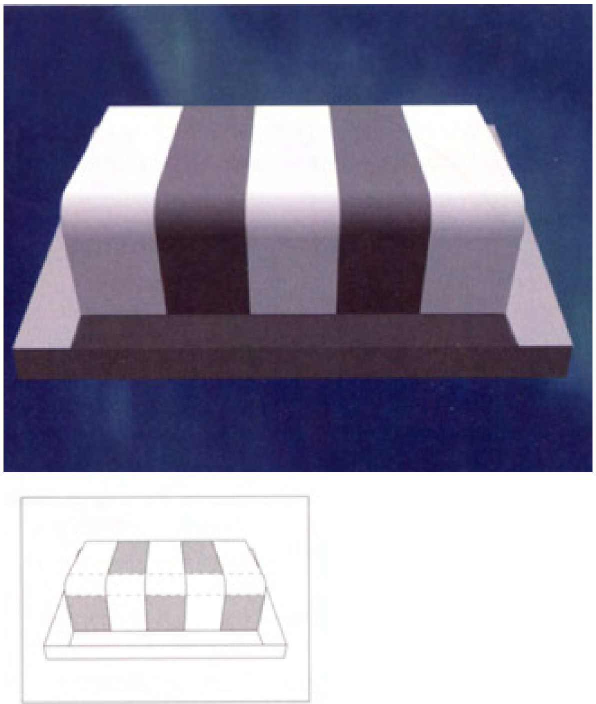


Fig. 1.24. Purves and Lotto's lightness illusion. Of the top and side fields indicated in the small sketch, which ones are darker in the larger image? In reality the measured lightness of both field types is identical. *Courtesy of Sinauer Associates Inc. (Purves, D. and R. B. Lotto, Why We See What We Do, 2003.) Illustration by S. Mark Williams. Used with permission.*

Fig. 1.23 Shepard's tabletop illusion. Which table is longer? Use a ruler to compare the length and width dimensions of both tables.

3.10 Is the world we perceive reconstructed from the real world or constructed in our mind? This is a question that we cannot answer with certainty. We experience the world only through our senses. We do not have independent information about it (what we read from instruments comes to us through the senses). The fact that we can operate successfully in the world indicates that there is a degree of truthfulness in our sensory experiences. But a considerable amount is based on best guesses of our brain/mind. Illusions show that the brain/mind is interpreting information coming through the eyes in the best way that it knows how, based on its capabilities, the visual experiences of the species, and the visual experiences of the individual.

Two observers can reasonably disagree about what they see (often in regard to color) because of subtle or not-so-subtle differences in their visual apparatus or visual experiences. There is no objective way to determine that one is right and the other wrong.

4 Light as an Illuminator

4.1 Light illuminates the world around us. Without light, we are blind. We experience electromagnetic radiation that reaches our eyes directly, or more often, indirectly, as light. Looking into the sky, we experience light, even when looking away from the sun. Photons have been *scattered* by molecules and particles of many different kinds in the atmosphere and come to the eyes from many different directions, not just the direction of the sun. The sky appears blue in color because it has mainly shorter wavelength photons (the light has a high correlated color temperature) (Fig. 1.25). Looking directly into the sun is dangerous because the intensity is such that it will quickly damage the light-sensitive cells in the eyes.

Fig. 1.25. Blue skies are the result of the scattering of short wavelength light.

4.2 Light is *reflected* by objects, providing information about the object. Most of the photons coming to the eyes are reflected from materials: In case of daylight, they come from the sun, bounce off some object, and enter an observer's eyes. In this manner they provide information about the surfaces of objects to our brain/mind (Fig. 1.26). Some information is interpreted as contour—where one object ends and another begins. Other information is interpreted as surface composition. Materials can reflect all photons of all wavelengths that strike them (white objects), some photons of all wavelengths (gray or black objects), or more of some wavelengths and less of others (colored objects).

Fig. 1.26. A living room scene generated by our brain/mind from the qualities and intensities of light reaching the eyes from the image.

4.3 Illumination can come from a *point source*, it can be a *diffuse illuminant*, or it can be a mixture of both.

In case of direct sunlight or direct light from point source lamps (e.g., a light bulb), objects form sharp shadows (Fig. 1.27). Colored objects appear to have strong colors and glossy objects show their *glossiness*.

Diffused light creates only weak and diffuse shadows. Diffuse light may come from sunlight on an overcast day or from bulbs or light tubes behind a *diffuser* (Fig. 1.28). In the latter case, the appearance of the objects is much more uniform in terms of color and structure: the colors are more subdued and all surfaces look matte (see also Chapter 2). For visual evaluations, diffused light sources are used. In nature, as well as in stores, the illumination is often a mixture of direct and diffuse light.

Fig. 1.27. Glass marbles viewed in point source light, showing distinct shadows, glossy appearance, and the bright image of the source in the form of small points on each marble. *Courtesy of John Wiley & Sons Inc. (Evans, R. M., An Introduction to Color, 1948). Used with permission.*

Fig. 1.28. Glass marbles viewed in diffuse light, with diffuse shadows and dull appearance *Courtesy of John Wiley & Sons Inc. (Evans, R. M., An Introduction to Color, 1948). Used with permission.*

5 Light Sources and Illuminants

5.1 Different terms are used for actual light sources and for sets of numbers in a table that describe lights in form of numbers, such as spectral power distributions (Fig. 1.29). The term *light source* refers to a real, physical light.

5.2 The word *illuminant* refers to a table of numbers that express the relative spectral power distribution of a specific light. A number of illuminants have been standardized by the International Commission on Illumination (Commission Internationale de l'Éclairage, CIE). Among the illuminants it has standardized are illuminants A, B, C, D_{65} and several fluorescent lights (Fig. 1.30). CIE illuminant A refers to tungsten lamp light at the correlated color temperature of 2856K. Illuminants B and C are no longer in practical use and refer to direct sunlight and an average daylight. Illuminant C has been replaced with CIE illuminant D_{65}. This refers to a light source with the spectral power distribution of daylight at a correlated color temperature of 6500K (Fig. 1.29). The CIE has issued a formula with which standard daylight illuminants at other correlated color temperatures, for example 5500K or 7500K, can be calculated. There will be more discussion of illuminants in Chapter 6.

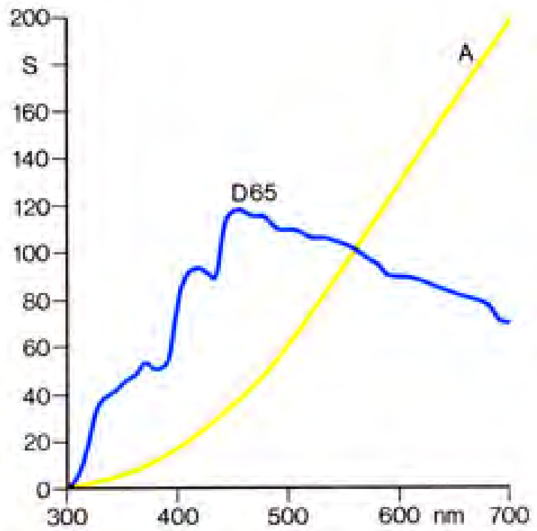


Fig. 1.29. Spectral power distribution graphs of CIE standard illuminants A (tungsten lamp) and daylight D6500 (D_{65}).
Courtesy of Bayer Business Services (Brockes, A., D. Strocka, and A. Berger-Schunn, Color Measurement in the Textile Industry, 1989). Used with permission.

λ (nm)	A $S(\lambda)$	B $S(\lambda)$	C $S(\lambda)$	D_{65} $S(\lambda)$
575	110.80	101.90	100.15	96.1
580	114.44	101.00	97.80	95.8
585	118.08	100.07	95.43	92.2
590	121.73	99.20	93.20	88.7
595	125.39	98.44	91.22	89.3
600	129.04	98.00	89.70	90.0
605	132.70	98.08	88.83	89.8
610	136.35	98.50	88.40	89.6
615	139.99	99.06	88.19	88.6
620	143.62	99.70	88.10	87.7
625	147.24	100.36	88.06	85.5
630	150.84	101.00	88.00	83.3
635	154.42	101.56	87.86	83.5
640	157.98	102.20	87.80	83.7
645	161.52	103.05	87.99	81.9

Fig. 1.30. An excerpt from a numerical table specifying the relative spectral power of CIE standard illuminants A, B, C, and D_{65} at every five nanometers.
Courtesy of John Wiley & Sons Inc. (Wyszecki, G. and W. S. Stiles, Color Science, 1982). Used with permission.

5.3 There are no artificial light sources that are an exact match for the spectral power distribution of daylight. The CIE has issued recommendations for complex filters, solutions of colored salts in water, which can be used in front of tungsten lamps to obtain a good approximation, but these filters are too cumbersome in practice. In light booths, daylight is approximated by glass or plastic filters in front of tungsten lamps (known as *filtered tungsten* lights), or by fluorescent light tubes with the same correlated color temperature (for example 6500K, Fig. 1.31). These sources and the related illuminants have noticeably different spectral power distributions compared to that of real daylight. While fluorescent daylight simulators have a UV component similar to that of daylight (see Fig. 1.31), filtered tungsten simulators require a separate source of UV radiation for good approximation of daylight. As mentioned above, good approximation of the UV content of real daylight is important when viewing optically-brightened white textiles or materials colored with fluorescent yellow or orange colorants. Real daylight is usually not used for critical color evaluation work because of the constant changes in its composition.

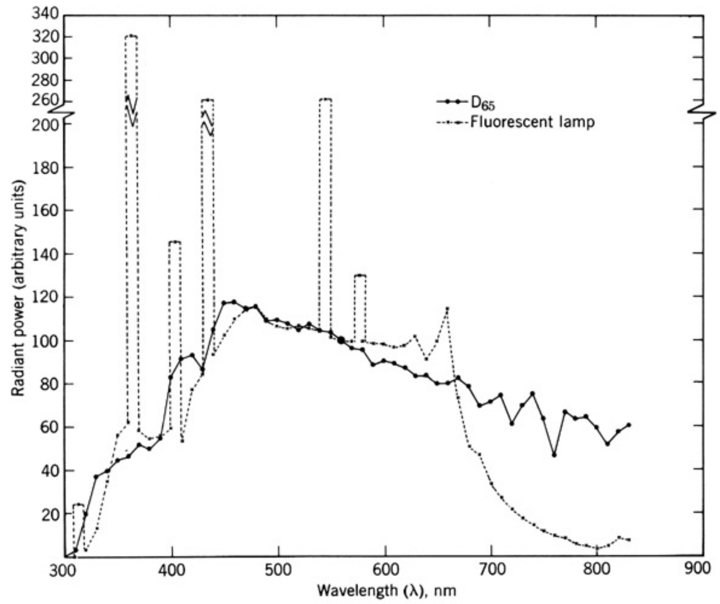


Fig. 1.31. A comparison of the spectral power distributions of CIE daylight D_{65} and a fluorescent daylight simulator lamp. *Courtesy of John Wiley & Sons Inc. (Judd, D. B. and G. Wyszecki, Color in Business, Science and Industry, 1975). Used with permission.*

6 Summary

In this chapter the nature of light is discussed as well as its role as a supplier of energy and information about the world for which animals and humans have the ability to sense light. For scientific and technical work, a number of light sources and corresponding numerical tables of illuminants have been standardized. In addition to color, light communicates several other aspects of the visual scene, for example form and movement.

Chapter 2 COLOR STIMULI: LIGHTS AND OBJECTS

1 Color Stimuli

1.1 Lights stimulate our eyes, causing our minds to experience colors. Such lights are called *color stimuli*.

1.2 Opinions on the status of white, black, and gray as colors have differed in the past. However, there is no strong reason to exclude them from being categorized as colors, They are special colors, known as *achromatic* (lacking hue). By including white, black, and gray as colors, any kind of visual experience can be regarded as having color. The three terms white, black, and gray are properly applied only to objects. Lights cannot have these appearances. However, the term “white” light is often used to indicate lights in which a white object appears white and not colored (see also section 2.3 below).

1.3 Color stimuli can come directly from light sources or indirectly from objects. In normal, awake conditions, all color experiences are caused by streams of photons—light. Light is the medium that transmits information about itself, or about the objects from which it was reflected, to the brain/mind. We experience this information, in a qualitative way, as colors (Fig. 2.1). Information about forms and motion of objects is also transmitted by light.

Fig. 2.1. Light reflected from objects provides information to our brain resulting in different experiences of form and color.

2 Direct Lights

2.1 Light that travels directly from a source to the eyes transmits information about itself. The transmitted information has to do with the spectral composition of the light and how intense it is (its radiant power). In both cases, the normal human visual apparatus can decode the information only approximately and not in its full detail. Humans are not highly sophisticated measuring instruments of spectral variation or radiant power. The reasons will be discussed in more detail in Chapter 5.

2.2. Light provides information about its spectral composition. The human visual apparatus decodes this information resulting in the hue aspect of a color experience. Hue refers to that aspect of color that we describe by hue names, such as red, green, yellow, and blue. Fig. 2.2 is a reproduction of the spectral colors. You experience the stimuli from this figure that enter your eyes from the monitor in your own personal way. For some of the hues we have commonly accepted names, such as those just mentioned. In the 17th century, the famous English physicist and mathematician Isaac Newton identified seven hues in the *spectrum* (beginning on the long wavelength end): red, orange, yellow, green, blue, indigo, and purple (Fig. 2.3). Some people may distinguish more or less separate hues in the spectrum. Different individuals apply particular hue names to different ranges of wavelengths. The ranges may be larger or smaller, or slightly shifted from one individual to another.

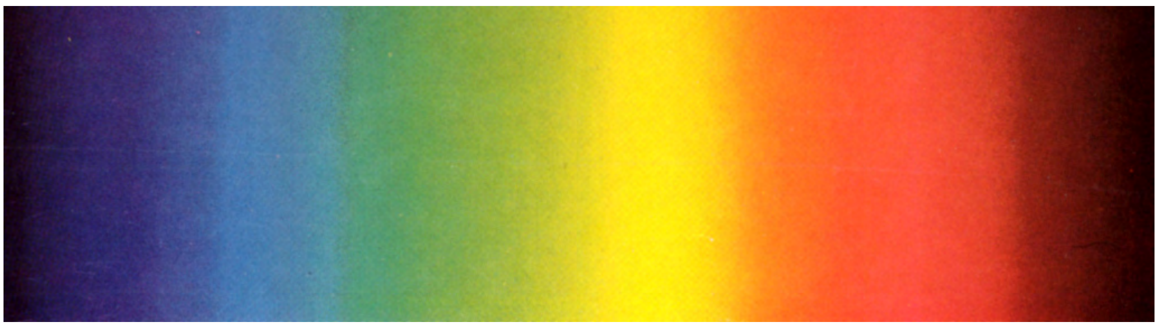


Fig. 2.2. The visible spectrum from approximately 400 nm on the left, to approximately 700 nm on the right.

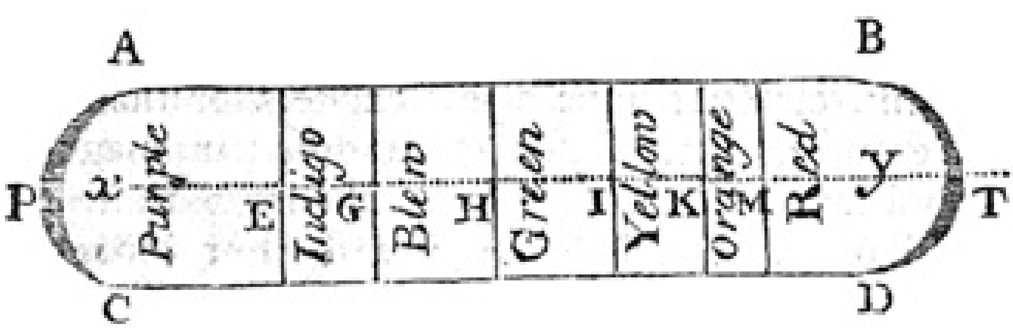


Fig. 2.3. Newton's sketch of the spectrum with the hue regions identified by name.
Newton, I., Opticks, 1704.

2.3 Lights that have roughly equal spectral power across the spectrum (400 – 700 nm) are seen as colorless if viewed directly, and as white if reflected from a white surface. Such lights are often, if inaccurately, termed “white” light. Daylight is an example of “white” light (see Fig. 2.4).

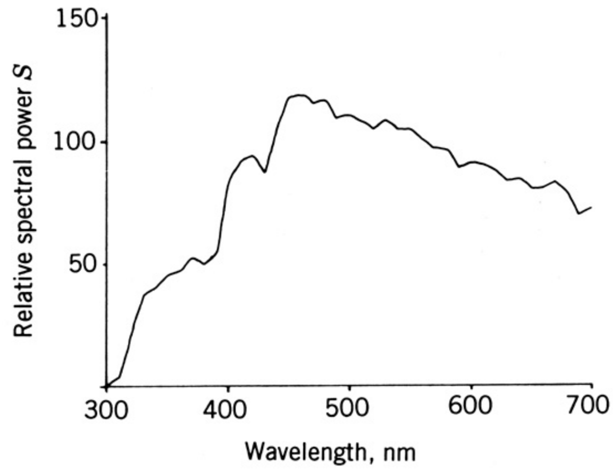


Fig. 2.4. The spectral power distribution curve of daylight at 6500K.

2.4 Light with varying power across the spectrum is seen as colored (having hue). The color depends in a complex manner on the spectral power distribution (see Chapter 5 for more details). Fig. 2.5 illustrates three idealized spectral power distributions and corresponding hue names.

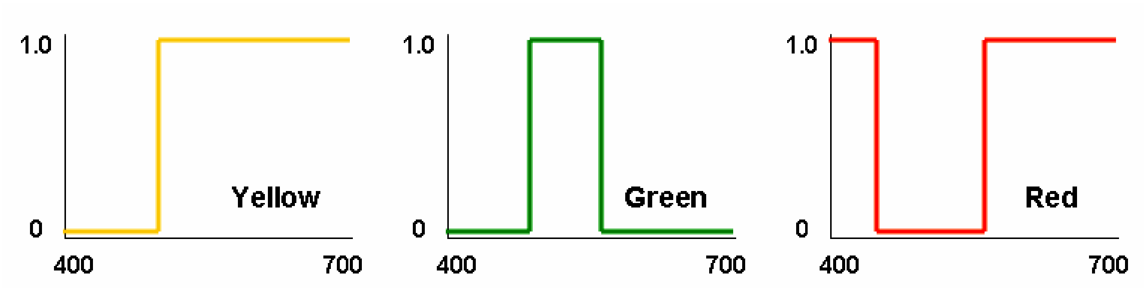


Fig. 2.5. Spectral power distributions of three lights with relatively broad spectral power resulting in different color perceptions.

3 Indirect Lights

3.1 Indirect lights are lights that have interacted in one of several ways with objects. Nassau (1983) has identified 15 different causes of colors (generation of photons and their interactions with materials that result in color stimuli).
They are:

1. Incandescence
2. Gas excitations
3. Vibrations and rotations
4. Transition metal compounds
5. Transition metal impurities
6. Organic compounds
7. Charge transfer
8. Metals and alloys
9. Pure semiconductors
10. Doped semiconductors
11. Color centers
12. Dispersion (refraction)
13. Scattering
14. Interference
15. Diffraction

This list is given for general information only. The first two subjects in the list have already been briefly discussed in Chapter 1. Some others will be discussed in some detail in Chapter 3 and a few are too technically complex for discussion in this text. Here, only dispersion and scattering will be discussed.

3.2 *Dispersion*, or refraction, refers to a process in which photons change the direction of their path when moving from one medium to another. The degree of change (the angle of refraction) depends on a property of the two media known as the index of refraction or the *refractive index*. By definition, the index of refraction of a *vacuum* (a space with nothing in it) is 1. It is close to 1 for air. For water, it is approximately 1.3 and for glass, between 1.5 and 1.9. The higher the value, the larger the change in direction of the light beam when entering from or exiting to air. One way to observe the refraction effect is to look at an object partly immersed in water (Fig. 2.6). There is a seeming discontinuity of the parts in and out of the water. This is due to light refraction at the interface of air and water.

Fig. 2.6. The apparent bending and double image of the pencil in the water is due to refraction effects.

3.3 A narrow beam of light with wavelengths from 400 to 700 nm is refracted twice as it enters and leaves a *glass prism*. Such double refraction sorts the photons of the beam according to their wavelength (Fig. 2.7). The result is the appearance of the hues of the visible spectrum as shown in Fig. 2.2. In a general way, wavelengths are related to perceived hues. That individual hue experiences from specific stimuli vary quite widely will be discussed in some detail in Chapter 5. The dispersion/refraction effect has been used in the past (less often today) by "color measuring" instruments to obtain information at specific wavelengths (see Chapter 3). Today, most instruments split the light beam into its spectral components by a process called diffraction (see "*diffraction grating*" in the glossary).

Fig. 2.7. Generation of the spectrum in a prism by dispersion of the "white" light beam entering from right. *Adam Hart-Davis/DHD Multimedia Gallery.*

3.4 The dispersion effect depends on the angle at which the light interacts with the medium. When a light beam strikes *transparent* glass, the beam is transmitted without change through the medium. If there are absorbing molecules in the medium (as in colored glass or plastic), some of the photons will be absorbed; the remaining photons are transmitted. Filters use this phenomenon to modify the intensity and spectral quality of light beams (Fig. 2.8).

3.5 Light meeting a *translucent* material (one having a degree of transparency) or an *opaque* material (having no transparency) is partly or fully scattered.

Photons may be absorbed at the surface or in the interior of a material or they may be scattered. In case of *absorption*, the energy of the photons is transferred to the absorbing molecule. Some of this energy is then emitted by the material at a higher wavelength (with lower energy), usually in the non-visible infrared region of electromagnetic radiation. Different kinds of absorbing molecules absorb light at different wavelengths. As a result the materials containing them appear to have different colors. Chemical substances that have specific absorption properties in the visible range of electromagnetic radiation are called *colorants* (*dyes* and *pigments*, see Chapter 3).

Fig. 2.8. Examples of filters that absorb certain regions of wavelengths in the spectral power distribution of "white" light.

At those wavelengths where the photons are not absorbed, they are scattered, that is, reflected back. If the surface is not smooth, they are scattered in many different directions (Figs. 2.9a and b).

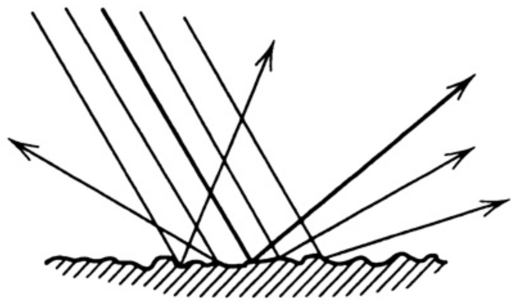


Fig. 2.9a. A light beam striking a scattering surface, with individual photons scattered in different directions.

Fig. 2.9b. Light scattering effect in a translucent owl made from colorless glass containing metallic particles that scatter light.

Reflection is a special case of scattering. If the surface is smooth (e.g., polished metal, a mirror) the angle of reflection (the angle at which the light leaves the smooth surface) is equal to the angle of incidence of the light beam (Fig. 2.10) and the photons are said to be reflected. Textile surfaces are not smooth, so the effect on photons is almost entirely one of scattering.

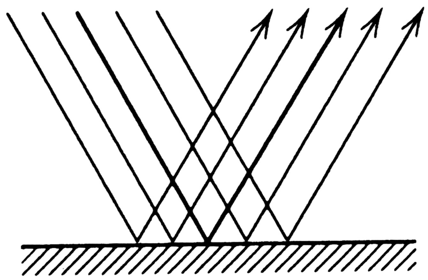


Fig. 2.10.Schematic sketch of light beam striking a flat reflecting surface with photons reflected at the same angle they strike the surface.

3.6 Most light sources are not perfect point sources. Often, there is a mixture of direct and diffuse light arriving at an object. *Dullness* is the result of a highly scattering surface or highly diffused light. Directly reflected light is termed *gloss* (see Chapter 3). Glossiness is most intense when direct light reaches a perfectly smooth surface (see Figs. 1.27 and 1.28). Glossy textile fabrics are made from:

- fibers with naturally smooth surfaces, such as silk;
- fibers with surfaces smoothed by chemical treatment, such as *mercerized cotton*;
- man-made fibers with smooth surfaces, such as nylon or polyester.

3.7 The amount of light absorbed at certain wavelengths and the amount scattered/reflected imparts information about an object to the observer's eyes and brain/mind.

At the receiving end, there must be a mechanism that can distinguish the number of photons in different wavelength regions, either accurately or approximately, and exploit this information in an appropriate manner. In case of a reflectance spectrophotometer, the result is a reflectance curve or a set of numbers. For a human observer, it is an experience of form and color. The color experience, together with form and/or motion experiences and stored information of past experiences, is used to infer the nature (apple or colored leaf?) or state (ripe or not?) of given objects in the observer's field of view. This is particularly useful when the object is located at a distance. When we have it within reach we can use additional sensory experiences (touch, smell, or taste) to come to a conclusion.

4 Summary

This chapter discussed color stimuli in the form of lights viewed directly from a source or after scattering or reflection into the observer's eyes. Two of many causes of color stimuli, dispersion or refraction and scattering or reflection, are explained, as is the appearance of glossiness and dullness.

Chapter 3 DYES, PIGMENTS, AND FIBERS

1 Dyes and Pigments

1.1 Dyes and pigments are materials that are used to impart color to the surface and/or interior of other materials. They are jointly referred to as colorants. Colorants are chemical substances with specific spectral *absorption* properties for light. As a result, light striking the surface of materials that contain colorants is partly absorbed and partly scattered or reflected and, in this reduced form, results in color experiences for observers.

1.2 Colorants are *broadband absorbers*. Colorants absorb broad bands of light. Usually, a portion of light is absorbed at all wavelengths of light and different colorants differ in the amount they absorb at each wavelength (Figs. 3.1 and 3.2).

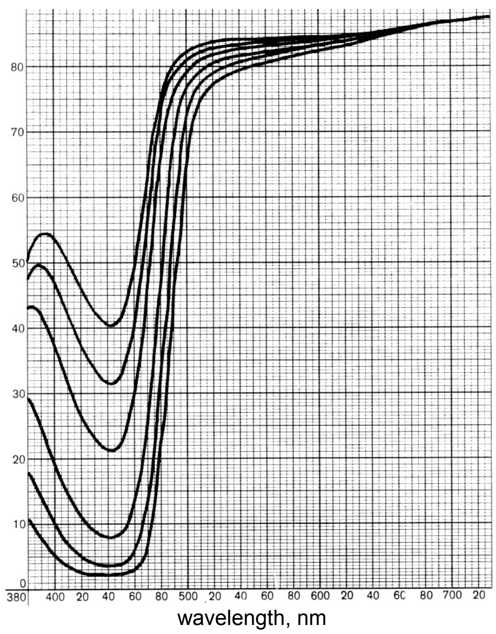


Fig. 3.1. Reflectance curves of a bright yellow dye dyed in several concentrations. The relative amount of light that is absorbed is that between the curves and the 100% line.

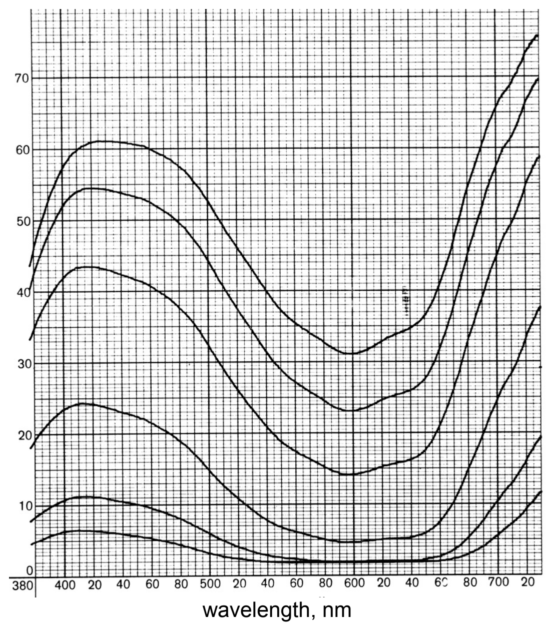


Fig. 3.2. Reflectance curves of a dull navy blue dye dyed in several concentrations.

1.3 The curves in Figs. 3.1 and 3.2 are so-called *reflectance curves*. Reflectance curves indicate the amount of light that is being scattered or reflected from a given object. Reflectance is expressed as a factor, from 0.0 to 1.0, or as a percentage, from 0% to 100%, as In Figs. 3.1 and 3.2. As the curves in these figures indicate, the reflectance depends on the concentration of the colorant on the fiber; the higher the concentration, the lower the reflectance.

1.4 The absorption of light is the result of the specific chemical structure of the colorant. Certain combinations of chemical elements in molecules of colorants are known to result in light absorption (Fig. 3.3). These combinations have been discovered by chemists mostly through trial and error over the past 150 years.

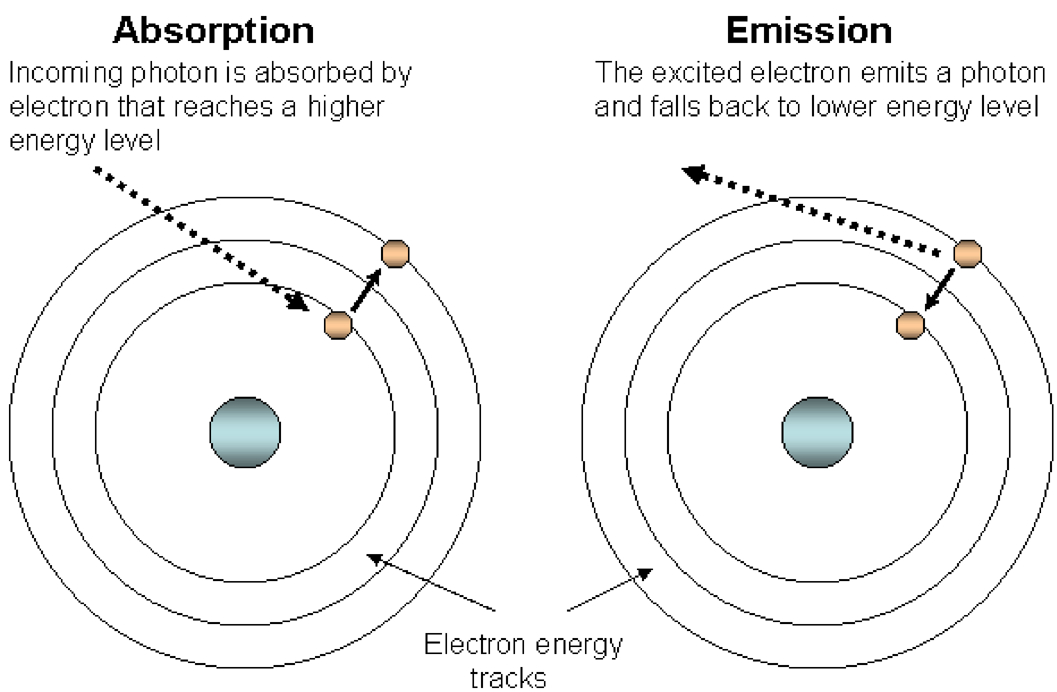


Fig. 3.3. A simplified, schematic representation of the absorption and emission processes in an atom. Electrons circling the central core of the atom at different levels of energy absorb incoming photons (left) and are transported up to a higher energy level where they are in a state of excitation. They then emit a photon of lower energy content (right) and fall back again to a lower energy track and loose their excited state.

1.5 Light absorption is not the only important property of colorants. To be practical, colorants must also have good to excellent *fastness properties* of various kinds, have low *toxicity*, and be inexpensive to produce and apply. Colorants applied in combinations should not have negative effects on each other.

Before describing dyes and pigments further it is useful to have a brief description of fibers.

2 Fibers

2.1 Fibers are natural or man-made products consisting of long, slender, elongated, hair-like assemblies of *molecules*. Natural fibers are produced by either plants (such as cotton, linen, or sisal) or animals (hair of sheep and other animals or bodily extrusions of the silk worm).

2.2 *Man-made fibers* are made from natural *polymers,* such as cellulose, or entirely by organic synthesis, such as nylon, acrylic, polyester, or polypropylene.
Solutions of or molten polymeric materials are pushed through, or *extruded* from, spinning heads (Fig. 3.4) forming continuous fibers (*filaments*).

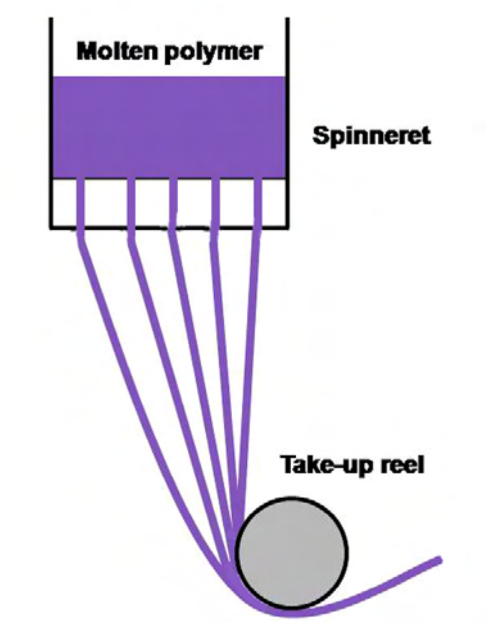


Fig. 3.4. A schematic sketch of the spinning process from a molten polymer (e.g., nylon or polyester).

2.3 Natural fibers are typically 1-3 inches long, except silk, which is a much longer, continuous fiber. Man-made fibers are either continuous or cut to lengths comparable to those of natural fibers.

2.4 Natural fibers have a wide range of diameters; man-made fibers can also be extruded in various diameters or *denier* (see glossary for definition). In textile fabrics, the fiber thickness influences the light-scattering properties of the fabric. *Microfibers* of various chemical compositions have diameters from 1/5 to 1/10 of that of natural fibers or the traditional versions of man-made fibers. They scatter light much more than regular fibers.

2.5 The surfaces of natural fibers are uneven (Fig. 3.5), except for those of silk. The surfaces of man-made synthetic fibers are smooth unless specially modified. Natural fibers scatter light much more than man-made synthetic fibers due to their irregular surfaces. They are translucent or opaque while synthetic fibers are translucent to

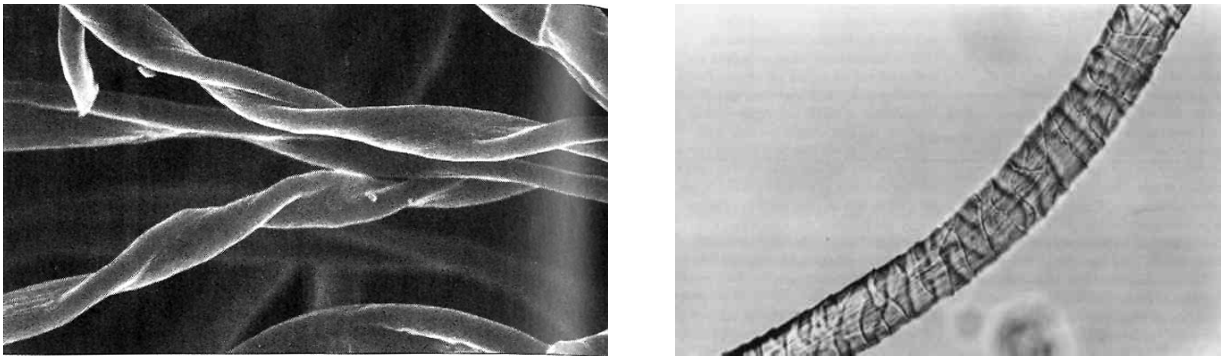


Fig. 3.5. Microscopic view of the twisted surface of cotton fibers (*left*) and microsopic view of the surface of a wool fiber showing the typical scales (*right*). *AATCC Technical Manual, Vol. 82, 2007.*

transparent. In synthetic fibers, transparency is often reduced by including white pigments in the extrusion mixture. The pigments scatter light within the fiber, resulting in an appearance of opacity. Wool generally has a dull appearance due to its light-scattering surface structure. The irregularity of the cotton surface also results in much scatter and a dull appearance. A glossy appearance is achieved on cotton by the *mercerization* process that straightens the fibers and makes their cross-sections more nearly circular. Synthetics such as nylon and polyester have a smooth surface resulting in glossiness. To reduce glossiness, synthetics are sometimes extruded through openings that have other than circular forms (Fig. 3.6).

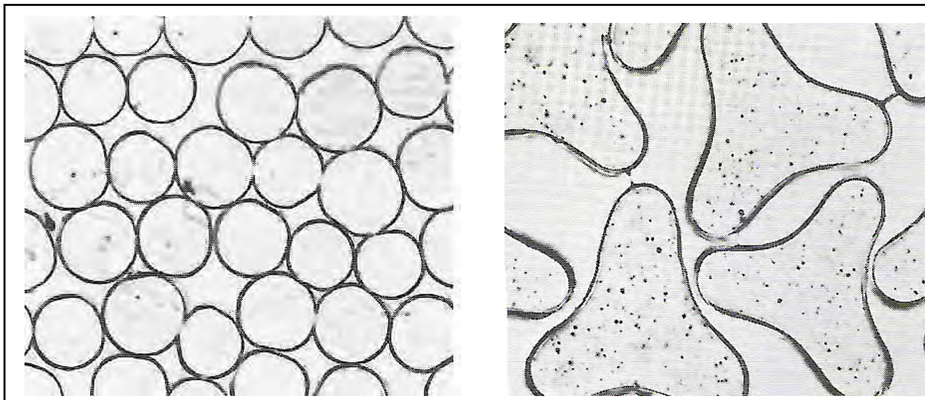


Fig. 3.6. Microscopic view of the circular cross-sections of one type of nylon fibers (*left*) and microscopic view of the non-circular cross-sections of another type of nylon fibers that increases scatter together with the included pigment particles (*right*). Most man-made fibers can be extruded with a variety of cross-sections. *AATCC Technical Manual, Vol. 82, 2007.*

2.6 In the *spinning* process, short fibers are arranged and twisted to form threads or *yarns*. Hand-spinning of fibers is a very old human skill (perhaps 8,000 years or older, Fig. 3.7). A mechanical spinning machine (the Spinning Jenny) was invented in England, in 1764, by James Hargreaves. Modern spinning machines have been refined to a high level of productivity (Fig. 3.8). The fibers are first combed, that is, aligned in the same direction to form a continuous loose fiber assembly called a roving (Fig. 3.8, bottom). The fibers are drawn out and twisted to form the yarn, which is wound on spools (Fig. 3.8, top).

Fig. 3.7. Hand-spinning from carded fiber to form of a continuous roving.

Fig. 3.8. Modern machine spinning of machine-carded cotton fiber roving. *Courtesy of North Carolina State University. Used with permission.*

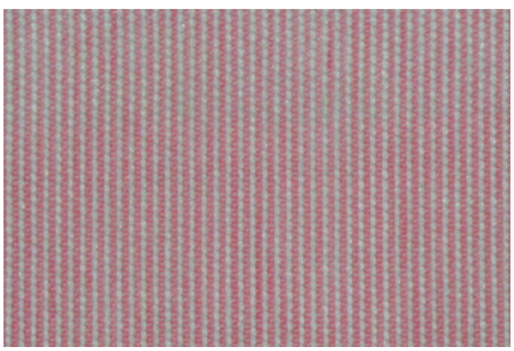
Fig. 3.9. Weaver Christine Homer manually pushes a bobbin of yarn (weft) through two separated sheets of yarns (warp). *Photograph by Robert Compton. Used with permission.*

2.7 Spun or filament yarn can be woven or knitted into fabrics. Manual *weaving*, the generation of fabric from threads, is probably as old as spinning (Fig. 3.9). It continued as manual operation until the invention of the power loom in England, in 1785, by Edmund Cartright. Weaving and *knitting* machines have also been highly refined (Figs. 3.10a and b).

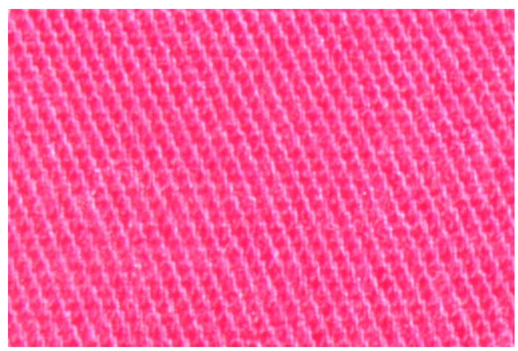
Fig. 3.10a. Modern weaving machine. *Courtesy of North Carolina State University. Used with permission.*

Fig. 3.10b. Modern knitting machine. *Courtesy of North Carolina State University. Used with permission.*

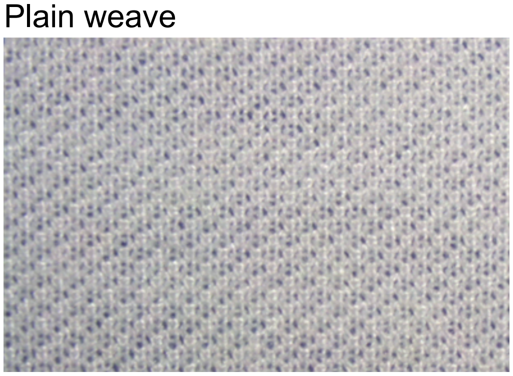
2.8 Different weaving and knitting techniques result in many different surface structures of fabrics (Fig. 3.11). The same dyed yarn has somewhat different reflectance properties and color appearance when woven or knitted in different ways.



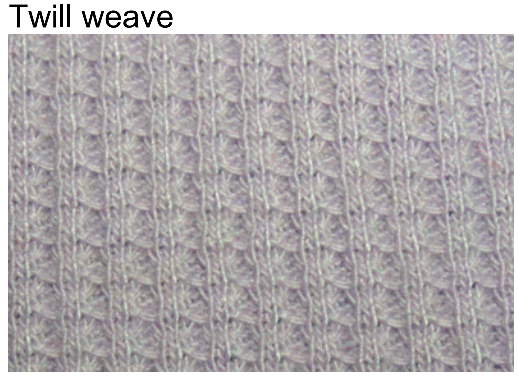
Plain weave



Twill weave



Pique knit



Thermal knit

Fig. 3.11. Different weaving and knitting structures.

2.9 The reflectance properties of textile materials can be modified with different technologies. The main technologies are: inclusion of colorants in man-made fibers before spinning, *dyeing*, and *printing*.

2.10 The chemical structures of different fiber types attract and bind dyes in different ways. Some fibers (e.g., wool and acrylic) have basic or acidic groups in their molecules. Dyes with the opposite properties are attracted to the groups (acid dyes are attracted to basic groups; basic dyes are attracted to acidic groups), forming organic "salts."

Natural plant fibers and the man-made cellulosic fiber rayon consist of cellulose molecules. They attract dyes by what is known as *intermolecular force*. Cellulosic fibers can also bond with certain dyes in direct chemical reaction, bonding one molecule to the other. These dyes are called reactive dyes. Unmodified polyester and polypropylene attract and hold dyes only by intermolecular force.

2.11 Man-made fibers of a given chemical type vary considerably in terms of the force with which they attract dyes (*affinity*) and the ease with which dyes travel within the fiber (*diffusion*).

3 Dyes

3.1 The distinction between dyes and pigments is not clear cut.
Dyes are colorants that are soluble either in the medium in which they are applied or in the substrate to which they are applied. Special steps may be required to achieve solubility. Pigments are colorants that have no or very little solubility in the application media or the substrate. A few chemical compounds can be used as either dyes or pigments.

3.2 All dyes are *organic* chemicals. Pigments can be organic or *inorganic*.
All organic chemicals contain the element carbon (C) in the molecule. Most biological products are organic chemicals.

3.3 Dyes are applied to textiles, paper, leather, food, and cosmetics, as well as used in other specialty fields such as inks, color photography, and copying. The textile industry is the largest user of dyes (Fig. 3.12).

Estimated world consumption of colorants

≈ 1.7 billion lbs/year	≈ 12 billion $/year
Textile colorants	≈ 55%
Paper, leather colorants	≈ 15%
Specialty colorants (FWA, food and cosmetics, etc.)	≈ 6%
Pigments	≈ 24%

Fig. 3.12. Estimated world consumption of colorants.

3.4 There are several classes of dyes used in the textile industry. These are not chemical classes but substrate- and application-related classes.

- Acid and premetalized dyes
- Mordant dyes
- Basic dyes
- Direct dyes
- Reactive or fiber-reactive dyes
- Sulfur dyes
- Vat dyes
- Naphthol dyes
- Disperse dyes

Within each class there are certain common chemical constituents, but the structure of the main molecular component of each dye, the so-called *chromophore* (color bearer), varies widely. The dye classes applicable to each fiber class are listed in Table 3.1.

TABLE 3.1.

Applicability of Dye Class vs. Fiber Class

Dye Class	Fiber Class							
	Cotton	Rayon	Acetate	Wool	Silk	Nylon	Acrylic	Polyester
Acid				X	X	X		
Premetalized				X	X	X		
Mordant				X				
Basic					(X)[a]		X	
Direct	X	X		(X)	(X)	(X)		
Reactive	X	X		(X)	(X)	(X)		
Sulfur	X	X						
Vat	X	X						
Naphthol	X	X						
Disperse (PES)			(X)			(X)	(X)	X
Disperse (Acet.)			X			(X)	(X)	(X)

[a](X) indicates possible, but rarely practiced, application with poor fastness properties.

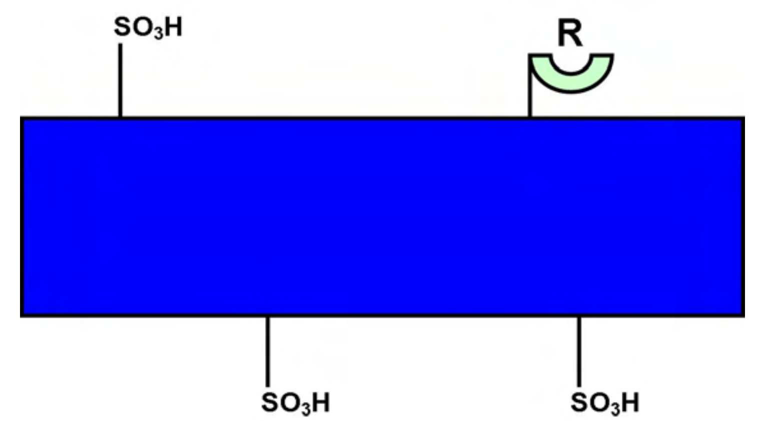


Fig. 3.13. Schematic of a reactive dye molecule consisting of the main chromophore body and auxochromes (blue), three sulfo groups (SO_3H) that provide water solubility and possibly ionic attachment, and a fiber-reactive group (R) that can chemically bond to cellulose and other molecules.

3.5 Schematically, dyes consist of a chromophore body and color-enhancing (*auxochrome*) groups. Solubilizing, and in one case, chemically-reactive groups may also be attached (Fig. 3.13). The auxochrome groups help shape the light absorption properties of the molecules. Solubilizing groups assure solubility of the molecules in water when desired and chemically reactive groups result in chemical attachment of the dye molecules to the fiber molecules.

3.6 Light absorption properties of dyes can be shaped to some degree by the chemist. Of all the colorants, dyes result in the most intense colors. Intenseness of color is indicated by steep reflectance curves (Fig. 3.1). In duller colors, the curves are flatter (Fig. 3.2), that is, light is absorbed more evenly at a wide range of wavelengths.

3.7 The most intense coloration is achieved with *fluorescent dyes*. As mentioned in Chapter 1, fluorescence refers to the property of inorganic or organic substances to absorb near ultraviolet (UV), or short wavelength visible radiation, and to emit most of the energy again at longer (50-100 nm) wavelengths in the visible range. The emitted light is added to the reflected light at these wavelengths and the total often exceeds the amount of incoming light at these wavelengths. Such dyeings appear to glow, especially when viewed against darker surrounds (Fig. 3.14). A well-known example is the fluorescent "hunter orange" fabric.

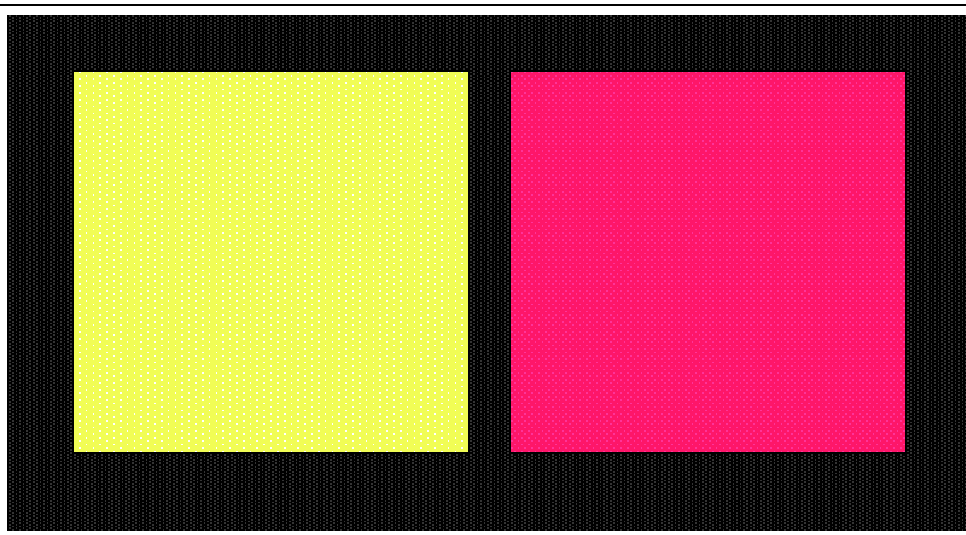


Fig.3.14. Two fluorescent dyes applied to a synthetic fiber fabric. Note that the true fluorescent effect cannot be demonstrated in a computer display.

3.8 *Fluorescent whitening agents* (FWAs) or "optical brighteners" are a special case of fluorescent colorants. By themselves, they have a colorless (or near-colorless) appearance. They absorb invisible near-UV radiation and emit it as short wavelength visible (blue) radiation (Fig. 3.15). By emitting bluish light, FWAs cover up any impurities in the fibers or other materials that make the fabric appear yellowish. The overall effect of the presence of an FWA is a whiter appearance of the fabric. This effect depends on the amount of UV light in the light source in which the material is viewed. The more UV, the more of it gets converted to short wavelength visible light and the whiter the appearance of the material.

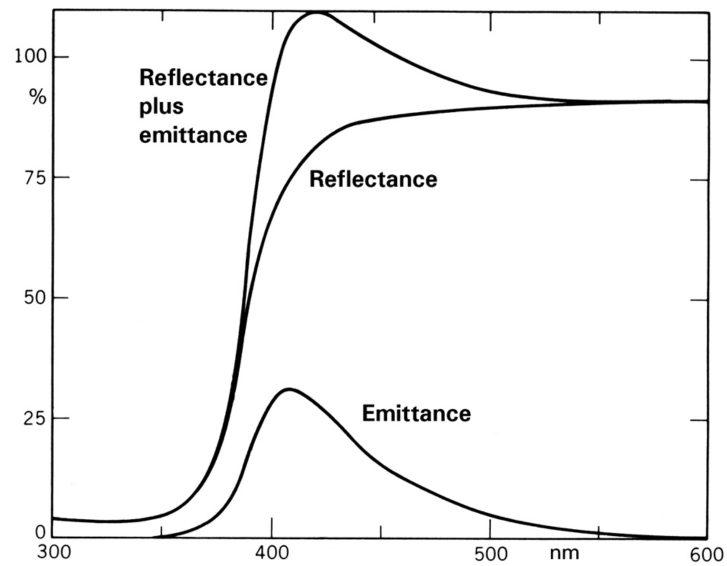


Fig. 3.15. Reflectance and emittance curves of bleached cotton alone (reflectance), bleached cotton with a fluorescent whitening agent (reflectance plus emittance), and the emitted light due the FWA (emittance).

3.9 Colorants are identified by their trade name and by their Colour Index (C.I.) designation (Fig. 3.16).

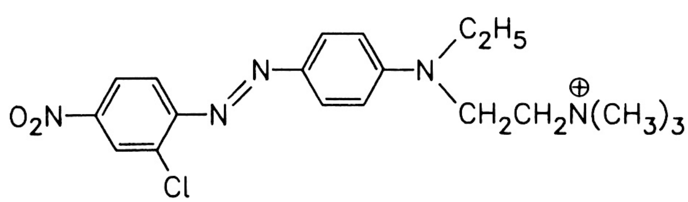


Fig. 3.16. The chemical structure formula of C.I. Basic Red 18, C.I. 11085.

For convenience in making comparisons, an international organization assigns general designations to specific chemical structures of dyes and pigments, their C.I. designations. There are two designations, the name, for example C.I. Basic Red 18, and the corresponding number, 11085. In most situations, the former is used for communication. Having the same C.I. name does not guarantee that two dyes are identical; it merely identifies the major portion of each commercial dye. Colored byproducts and diluting (cutting) agents will likely vary among different manufacturers. The concentration of the active dye ingredient may also vary. Colorants representing a mixture of C.I.-named products do not have a C.I. designation of their own.

3.10 Aside from the active ingredient, commercial dyes contain manufacturing byproducts (often colored) and diluting agents. The *standardization* process of the manufacturer assures, within a specified tolerance, that the active ingredient from batch to batch of the colorant is the same.

3.11 Commercial pigments may be nearly pure when sold as powder (Fig. 3.17). For textile and other purposes they are usually sold in standardized form as a liquid dispersion.

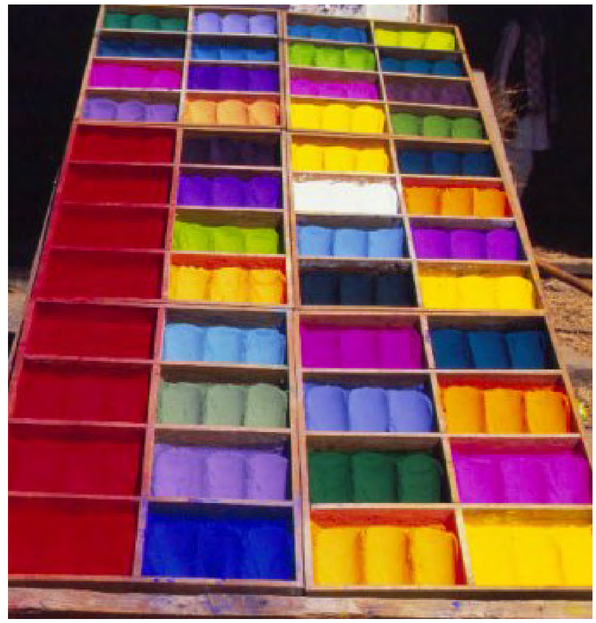


Fig. 3.17. Pure pigment powders arranged for sale in the Orient.

4 Textile Dye Classes

4.1 Acid and premetalized dye molecules have one or more acidic groups and possibly other solubilizing groups (Fig. 3.18).

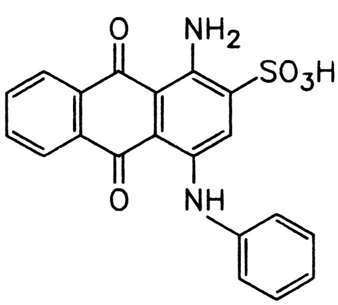


Fig. 3.18. The chemical structure of C.I. Acid Blue 25, a typical acid dye with a sulfo group that can form an ionic salt bond with wool and nylon fibers.

Acid dyes bond with basic molecular groups on fibers such as wool, silk, or nylon, forming what is known as a *salt bond*. The more acid groups the dye molecules have, the more strongly they can bond to the fiber, and the less likely they will be to come off in subsequent treatments (such as washing). One subset of dyes is known as monosulfonic acid dyes (each has one acidic group), another as disulfonic (two acidic groups). Acid dyes can be used to create brightly-colored fabrics.

Premetalized dyes contain a metal atom (cobalt, copper, or chromium) that has an electric charge and can form a separate bond with the fiber, increasing the dye's wet fastness, and usually, its light fastness (Fig. 3.19). Typically, the metal atom broadens the light absorption curve of the dye molecule. As discussed previously, a broader absorption curve indicates a duller appearance.

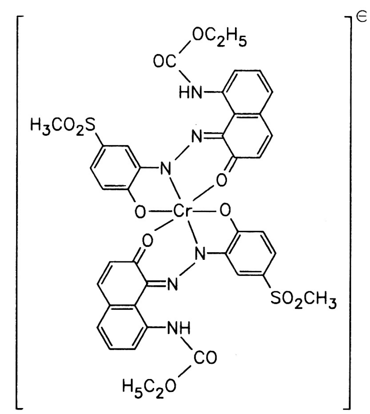


Fig. 3.19. The chemical structure of C.I. Acid Black 58, a 2:1 premetalized dye with two dye molecules attached to the central chromium atom (Cr).

Depending on dye, fiber, and dyeing conditions, up to 100% of the dye can leave the dyebath and fix to the fiber.

4.2 Mordant dyes are a special class of acid dyes treated after dyeing with a metal salt solution (a mordant) which bonds to the dye molecule and the fiber increasing wet fastness and light fastness. A very old mordant dyeing process involves pretreating the fibers with a metal salt that attracts and bonds with dyes in the dyebath.

4.3 Basic dyes have basic groups incorporated into their molecules that interact with acid-group-containing fibers (e.g., acrylic or modified polyester) (Fig. 3.20).

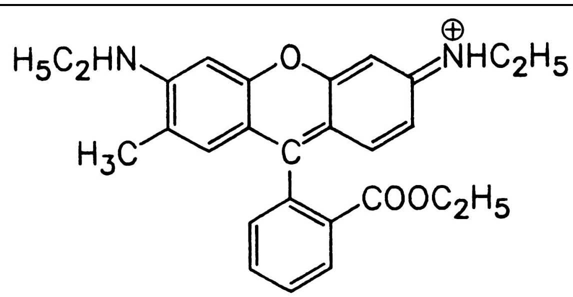


Fig. 3.20. The chemical structure of C.I. Basic Red 1, a strongly fluorescent dye known as rhodamine. The basic ion group is market with a "+."

The result of the acid-base interaction is the formation of a salt bond between fiber and dye. Depending on conditions, basic dyes exhaust up to 100% out of the dyebath. Basic dyes can result in bright dyeings.

4.4 Direct dyes have large molecules with one or more acidic groups to make them water-soluble (Fig. 3.21).

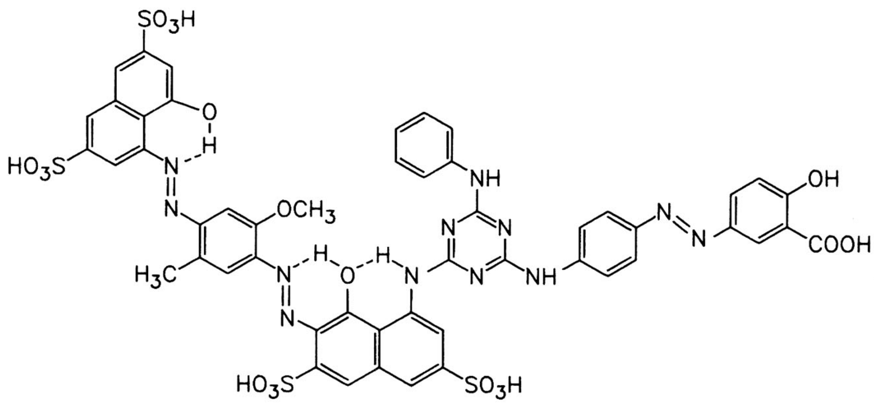


Fig. 3.21. The chemical structure of the large molecule of C.I. Direct Green 26 consisting of chemically-combined yellow and blue dye molecules, with four sulfo groups for water solubility.

They have been specifically developed for cotton and other cellulosic fibers. The dyes attach themselves to the fibers only by intermolecular forces. These forces are weak, resulting in poor wet fastness properties. Direct dyes are usually dyed only in light to medium shades and have largely been replaced by reactive dyes. Wet fastness can be improved with an aftertreatment using special compounds. The treatments usually change the color of the dyeing somewhat. Direct dyes are "pushed" out of the dyebath and onto the fiber by the addition of common salt. Direct dyes usually only exhaust out of the dyebath to 80% - 90%.

4.5 Reactive dyes are technically acid dyes to which a reactive group has been added. Under specific circumstances, heat and the presence of an alkali compound, such as sodium hydroxide, the reactive group can be made to undergo a chemical bond with the cellulosic fiber (Fig. 3.22). There are dyes with different kinds of reactive groups on the market: cold dyers and hot dyers. They differ in *reactivity*, with the cold dyers much more reactive than the hot dyers. Some dyes have more than one reactive group, increasing their chance of bonding to the fiber. Dyes with single reactive groups only fix at 65% - 85% to the fiber. Dyes with more than one reactive group can fix at up to 95%. Reactive dyes produce the brightest dyeings available on cotton.

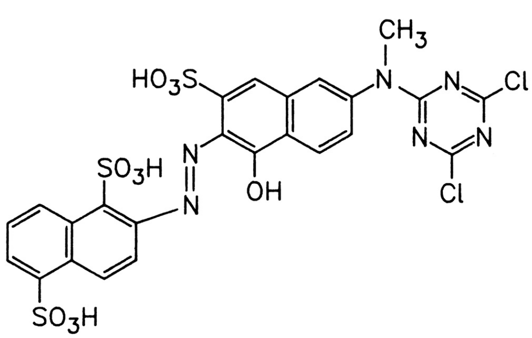


Fig. 3.22. The chemical structure of C.I. Reactive Orange 4, with a dichloro-triazine reactive group (on the right). When the two chlorine (Cl) atoms split off, the remaining dye undergoes a chemical reaction with cellulosic fibers, forming a stable bond. This dye is highly reactive and can be dyed at room temperature.

4.5 Sulfur, vat, and naphthol dyes are dye classes for cellulosic fibers that produce dyeings with better wet fastness than direct dyes and were developed before the invention of reactive dyes.

Sulfur dyes are water-insoluble dyes that can be temporarily made soluble by addition of sulfur-containing salts. Once they have transferred from the dyebath to the fiber they become insoluble by chemical *oxidation*. Sulfur dyes are inexpensive but provide only a limited range of colors. The environmental impact of their application has limited their use in recent years.

Vat dyes are water-insoluble colorants that can be made soluble in an alkaline bath by *reduction* with a reducing agent (Fig. 3.23). After they have transferred to the fiber, they are oxidized, typically with hydrogen peroxide, forming insoluble pigment particles. Among the dye classes for cellulosic fibers, vat dyes have the highest wetfastness and lightfastness. In their normal, oxidized form some may be used as pigments.

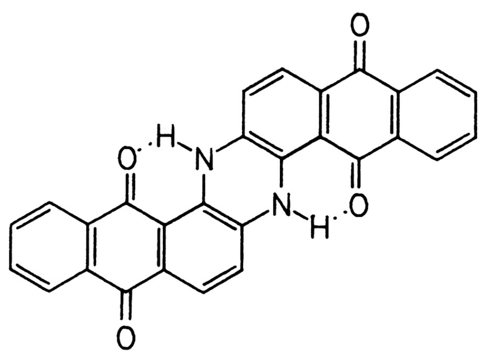


Fig. 3.23. The chemical structure of C. I. Vat Blue 4 in its water-insoluble form (no sulfo or other-water solubilizing groups). In this form, it is a pigment. To dye cellulosic fibers, it needs to be chemically reduced, applied, and oxidized back to this form.

Naphthol dyes are applied on cellulosic fibers as two relatively colorless components, the naphthol and the color base. Cotton is first impregnated with the naphthol compound in a strong alkali. After the alkali is rinsed off, the dye is developed by coupling with the color base. The generation of the dye is nearly instantaneous. Rinsing and boiling with soap removes any unfixed dye, and promotes formation of insoluble pigment particles within the fiber. Ecological issues connected with the application processes have resulted in wide replacement of naphthol dyes with reactive dyes.

4.6 Disperse dyes have very low solubility in water and are sold as dispersions (Fig. 3.24).

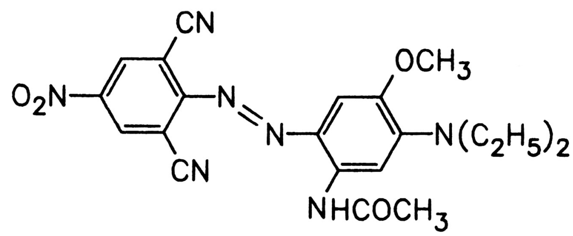


Fig. 3.24. The chemical structure of C. I. Disperse Blue 165 with very low solubility in water, but high solubility in polyester fibers.

Disperse dyes were invented to dye acetate fibers developed in the 1920s. After polyester was invented, new disperse dyes with better solubility in polyester where developed. These dyes have much better solubility in polyester fiber than in water. At the boil, or under pressure at even higher temperatures, the small amount of dye soluble in water transfers by intermolecular force to the fiber while more of the dispersed dye dissolves in the water. This process continues until the dye is as fully transferred as possible from the dispersed state in water to the dissolved state in the fiber. When cooled, the fiber structure tightens, trapping the dye molecules, and resulting in excellent wetfastness properties. Depending on the conditions, 90%-98% of a disperse dye transfers to the fiber.

4.7 Dyeing Processes

An important dyeing process is exhaust dyeing. In this process the dyes, dissolved or dispersed in a larger or smaller volume of water are exhausted onto the fiber at elevated temperatures in machines that move the material against the dye liquor (beck dyeing), the dye liquor against the material (package dyeing), or both at the same time (jet dyeing). (Fig. 3.25).

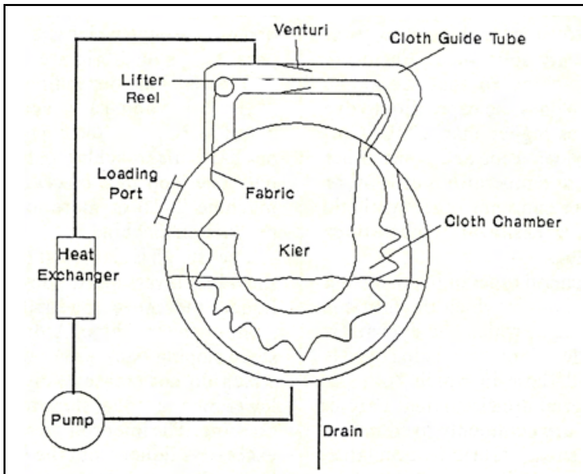


Fig. 3.25. A jet dyeing machine (exhaust dyeing). A circular batch of fabric is transported through the equipment with a pressure jet of dye liquor. *Perkins, Warren S., Textile Chemist and Colorist, Vol. 23, No. 8, August 1991, pp23-27.*

Semi-continuous dyeing refers to application of dye from concentrated solutions with chemicals, using an extended fixation treatment, as in cold-pad batch or jig dyeing.

Continuous dyeing involves application of dyes from concentrated solutions or dispersions and rapid fixation by steam or high temperature, in pad-steam or pad-dry-thermosol dyeing processes (Fig. 3.26).

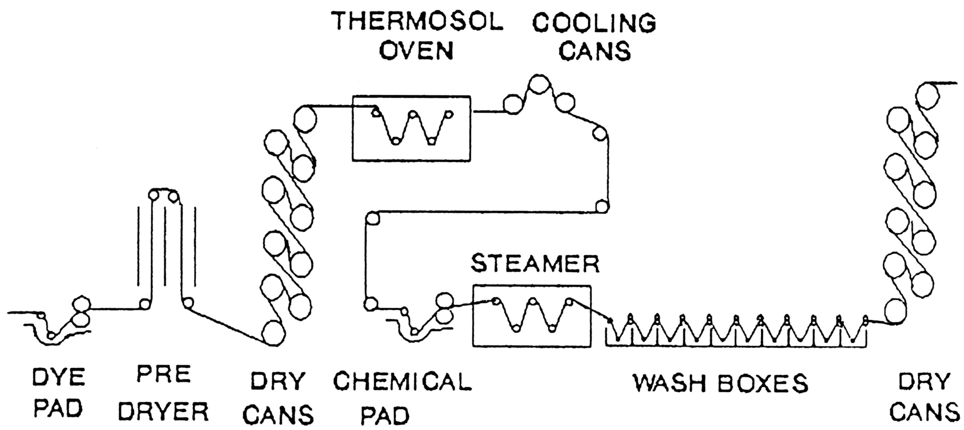


Fig. 3.26. A schematic diagram of a continuous dyeing range. *Perkins, Warren S., Textile Chemist and Colorist, Vol. 23, No. 8, August 1991, pp23-27.*

4.8 During the dyeing process, dyes are moving either slowly or rapidly from the surface to the interior of the fibers by a process called diffusion. The measured reflectance of a dyed sample, the apparent color, and fastness properties depend on the degree of diffusion. In an optimal process, the dye is evenly distributed throughout the fiber (Fig. 3.27). The economics of dyeing depend to some extent on the minimal time and energy required to reach this state.

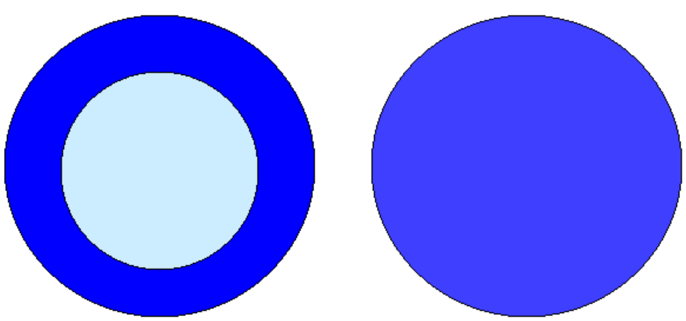


Fig. 3.27. Cross-sections of two dyed fibers. Left: A ring-dyed fiber with incomplete dye diffusion. Right: A fiber with complete diffusion. If both fibers contain the same amount of dye, the uniformly-dyed fiber reflects less light, appearing darker and more strongly dyed.

4.9 A single dye, or (especially) a combination of dyes should reach an even distribution throughout the entirety of textile material dyed in a lot. This is called “level” dyeing and is essential for uniformity of color within the dye lot.

In exhaust dyeing processes, uniformity is achieved by rapidly moving fabric against dye liquor, dye liquor against fabric, or both. After the dye has transferred to the fiber, there is a migration period during which dye distribution within a fiber and from fiber to fiber levels out. In semi-continuous and continuous dyeing, the dye must be applied and fixed uniformly to ensure uniformity of appearance.

4.10 Each dye has a specific power of attraction to the fiber (affinity) and *speed of diffusion* within the fiber. Dyes with similar affinity and diffusion properties are best suited for use in combinations. In order to obtain level dyeings, the dyeing process should be adapted to the affinity and diffusion properties of the textile fibers being dyed.

4.11 *Repeatability* (from one lot to the next) and *reproducibility* (different manufacturers dyeing the same color) of the dyeing process must be tightly controlled for manufacturing competitiveness.

5 Pigments

Fig. 3.28. Pigment manufacture: crude pigment after drying and before milling. *Fabricolor.*

5.1 Pigments form the second major class of colorants; they are inorganic or organic chromophore compounds with very low solubility in water. Some pigments, like the earlier-described naphthol dyes, are azo compounds. In manufacturing, pigments form solid cakes that are mechanically ground until the particle size is very small (Fig. 3.28). Pigments are sold as powders or as dispersions in water.

5.2 Pigments called lakes are dyes precipitated in water-insoluble form when combined with metal salts such as barium carbonate.

5.3 Major uses of pigments are in the coloration of plastics, paints, and printing inks (Fig. 3.29).

Fig. 3.29. Typical applications of pigments in interior decoration.

On textiles, pigments are applied primarily in printing. They are "glued" to the fiber surface with a polymeric binder. In case of man-made fibers, to obtain high fastness properties pigments can be included in the dissolved or molten fiber mass before extrusion, a process known as mass coloration.

5.4 There are also fluorescent pigments with the same optical characteristics as discussed above for fluorescent dyes.

6 Absorption and Scattering

6.1 The light scattered from a dyed textile material depends on the light arriving at the fabric and the portion absorbed by the fabric and the colorants. The specific scattering pattern of the light depends on the fiber type and surface, any internal pigment content, and the weaving/knitting structure of the fabric.

6.2 Dyes, because they are usually in the form of single molecules on the fiber, are considered to absorb, but not scatter, light. It is possible that some dyes form agglomerates within the fiber, but because the specifics are not known, this possibility is neglected in calculations.

6.3 Pigments, in the form of small particles, absorb and also scatter light (Fig. 3.30).

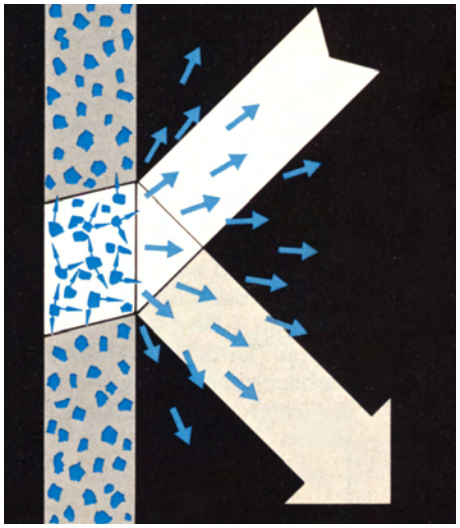


Fig. 3.30. A schematic representation of the absorption and scattering of a light beam in a paint layer. The light beam arrives from the upper right. Some of the light is reflected directly on the surface. Other light is absorbed or scattered by the blue pigment particles. *Gall, L., Farbmetrik auf dem Pigmentgebiet, BASF, Ludwigshafen, ca. 1972.*

Absorption and scattering depend on the size of the pigment particles. Average particle size and particle size distribution (percentage of particles of a given size in the total product) must be tightly controlled by the manufacturer for good repeatability of results (Fig. 3.31).

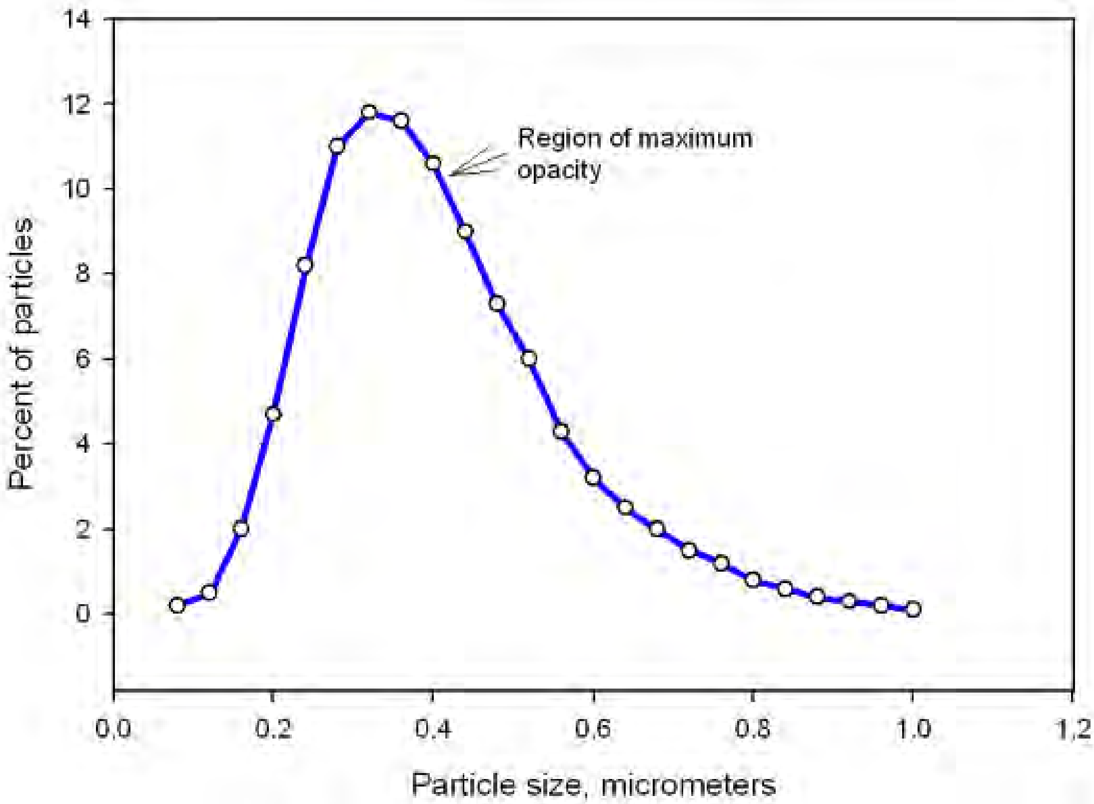


Fig. 3.31. Graphical representation of the particle size distribution of a commercial pigment, showing the percentage of particles with a given range of diameters. The diameter at which maximal opacity is obtained is indicated.

6.4 Absorption properties of dyes and pigments are based on their chemical properties. Each molecular type of colorant has specific absorption properties (but keep in mind section 6.3 above).

6.5 The absorption of light by a given colorant depends on its concentration and distribution on and in the fibers of the fabric in a nonlinear manner. Different “laws” apply to dyes and pigments. Another law applies to dyes dissolved in a solvent such as water.

6.6 In solution, dyes absorb some light and transmit the rest. The property measured for analytical purposes is *transmittance*, the portion of light that is transmitted through the solution (Fig. 3.32). Transmittance of colored solutions is usually measured in special glass containers called *cuvettes*. The measurement is expressed as a spectral transmittance curve (Fig. 3.33). This curve shows the percentage of light that passes through the solution at each wavelength. The light that does not pass through is absorbed by the dye. Transmittance is commonly expressed as a factor (0.0 to 1.0).

Fig. 3.32 Glass cuvettes with green and blue dye solutions are shown with a spectrophotometer cuvette holder for transmittance measurement.

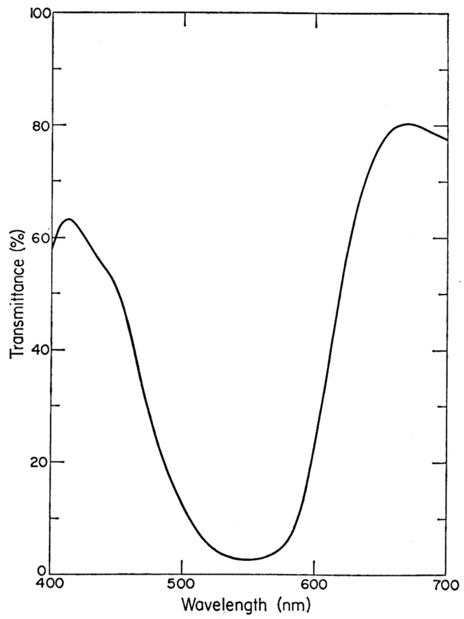


Fig. 3.33. The transmittance curve of a solution of a magenta dye in water. *Courtesy of John Wiley & Sons Inc. (Grum, F. R., Physical Methods of Chemistry, Vol. I, Part 3B, 1972). Used with permission.*

6.7 As mentioned in section 6.5, the relationship between dye concentration and transmittance is not a simple proportion. Instead, transmittance is logarithmically related to the concentration of the dye in the liquid and the thickness of the layer. The so-called Lambert-Beer law applies: $\log(1/T) = a_\lambda \times c \times d$, where log means the base 10 logarithm; $1/T$ is the inverse of transmittance, referring to the absorbed light; a_λ is the specific absorption value at a given wavelength λ; c is the concentration of the dye; and d is the thickness of the layer through which the light passes.

The Lambert-Beer law only applies exactly under ideal conditions. Because at higher concentrations dyes tend to agglomerate, the law usually no longer applies under those conditions. When plotting the absorption value against concentration (Fig. 3.34), the lines are often curved, indicating that the law does not apply perfectly. The absorption value at a given wavelength for a dye often depends on the exact conditions of the solution: temperature, pH, and other variables. For the purposes of accurately measuring the content of a sample dye in a solution relative to a standard dye, specific conditions must be maintained. If a glass container of the dye solution has a flat surface and the beam of light meets it at a 90º angle there is essentially no reflection or scattering of the light; almost all of the light is transmitted through glass and the dye solution. At a different angle, more or less light may be scattered or reflected.

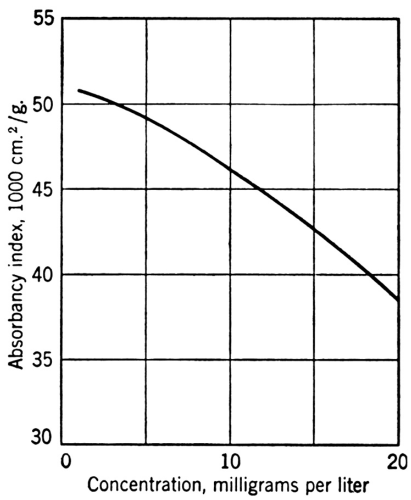


Fig. 3.34 Light absorbance versus concentrations of a dye in a solution. If the dye followed the Lambert-Beer law, the line would be straight. *Courtesy of John Wiley & Sons Inc. (Stearns,E. I., The Practice of Absorption Spectrophotometry,1969). Used with permission.*

6.8 Translucent materials absorb some light, and transmit, scatter, or reflect the portion not absorbed, depending on the surface and interior properties. Such materials may have opaque or transparent particles of a different material embedded in them, or an irregular surface may result in scattering. Most fibers are relatively translucent, with complex light paths (see Fig. 3.30 for a simplified, schematic sketch).

6.9 Opaque materials absorb some light and reflect or scatter the remaining portion. Metals are opaque materials which may scatter or reflect unabsorbed light depending on their surface properties (rough or polished).

6.10 The absorption properties of materials are determined by the presence of light-absorbing molecules. The molecular structure of the material itself may absorb some of the light, or the surface or interior of the material may contain colorants such as dyes or pigments.

6.11 The scattering properties of materials are determined by their surface properties and the size, shape, and distribution of any particles within them. While some pigment particles are nearly transparent, the small and irregular shape of the particles results in a mixture of light absorption, transmission, and scatter.

6.12 Reflectance data are the combined result of absorption and scattering of light by a material at different wavelengths. As discussed in Chapter 2, reflectance is the ratio between the amount of light falling on a given material and the amount scattered or reflected by the material (see Chapter 4 for the special case of fluorescent colorants). Measurements are taken at many points across the spectrum and reported as a series of numbers or plotted as a reflectance curve (Fig. 3.35). The horizontal axis expresses wavelength; the vertical axis indicates the fraction (from 0 to 1.0) or percentage (0% to 100%) of light reflected. Reflectance measurement will be discussed in more detail in Chapter 4.

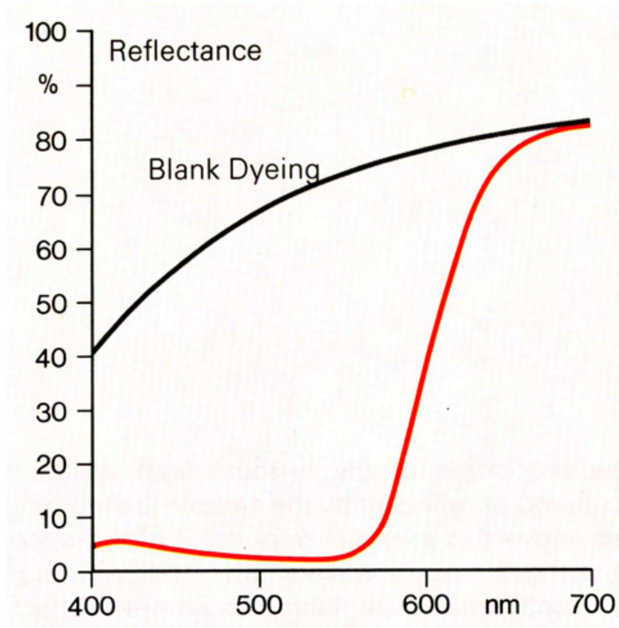


Fig. 3.35. The reflectance curve of an undyed piece of textile fabric (blank dyeing) and a dyeing with a red dye. *Courtesy of Bayer Business Services (Brockes, A., D. Strocka, and A. Berger-Schunn, Color Measurement in the Textile Industry, 1989). Used with permission.*

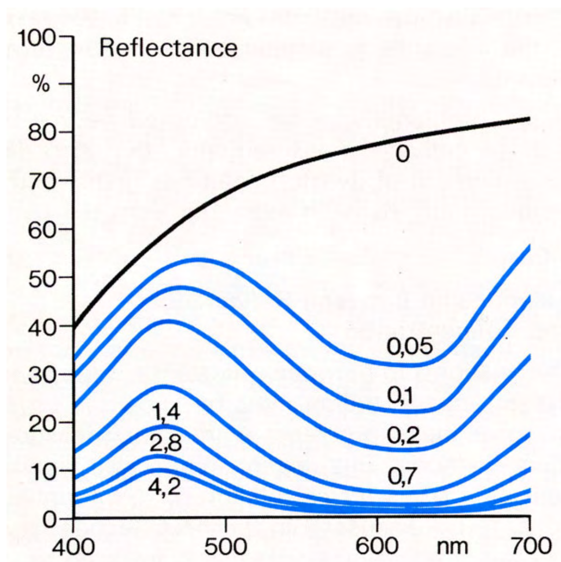


Fig. 3.36. Reflectance curves of undyed fabric and seven fabrics dyed with increasing percentages of a blue dye. *Courtesy of Bayer Business Services (Brockes, A., D. Strocka, and A. Berger-Schunn, Color Measurement in the Textile Industry, 1989). Used with permission.*

6.13 For non-fluorescent materials, reflectance is independent of the quality and quantity of light striking them. For this reason reflectance data are useful relative data describing what happens to a given light when it strikes a given material. In colored textile materials, the reflectance curve is a quantitative measure of which dyes (or pigments) and what quantities have been applied to the undyed material. Fig. 3.36 shows reflectance curves of a material, undyed and dyed at different concentrations. The shape of the curves is specific to the chemical dye structure. The relative amount of light that is reflected is that below the curve, the amount absorbed is above the curve, up to the value 1.0 or 100%.

6.14 Absorption of light by undyed textile fibers is due to impurities which can be almost completely removed by bleaching processes (Fig. 3.37). Scattering of light is due to the nature of the textile material, the inclusion of white pigment particles, the surface structure of the fibers, and the spinning, *twisting*, weaving or knitting patterns into which the fibers have been worked (Fig. 3.38).

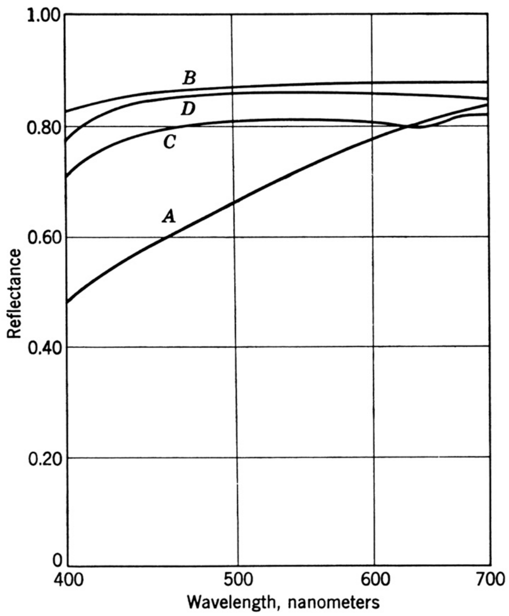


Fig. 3.37. The effect of bleaching on the reflectance of a cotton fabric. A: raw cotton, B: bleached cotton, C: undyed acrylic fabric, D: undyed polyester fabric. *Courtesy of John Wiley & Sons Inc. (Stearns,E. I., The Practice of Absorption Spectrophotometry,1969). Used with permission*

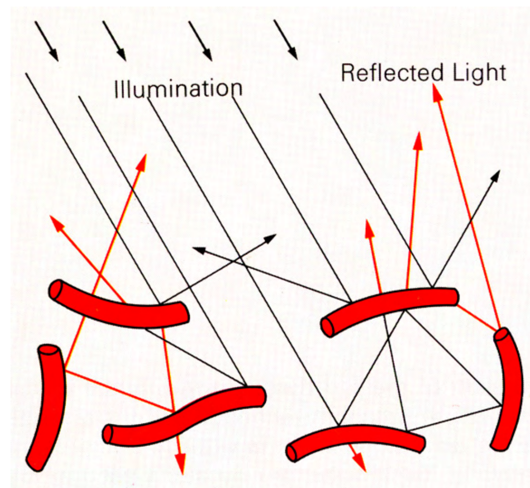


Fig. 3.38. A schematic illustration of the scatter of light from textile fibers. The light rays enter from the upper left and interact in different ways with the fibers. Some of the light is absorbed and the remaining red rays are scattered in different directions. *Courtesy of Bayer Business Services (Brockes, A., D. Strocka, and A. Berger-Schunn, Color Measurement in the Textile Industry, 1989). Used with permission.*

6.15 The reflectance curve is the combined result of light absorption and light scattering. Simplified approximations can be used to describe many different reflectance and scattering situations. The resulting “law” is known as the Kubelka-Munk law.

6.16 Kubelka and Munk defined absorption (K) and scattering (S) values in terms of reflectance (Fig. 3.39).

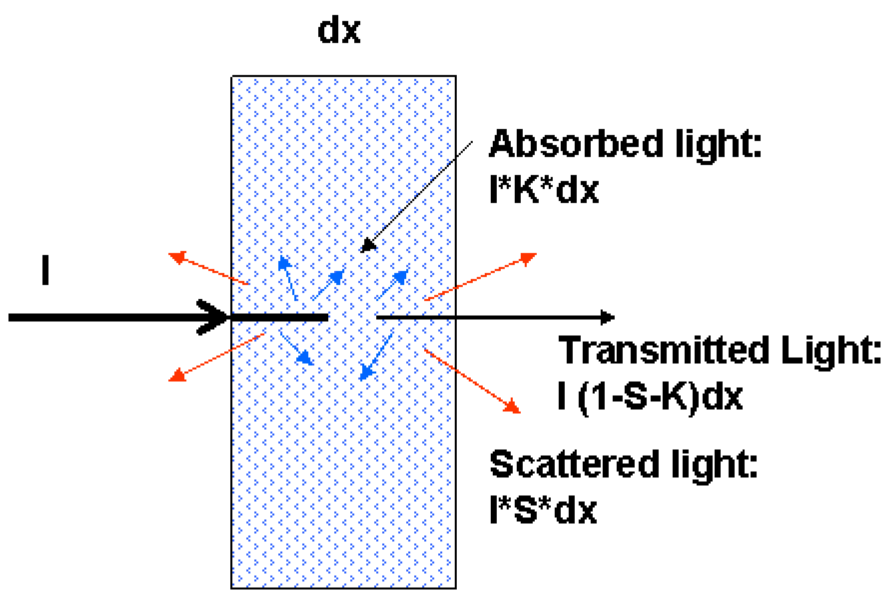


Fig. 3.39. A schematic illustration of the basis of the Kubelka-Munk law. A light beam with intensity *I* meets a translucent object of thickness *dx*. Some of the light is absorbed (blue arrows), some scattered (red arrows), and some transmitted (black arrow). The components add up to the total light. (Colors are for purposes of identification only.)

In real, opaque materials the translucent layers add up until no more light is left to move forward (toward the right) and the reflected/scattered light is the sum of light moving backwards (toward the left).

The equations behind the law are beyond the scope of this text. The definition of K/S (the so-called "K over S value") is expressed below in terms of reflectance. It is applicable at any wavelength of the spectrum.

$$K/S = (1 - R_\infty)2/2R$$

where K is the absorption constant at a given wavelength, S is the scattering constant, and R_∞ is the reflectance (as a fraction between 0 and 1.0) of the material at infinite thickness.

This equation only applies if the measured material is thick enough not to let any light pass through (opaque). To make use of the equation requires knowledge of either the K or the S value as well as of the reflectance value at a given wavelength. For work with textile materials, the relative value of the scattering coefficient is set to 1.0 at every wavelength, because dyes are assumed not to scatter light. The equation becomes

$$K/1 = K = (1 - R_\infty)2/2R.$$

6.17 The scattering constant cannot be disregarded when comparing textile fibers of different deniers. Microfibers scatter light much more than conventional fibers of the same chemical composition. The same concentration of dyes in the two fibers looks much weaker on the microfiber than on the conventional fiber. The formula must be adjusted to obtain the same color. For the purpose of computer color matching (see Chapter 9) separate calibration dyeings are prepared on the two types of fibers.

6.18 Using a value of 1 for the scattering constant at every wavelength is known as the one-constant application of *K/S*. Fig. 3.40 shows the relationship between reflectance and dye concentration at a wavelength of 620 nm for the dyeings of Fig. 3.36. Applying the Kubelka-Munk law makes the relationship more directly proportional, as shown in Fig. 3.41. For various reasons, direct proportionality often begins to fade at higher dye concentrations. Within the region of direct proportionality the unknown concentration of a given dye on a given textile material can easily be calculated from reflectance measurements and application of the Kubelka-Munk law. Outside this region, more complicated calculations are required.

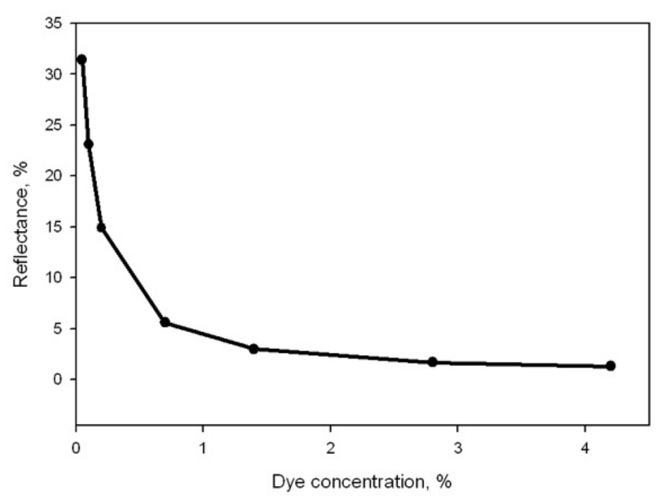


Fig. 3.40. The relationship between reflectance and dye concentration at 620 nm for the dyeings of Fig. 3.36.

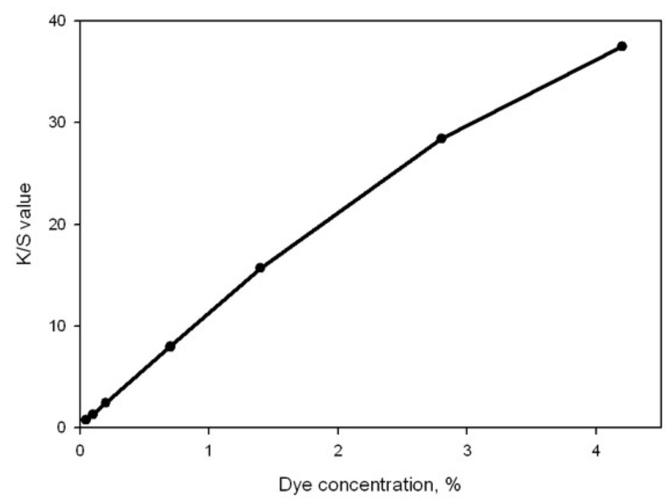


Fig. 3.41. *K/S* values versus dye concentration for the dyeings of Fig. 3.36 and 3.40.

6.19 The *K/S* value at a given wavelength of a three-dye combination on a particular textile material is the sum of the values of the three dyes at their respective concentrations and that of the undyed textile material.

$$K/S_D = [(c_A \times K/S_A) + (c_B \times K/S_B) + (c_C \times K/S_C) + K/S_{substrate}]$$

where *c* refers to the concentrations of dyes A, B, and C and *K/S* refers to the *K/S* value of dyes A, B, and C at unit concentration (typically 1%); the subscript *D* refers to the complete dyeing and “substrate” refers to the undyed textile material. This equation is used for the purpose of dye recipe formulation, as will be described in more detail in Chapter 9.

6.20 Pigment particles do scatter light, so absorption and scattering must be considered separately. Pigment scattering depends on the size of the particles (see Fig. 3.31) and their transparency or opaqueness. Optimum scatter is obtained under specific conditions for all three factors. The scattering curve for a given pigment is applicable only for that particle size distribution. Manufacturers standardize their products so that both absorption and scattering are controlled.

Fig. 3.42 shows the absorption and scattering curves of a yellow pigment. The reflectance curve is shown as the heavy line in Fig. 3.43. Absorption and scattering curves are calculated from reflectance curves of paintings (in a binder system) of the pure pigment and of mixtures of the pigment with various amounts of a white and a black pigment. The change in the reflectance curve through addition of four different concentrations of a white pigment and three of a black pigment are shown in Fig. 3.43.

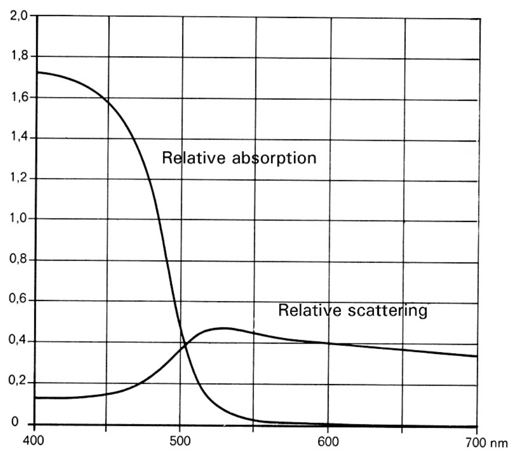


Fig. 3.42. Relative absorption and scattering curves of a yellow pigment. *Gall, L., Farbmetrik auf dem Pigmentgebiet, BASF, Ludwigshafen, ca. 1972.*

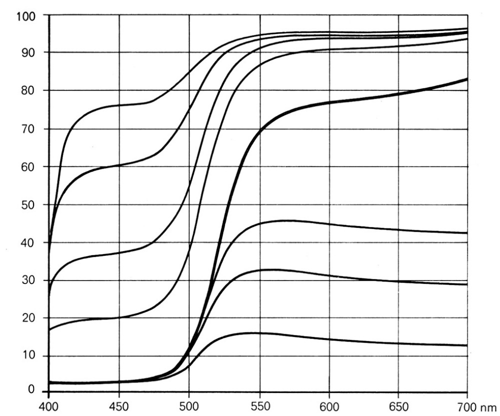


Fig. 3.43. Reflectance curve of a pure yellow pigment (heavy line) and curves of four different additions of a white and three of a black pigment. *Gall, L., Farbmetrik auf dem Pigmentgebiet, BASF, Ludwigshafen, ca. 1972.*

6.21 Scattering materials, including textiles, may scatter light differently in all directions. This poses some problems for reflectance measurements of such materials, a subject discussed in more detail in Chapter 4.

7 Secondary Properties of Dyes and Pigments

7.1 The primary purpose of dyes and pigments is to absorb light in specific ways to result in color perceptions.

7.2 Commercially important properties include
- maintaining the light absorption properties during use of the colored materials
- moderate cost by themselves and in their application processes
- minimal toxicity
- small environmental impact during application
- important fastness properties such as fastness to light, wet processing (washing or dry cleaning), and rubbing (Fig. 3.44)

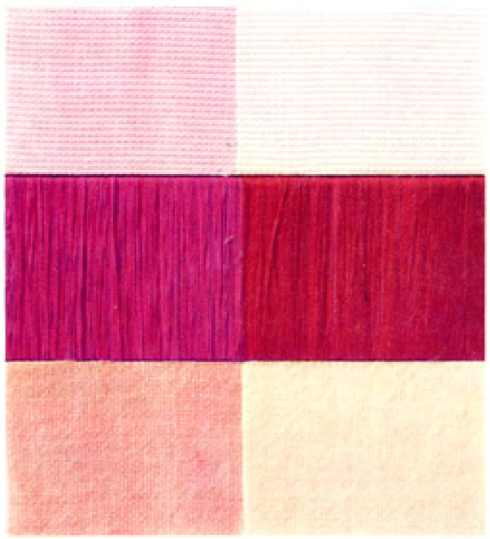


Fig. 3.44. An example of the wetfastness properties of two dyed yarns (center row) with different degrees of staining on adjacent fabrics (top and bottom rows).

7.3 Over the last 150 years several 100,000 different dye and pigment molecules have been synthesized by chemists and several thousand have been commercially produced. Increasing restrictions on toxicity and environmental impact, increasing demands for excellent fastness properties, and commercial competitiveness continue to trim the lists of available products and raise the hurdles for new products. New products or product mixtures nevertheless regularly appear on the market.

8 Summary

Dyes and pigments absorb light in broad irregular bands across the spectrum. Fibers are natural or man-made hair-like assemblies of molecules. In woven or knotted form they offer opacity by scattering light. The light absorption properties of fibers can be modified with the application of dyes or pigments. There are several chemical classes of fibers and suitable dye classes have been developed for each.

Dyes absorb light while pigments absorb and scatter light. Both affect the light reflecting properties of colored textiles or other materials. The Kubelka-Munk theory describes how absorption and scattering are related to reflectance.

Fastness properties, the economics of their application, and the safety of colorants are also important factors affecting their use.

Chapter 4 MEASURING COLOR STIMULI

1 A Review of Color Stimuli

1.1 For textile materials, most measurable color stimuli are lights. As a result, measurement of color stimuli refers to measurement of the absolute or relative amounts of light under specific conditions. The transmittance or reflectance data of the sample are determined from the measurements of light before and after interacting with a sample.

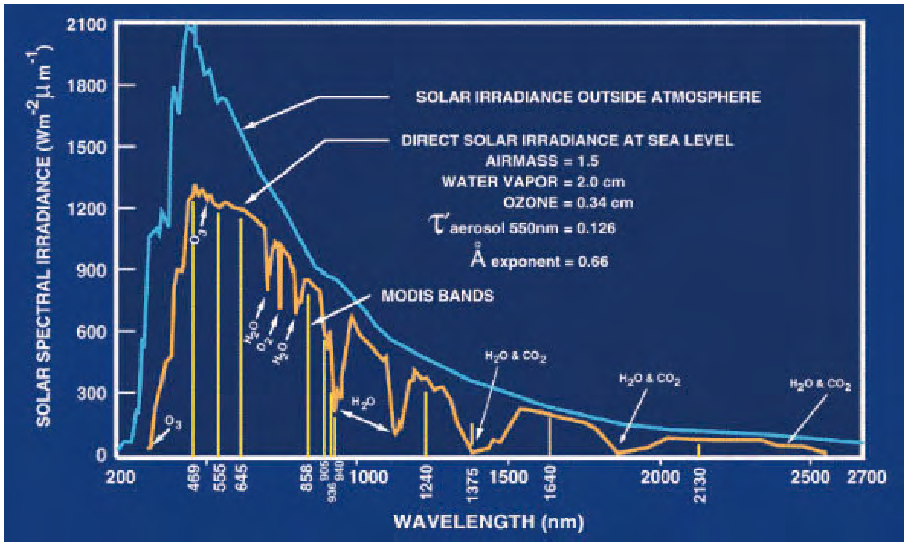


Fig. 4.1. Example of absolute spectral power distribution: Sunlight above the atmosphere and at sea level between 200 and 2700 nm. Note the absolute spectral power on the vertical scale in the form of irradiance (see next section). *Courtesy of NASA (Dr. Nicholas Short's Remote Sensing Tutorial).*

1.2 Measurement of direct lights, such as the light illuminating apparel goods in a store, is an absolute measurement of the spectral intensity of light and results in an absolute spectral power distribution curve (or set of numbers). Absolute measurements can be made relative by setting a given wavelength (typically 555 nm) equal to 1 or 100, and recalculating the values at all other wavelengths accordingly (Figs. 4.1 and 4.2).

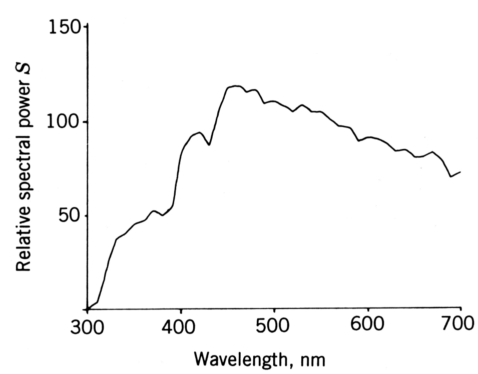


Fig. 4.2. The relative spectral power distribution of daylight from 300 to 700 nm. Note the relative scale of spectral power with a value of 100 at 555 nm.

1.3 Measurement of indirect lights (transmitted or scattered/reflected) is always relative. An instrument compares the amount of light before transmission through a material, or reflectance from a material, against the amount after transmission or reflectance (Figs. 4.3 and 4.4). The resulting ratio is the transmittance or reflectance factor. It may also be expressed as a percentage, as shown in these figures.

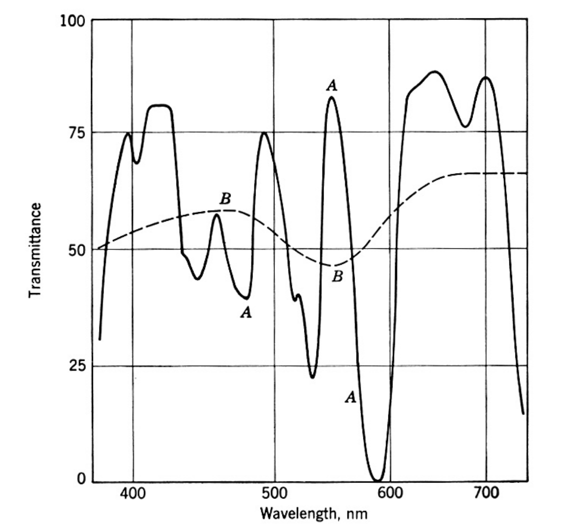


Fig. 4.3. Transmittance curves of two filters. A: complex spectral curve. B: smooth simple curve. *Courtesy of John Wiley & Sons Inc. (Grum, F. R., Physical Methods of Chemistry, Vol. I, Part 3B, 1972). Used with permission.*

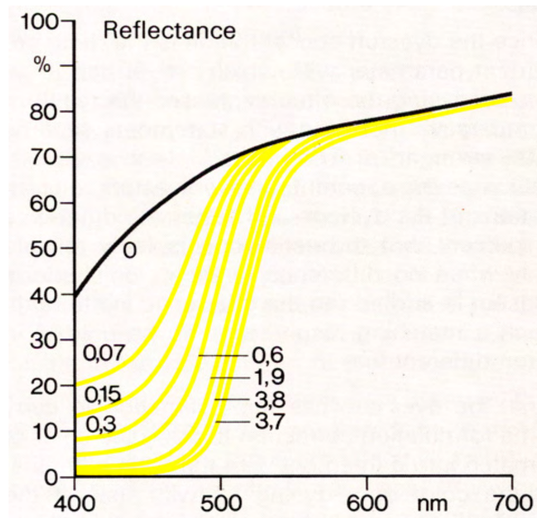


Fig. 4.4. Reflectance curves of undyed fabric (black line) and with seven different concentrations of a yellow dye. *Courtesy of Bayer Business Services (Brockes, A., D. Strocka, and A. Berger-Schunn, Color Measurement in the Textile Industry, 1989). Used with permission.*

2 Measurement of Direct Light

2.1 The intensity of light is measured either by a change in the temperature of a material caused by the light or through a change in the electric current resulting from photon absorption.

The *bolometer*, invented in 1878 by Samuel P. Langley (1834-1906), can measure temperature differences of 0.00001C by measuring the change in electrical current between two thin strips of metal when exposed to light. The change in current is proportional to the number of impacting photons.

There are several kinds of *photoelectric cells* that use changes in electric current or the generation of electric current from impact of photons to measure light intensity. Silicon photodiodes are the most commonly used type (Fig. 4.5). They have excellent stability and proportionality of the generated electric current to the intensity of light.

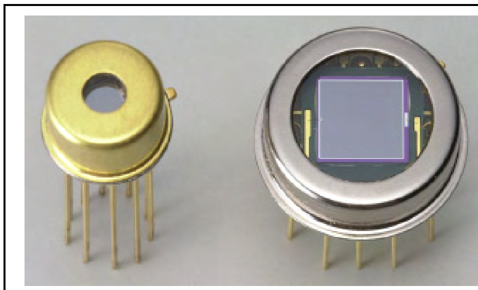


Fig. 4.5. Some examples of commercial photodiodes. *Courtesy of Hamamatsu Corp. Used with permission.*

2.2 In *radiometry* the intensity of light is measured absolutely and expressed in terms of energy or power. Radiometry describes a physical measurement (independent of the visual sense).

2.3 In *photometry* the spectral power of the light is adjusted by filters or calculations to represent the visual response (brightness) of the average human observer. Photometry describes a *psychophysical* measurement, representing the average human response to a light.

2.4 There are several radiometric units.

- Energy is typically expressed in watts. For example, you can purchase light bulbs with an output of 40 watts or 100 watts.
- Power or radiant flux expresses the energy output of a light per unit time (watts per second).
- *Irradiance* is the power of light per unit area, such as watts per square meter, and describes the amount of light on a surface, such as a desk.
- *Radiant intensity* expresses the amount of light from a small circular source (light bulb) in a *solid angle* of an imaginary sphere around the source (Fig. 4.6).

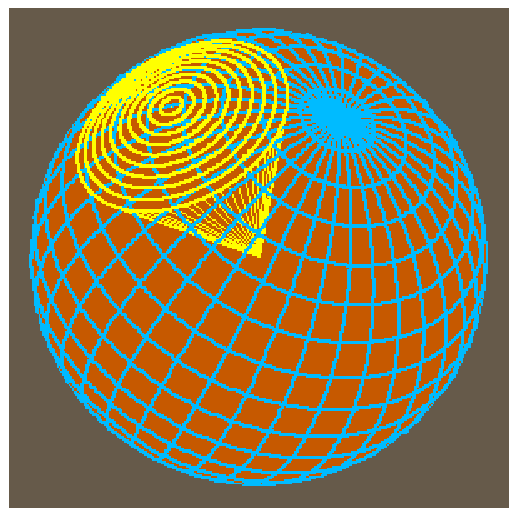


Fig. 4.6. Illustration of solid angle expanding from the center of a sphere to its surface. It is the basis of the definition of radiant intensity.

The radiometric units can express the amount of light at a specific wavelength or the total amount for the whole spectrum.

2.5 There are also several photometric units.

- A *lumen* is the photometric unit comparable to power in radiometry. Lumen per square meter or *lux* is the parallel unit of irradiance. *Candela* is comparable to radiant intensity.
- *Luminance* is used to express the brightness in regard to solid angle of the sphere around the bulb, expressed per area (e.g., candela per square meter, also called *nit*). The brightness of a laptop screen is usually expressed in this manner, with a typical value of about 200 nits. Sunlight-readable laptops have up to 1000 nits. Note that this refers to the amount of light given off by the surface that itself is a light source. It also applies to the average light given off by the diffused light of a lightbox.

Photometric units also measure light at individual wavelengths or over the entire spectrum of light related to the brightness perception of the average observer.

2.6 Light emitted by a uniform spherical light source (approximated by a light bulb) is called *isotropic*. Isotropic means uniform in all directions of space from a point (or small sphere).

Light given off by a flat source is called *lambertian*. Lambertian (derived from the name of the physicist Lambert of the Lambert-Beer law) means given off uniformly from a source open only in one direction (Fig. 4.7).

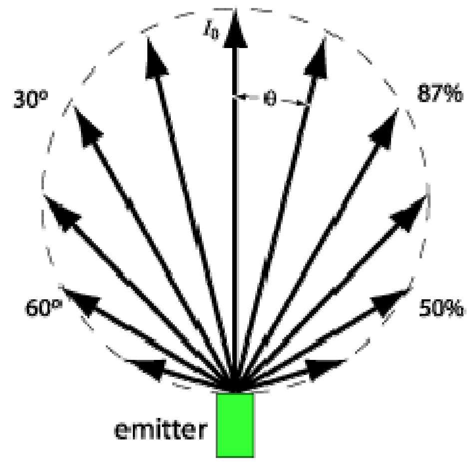


Fig. 4.7. Schematic representation of a lambertian light source giving off radiation in all directions from its flat surface.

2.7 The defined standard observer used in most photometric measurements is the CIE 1924 *standard photopic observer*. This observer was internationally defined in 1924 by the International Commission on Illumination (CIE) and is represented by the spectral *luminous efficiency function* *V(λ)* (Fig. 4.8), the Greek letter *λ* (lambda) refers to wavelength in nanometers.

The photopic observer defines the efficiency of the average human to convert light power to perceived brightness of light under daylight conditions. The peak of the curve is at 555 nm. The curve drops off relatively sharply in both directions and approaches zero at 400 and 700 nm. This indicates that at these, wavelengths approximately 100 times more light must be present for us to experience the same level of brightness as at 555 nm. At a daylight level of light, we have the highest brightness perception from a given amount of light energy at that wavelength. A different luminous efficiency function applies in very dim light, but is not of concern to us in this discussion.

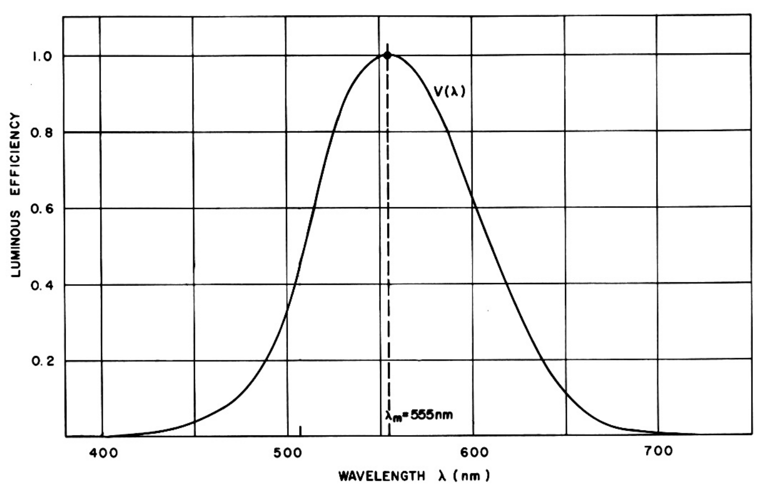


Fig. 4.8. CIE spectral luminosity function *V(λ)* of the standard photopic observer. *Courtesy of John Wiley & Sons Inc. (Wyszecki, G. and W. S. Stiles, Color Science, 1982). Used with permission.*

2.8 There are many kinds of radiometers and photometers commercially available. Of greatest value are instruments that make spectral measurements possible, *spectroradiometers* or *spectrophotometers*. These can be used to measure the intensity and composition of light in light boxes for visual evaluations or of store lighting. Radiometric or photometric measurements should be routinely used to make comparisons of visual color inspection stations throughout a corporation or a supply chain.

3 Measurement of Transmitted Light

3.1 Light interacts with materials either by passing through transparent materials or by being partially or completely scattered or reflected in translucent or opaque materials.

3.2 Transmission through (non-fluorescent) materials results in some portion of the light being absorbed, and the remainder passing through the material. Examples of materials which transmit light are a colored filter or a solution of dye in a solvent.

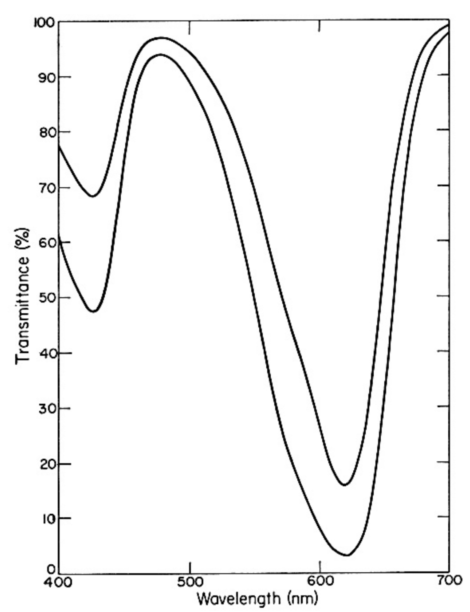


Fig. 4.9. Transmittance curves of a dye at two different concentrations. *Courtesy of John Wiley & Sons Inc. (Grum, F. R., Physical Methods of Chemistry, Vol. I, Part 3B, 1972). Used with permission.*

3.3 Transmittance refers to the portion of light passing unabsorbed through the material. Transmittance is measured by comparing the amount of light from the light source in the absence of the transparent material to that in its presence. Some instruments have two beams of light running in parallel—the reference beam and the measurement beam.

To measure the transmittance of a dye in solution in a *two-beam instrument*, a cuvette (see Fig. 3.32) containing only the solvent is placed in the reference beam and the dye solution in the sample beam. The ratio of light between the two is the transmittance applicable to the dye only (Fig. 4.9). In *one-beam instruments*, the cuvette with the blank solvent is first placed in the beam for a measurement and the cuvette with the dye solution second (Fig. 4.10). The microcomputer of the instrument then calculates the transmittance of the dye in the solution.

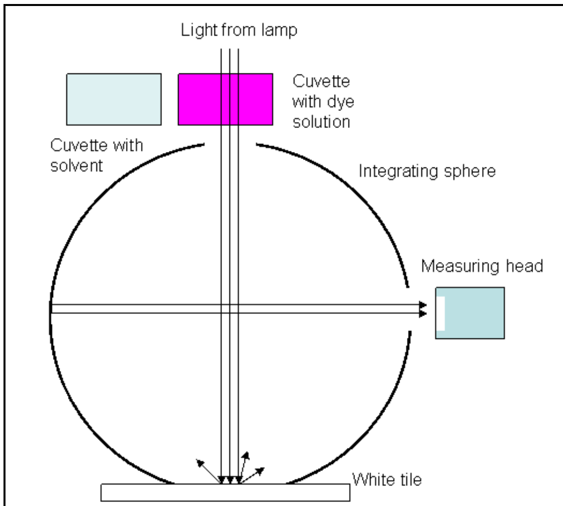


Fig. 4.10. Transmittance measurement of a dye in solution using a spectrophotometer with an integrating sphere. The blank solvent is measured before the dye solution.

3.4 A well-defined beam of reflected light can be measured in a relatively small area.
To measure the reflectance curve of an opaque, highly glossy material is comparatively simple, given the law of reflection. Measuring the reflectance of other materials is more complex because of scatter on the surface or internally.

4 Measurement of Reflected or Scattered Light

4.1 Reflection specifically refers to a well-defined direction of light return caused by the smooth surface of the reflecting material. The law of reflection states that the angle from the normal at which the light approaches the smooth surface is equal to the angle in the opposite direction at which it is reflected (Fig. 4.11).

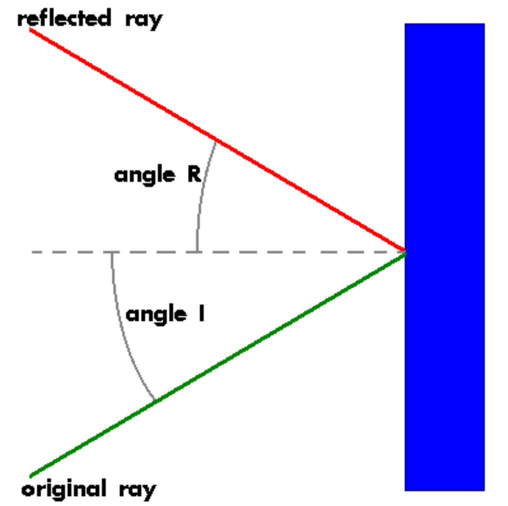


Fig. 4.11. A schematic view of the law of reflection.

4.2 Scattering refers to reflection in multiple directions due to the structural detail of opaque surfaces or the size, shape, and number of opaque particles in transparent media (Fig. 4.12, see also Fig. 3.30).

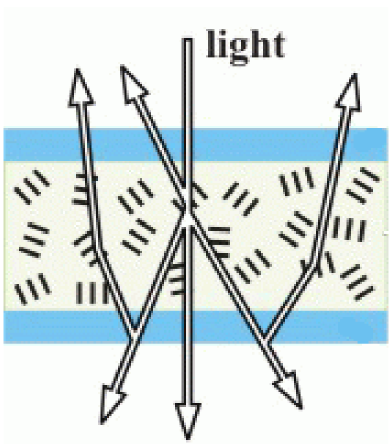


Fig. 4.12. A schematic figure of the internal scattering of light by particles in a transparent medium.

All textile materials are scattering materials. Depending on the surface structure (weaving or knitting pattern) and the fibers, there may be some directions of preferred scatter. Note that even if the measured material scatters light, the term “reflectance data” is applied to the results.

4.3 Reflectance of translucent or opaque materials refers to the relative amount of light returning from the material compared to the amount of light reflected from a white standard material (Fig. 4.13).

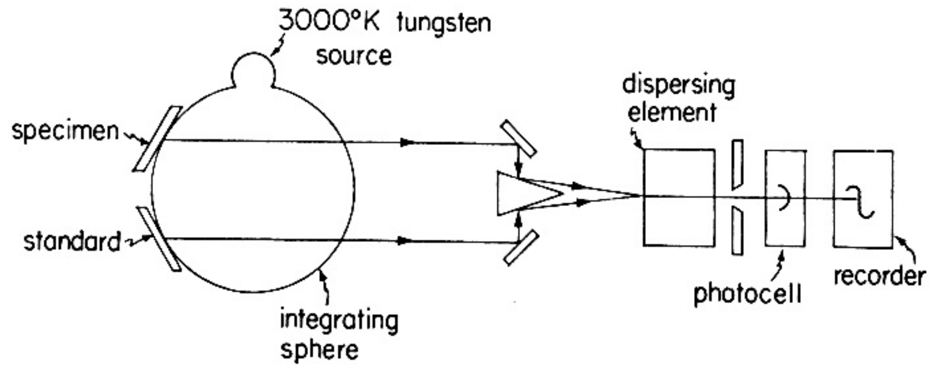


Fig. 4.13. A two-beam reflectance spectrophotometer. *Courtesy of John Wiley & Sons Inc. (Grum, F. R., Physical Methods of Chemistry, Vol. I, Part 3B, 1972). Used with permission.*

In a two-beam instrument, the light reflected from a white standard material is directly compared to that reflected from the test material. One-beam instruments are calibrated against a white standard material (the light returned from that material is registered in the instrument) and the light reflected from the test material is compared to the stored data. Many modern instruments are one-beam instruments.

4.4 Scattering materials are best measured in a layer thick enough to assure complete opacity to be in agreement with the requirements of the Kubelka-Munk law (see section 4.6 below).

Complete opacity may be a natural property of the material, as in an opaque paint layer applied to a solid wall surface. Most textile fibers are translucent. Thin materials can be doubled and re-doubled to obtain opacity. A simple test for opacity is to view the material against a strong light source, doubling it until no more light can be seen through the material.

4.5 Measurement at opacity provides the highest degree of agreement with the Kubelka-Munk law. If the reflectance data are to be used for computer colorant formulation (see Chapter 9) or calculation of colorant concentration for quality control purposes (Chapter 10), best results with the simple one-constant Kubelka-Munk formula (see Chapter 3) are obtained with opaque samples.

4.6 If measurement at opacity is not possible, the conditions of measurement must be defined and reported. If, for example, the reflectance curve of small pieces of thin fabrics are determined without enough material available to obtain opacity, the fabric must be backed-up with a defined opaque material (for example a white, opaque material) and the back-up conditions must be noted in the result.

4.7 Repeatability of results for textile materials is highest if measurements are made with diffuse illumination or *diffuse measurement*. Diffuse illumination and measurement are described in the next section.

5 Standard Measuring Geometries for Reflectance Data

5.1 The CIE has defined four basic geometric arrangements for measuring reflectance data: 45°/normal, normal/45°, diffuse/normal and normal/diffuse.
The first term refers to the direction of illumination arriving at the sample, the second to the direction of light from the sample. A geometry of 45° means that either the light source or the measuring head is at an angle of 45° to the sample. “Normal” indicates that the light source or measuring head is at 90° (Figs. 4.14a and b).

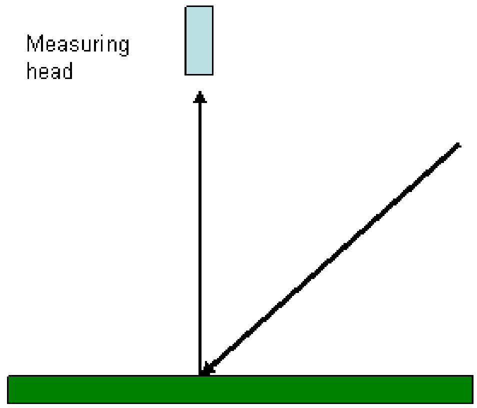


Fig. 4.14a. 45°/normal measuring geometry.

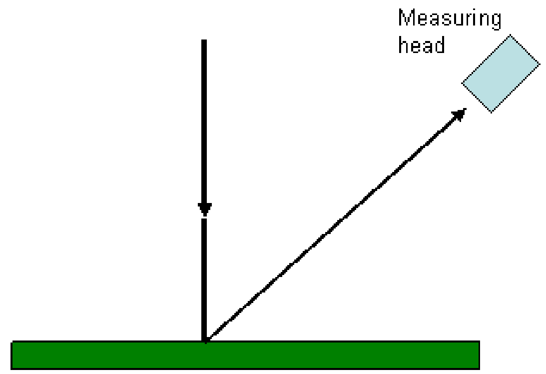


Fig. 4.14b. Normal/45° measuring geometry.

“Diffuse” means that the sample is illuminated diffusely, with the sample attached to a hollow *integrating sphere* and the measuring head placed on the normal. The sample may also be illuminated from the normal direction with the measuring head placed to receive the diffused scattered light (Figs. 4.15a and b).

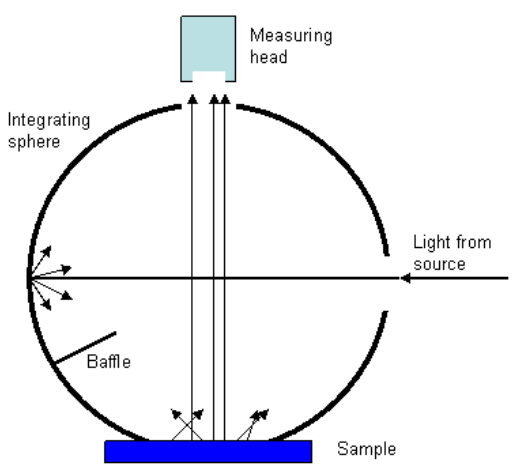


Fig. 4.15a. Diffuse/normal measuring geometry.

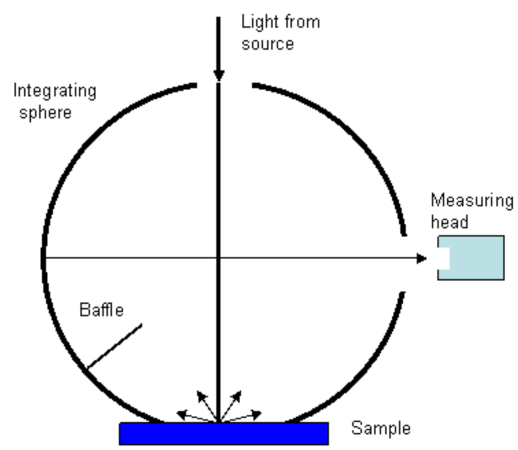


Fig. 4.15b. Normal/diffuse measuring geometry.

5.2 Depending on the arrangement, the integrating sphere distributes light onto the sample diffusely from many directions or collects light diffusely from many directions. Integrating spheres are hollow spheres painted white on the inside. There are two openings, one for the light to enter and one for the scattered light to leave toward the measuring head.

5.3 The preferred geometric arrangement for measuring textile samples is diffuse/normal and most modern instruments for textiles measure in this configuration. In this arrangement the sample is illuminated diffusely from all angles, reducing the possibility of shadows caused by the fabric surface structure. Often a baffle is included in the sphere to assure that no direct light from the lamp strikes the sample (Fig. 4.15a and b). Angular illumination/measuring geometries usually produce considerably varying results for textile materials, depending on how the sample is placed on the sample opening (Fig. 4.16).

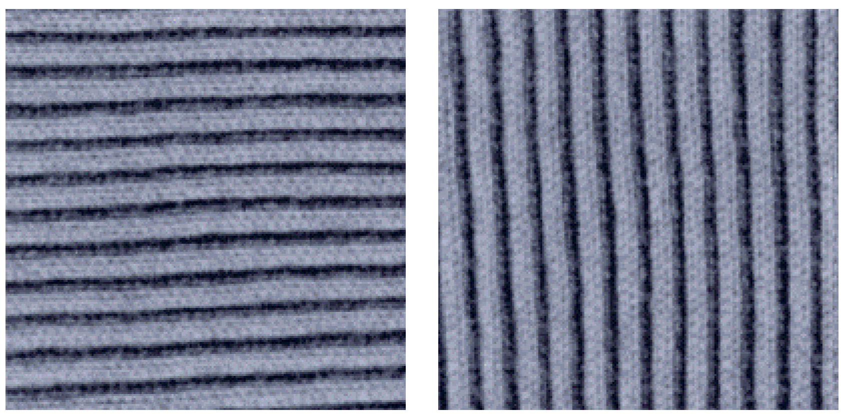


Fig. 4.16. Rib-knit fabric reflects light differently depending on the position of the sample on the sample port.

5.4 Despite diffuse illumination, there is no guarantee that the measurement results on a given instrument will be identical for all positions of the sample on the sphere opening. For this reason it is common practice to make two or three measurements with the sample rotated by 90° between measurements. The measurements are then averaged.

5.5 The CIE standard geometries are limited to the four arrangements mentioned above. Beyond that, instrument manufacturers have wide latitude to design the light path and interaction with the sample and measuring head in different ways. For this reason, differences between measurement results obtained from instruments of different suppliers are typical.

6 SIN and SEX

6.1 The acronyms stand for “*specular included*” and “*specular excluded*.”
Many materials, including textiles, have some specular (mirrorlike) reflection. “Gloss” is the portion of light that is reflected according to the law of reflection (angle of incidence equals angle of reflection, see Fig. 4.11). Depending on the degree of glossiness, the reflected portion of light (compared to the scattered portion) may be small, with a broad distribution, or large and narrowly distributed.

6.2 The distribution of scatter and reflection in the space above the sample can be measured with an instrument called a *goniospectrometer* that measures light from a sample at different angles (Fig. 4.17). The result requires a three-dimensional plot, often shown as a two-dimensional cross section. Figure 4.18 shows the so-called *indicatrix* of scatter/reflection for materials with gloss.

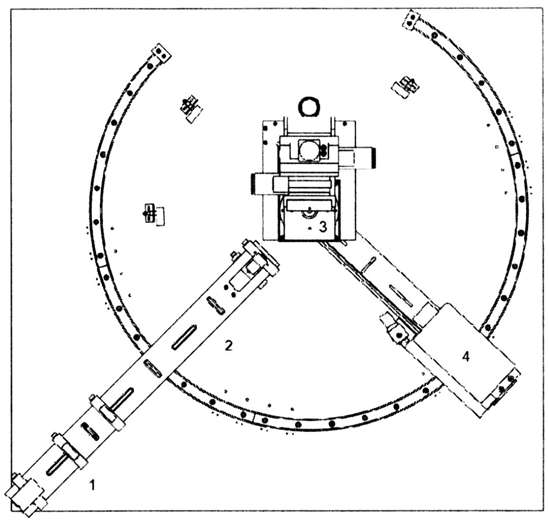


Fig. 4.17. Top view of a goniospectrometer: 1. Light source, 2 Optical bench, 3. Sample holder, 4. Light detector (spectroradiometer). The light source and detector can be moved along the circular rail to obtain measurements at different angles of illumination and viewing. *Courtesy of Wiley-Blackwell Publishing Ltd. (Pointer, Michael R., et al., Coloration Technology, Vol. 121, No. 2, 2005, pp96-103.) Used with permission.*

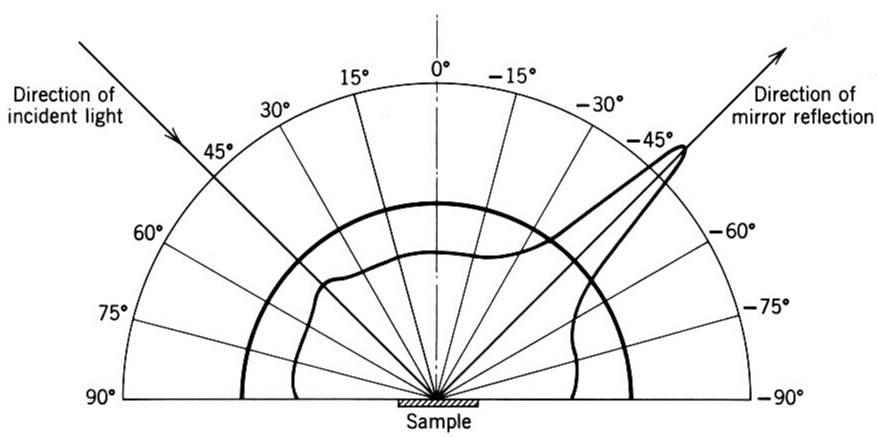


Fig. 4.18. A cross-section through the hemisphere above a sample. The uniform, heavy semicircle is the indicatrix of a perfectly diffuse sample, the irregular, heavy line is that of a glossy sample showing a considerable amount of mirror reflection. *Courtesy of John Wiley & Sons Inc. (Judd, D. B. and G. Wyszecki, Color in Business, Science and Industry, 1975). Used with permission.*

6.3 Many instruments with integrating spheres have a built-in "*gloss trap*" or *specular port* that allows exclusion (partially or completely) of the reflected (specular) portion of light. Figure 4.19 schematically illustrates the geometry of a diffuse/normal type instrument with a gloss trap. The measurement is not exactly at the normal but at an angle of about 8° to the normal. In this arrangement, light that comes from the sphere area opposite the measurement opening contains the specular component (reflected, gloss portion). The gloss trap is a black, highly light-absorbing material that absorbs the specular portion of light. However, the gloss bulge of the indicatrix of textile materials is usually broad and the angular size of the gloss trap limited, resulting in only partial exclusion of the specular portion. For textiles (except highly glossy ones), it is recommended to measure in the specular included (SIN) mode. If measuring in the SIN mode is not standard in a product supply chain, the actual measuring method must be indicated in the report.

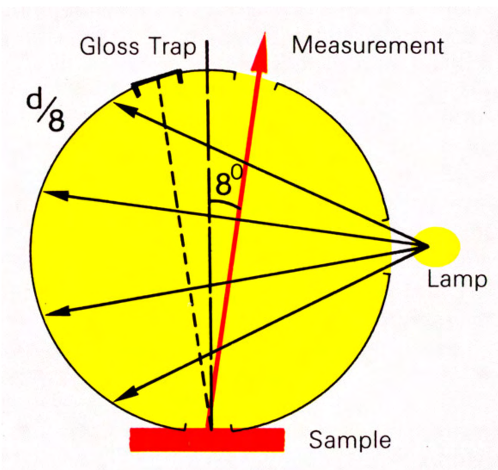


Fig. 4.19. A measuring arrangement with diffuse illumination and measurement at an angle of 8º to the normal. Under these conditions, the spectral component is trapped by the gloss trap and does not become part of the measurement. *Courtesy of Bayer Business Services (Brockes, A., D. Strocka, and A. Berger-Schunn, Color Measurement in the Textile Industry, 1989). Used with permission.*

7 Measuring Spectral Information

7.1 Measurement of spectral information requires the breakdown of the broadband light of the light source into spectral components. This may be done using filters, a glass prism, or a diffraction grating.

7.2 Filter combinations with steep absorption curves can be used to filter out selected broad portions of the reflected light, leaving only narrow bands that are transmitted to the light-measuring head. This method is no longer widely used. The results depend on the specific choices of filters.

7.3 Glass prisms result in good light dispersion. They have been widely used in the past but the quality of the spectrum depends on the quality and index of refraction (see Chapter 2) of the glass. Prisms also require the mechanical movement of either the prism or a slit through which light passes during measurement, making instruments subject to mechanical malfunction or breakdown.

7.4 Today, diffraction gratings are used almost universally for dispersion of the light beam (Fig. 4.20). Diffraction gratings consist of finely-engraved lines on glass or metal. Looking at a compact disk in a light beam gives a picture of the grating diffraction effect. Gratings are engraved typically at a density of 1200 lines per millimeter (approximately 305,000 lines per inch). If the gratings are manufactured accurately, the light dispersion is very repeatable from one grating to the next. By placing an array of *photodetectors* (*silicon photodiodes*) in the path of the dispersed spectral light the system requires no moving parts and the measurement is nearly instantaneous (Fig. 4.21).

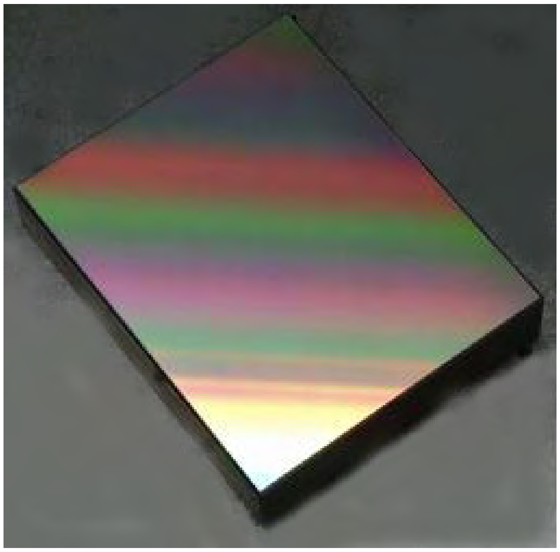


Fig. 4.20. A diffraction grating plate.

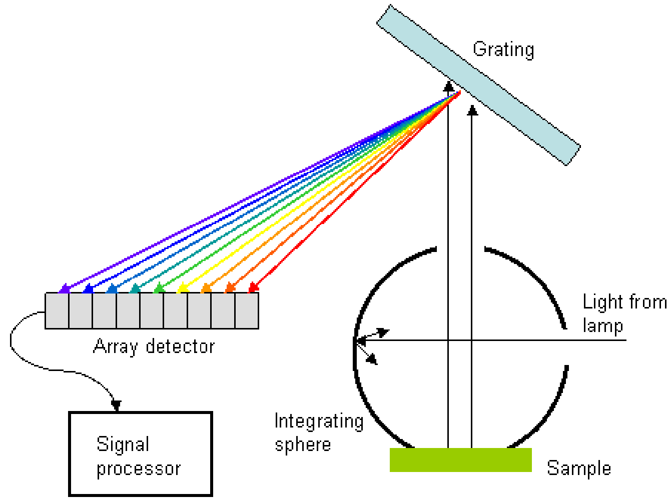


Fig. 4.21. A spectrophotometer with diffuse/normal geometry, grating dispersion, and an array detector.

7.5 The number of photodetectors in an array is limited and it is not possible (or at least not practical) to directly measure lights nanometer by nanometer. The measurement involves a band of light, for example 20 nm in width. The amount of light assigned to a particular wavelength is calculated from the whole band. Intermediate values are interpolated (calculated from the two nearest measured values). Thus, the number of photodetectors involved and the calculation method may be specific to an instrument type, potentially resulting in different data from different instruments.

7.6 A typical spectrophotometer useful for measuring textile samples consists of a light source, an integrating sphere, a light dispersing device, an array of photodetectors, a small computer, and an output device. The output device is usually a video display and a printer. The output may consist of reflectance values at selected intervals (5, 10, or 20 nm) and of a plotted reflectance curve.

7.7 For non-fluorescent samples, the spectral composition of the light is not important as long as there is enough light at a given wavelength to measure dark samples without unacceptably large errors. In actual instruments, different light sources are used, usually *tungsten light bulbs* with a filter or xenon lamps. Both lamps are approximations to daylight (see Chapter 1), but tungsten bulbs result in much higher sample temperatures during extended measuring periods. This may cause problems with samples in which the reflectance can change relative to temperature and humidity.

7.8 Some dyes are sensitive to temperature and moisture variation in the fabric, changing their light absorption behavior. Samples can be normalized by exposing them for the recommended time in a temperature and moisture content stabilization apparatus before measurement. Conditioned samples should be measured rapidly once the sample is attached to the sample opening of the reflectance spectrophotometer.

7.9 Measuring white samples treated with fluorescent whitening agents or colored fluorescent samples requires control of the ultraviolet (UV) component of the light illuminating the sample and a light source that approximates daylight in the visible range. In the case of filtered tungsten lights, the ultraviolet component of the light may be very small and require the presence of a separate ultraviolet light that can be directly adjusted, or modified with filters, so that the combined spectral power of the light matches D_{65}, for example. Special calibration of such lights is a necessity.

7.10 To measure reflectance and *emission* of fluorescent samples correctly requires that the sample be illuminated with the full light of the source rather than only with a narrow spectral band. Most modern spectrophotometers are configured appropriately. Illumination with the broadband light of appropriate spectral power distribution assures that light of the proper wavelengths is absorbed, to be emitted at longer wavelengths.

8 Instrument Calibration

8.1 Instruments must undergo proper calibration to provide accurate, repeatable, and reproducible results. *Accurate* means that the data are true, or that they agree with data obtained or obtainable on a highly-controlled instrument. As mentioned, different instrument types will result in different data and there is no obvious reason for declaring one type more accurate than another. Repeatable means that the data from successive measurements of the same sample do not differ, or do so only minimally. Reproducible means that the data from the same sample measured on different instruments are very close. Reproducibility can be expected to be good, at least for instruments of the same type.

8.2 Calibration involves the *spectral scale* as well as the intensity or *reflectance scale* of the instrument. The spectral scale is the wavelength scale, typically from 400 to 700 nm. The reflectance scale runs from 0 to 1 when reflectance is reported as a ratio, or from 0% to 100% when it is reported as a percentage. The scale may exceed 1 or 100% when there is light emission, such as in case of optically-brightened or colored fluorescent samples.

8.3 Reflectance scale calibration assures the best possible accuracy and reproducibility of reflectance measurement data when they are obtained from instruments with different construction details.

There are no perfect white materials that reflect 100% of light at all wavelengths of the spectral range of the instrument. The best materials, such as barium sulfate powder, do not form durable and cleanable solids. For this reason, white reference materials usually consist of ceramic or opaque glass-type materials with a reflectance in the 90% region. Such *working standards* are calibrated by instrument manufacturers against the theoretical 100%-reflecting white by using *reference standard* materials certified by a national or international standards laboratory, such as NIST (National Institute of Standards and Testing) in the U.S. From the calibration values, the instrument manufacturer calculates how to adjust the measured values so that they are as if measured against the theoretical 100% standard.

8.4 Accuracy of measurement requires not only fixing the 100% line of the scale for a given instrument but also the 0% line. This is achieved using a black standard in a process comparable to that described for the white standard.

8.5 With regular (usually daily) calibration, instruments can be expected to provide accurate and repeatable results applicable to the specific instrument design. For best results, the calibration schedule of the instrument manufacturer should be followed.

8.6 In modern instruments, the wavelength scale is set by the design of the diffraction grating and the instrument geometry. As a result, they do not require the elaborate wavelength accuracy checks necessary for older, mechanical instruments. Manufacturers often also provide some colored tiles for occasional checks of the wavelength scale and the intermediate reflectance scale. Significant deviations in measurement data of such tiles indicate major instrument malfunction.

8.7 Instrument calibration of the UV content of light sources for whiteness measurements requires special fluorescent standards. These standard materials have limited stability and must be replaced at regular intervals. The recommendations of instrument manufacturers should be followed in regard to all aspects of this kind of calibration.

8.8 There are occasional changes in recommended calibration procedures based on improvements in technology. Instrument manufacturers keep track of activities in this respect and are the best source of information for maintaining up-to-date calibration procedures for a particular kind of instrument.

8.9 In a commercial organization or within a supply chain, a standard method and schedule of instrument calibration should be observed. Such a procedure assures a high degree of repeatability and reproducibility of reflectance data. Regular (once or twice a year) round-robins, where identical samples are shipped to be measured with every instrument in the organization for comparison, are an additional tool for assuring reproducibility of data.

9 Textile Sample Presentation

9.1 Textile fiber materials come in many forms that require different treatment for repeatable measuring results. Loose fibers, yarns, and woven or knitted fabrics may need to be measured.

9.2 There are no official standard methods for presenting samples to the instrument but it is important to have uniform presentation procedures within a company or supply chain. Fig. 4.22 shows some typical sample preparations for measurement.

Fig. 4.22. Examples of presentation methods for different textile materials. *Courtesy of Bayer Business Services (Brockes, A., D. Strocka, and A. Berger-Schunn, Color Measurement in the Textile Industry, 1989). Used with permission.*

Loose fibers: When presented as a loose "ball' (Fig. 4.22, lower right) fibers protrude in different ways into the sample opening, producing different results. Such balls of fiber can be pressed against a flat glass plate (Fig. 4.22, center right) in a special sample holder. Glass distorts the measurement but can be corrected for by calculation with a correction formula.

Yarn: Filament yarn may be best measured after pulling a skein of yarn through a plastic tube (Fig. 4.22, lower left) and cutting the skein with a sharp knife. The measurement is made head-on against the cut. Yarns can either be presented to the instrument after attaching the skein to a special yarn holder (Fig. 4.22, upper left) or after winding the yarn in multiple layers onto a cardboard or plastic strip (Fig. 4.22, upper right). It is important to keep the requirement for opaque layers in mind.

Fabrics: Fabrics are presented in an opaque layer (if possible), placed on a solid back-up material and attached to the sample opening of the instrument.

10 Summary

All measurements of color stimuli are light measurements. Different light measurement technologies have been invented, most involving changes in electrical current as the result of the impact of light on electrically-charged materials.

Light measurement is expressed either in radiometric units that do not involve human vision, or photometric units that consider the spectral response of the photopic standard observer. Light transmitted through transparent material or reflected from opaque material is measured and expressed as spectral.

There are several standard measuring geometries. Textile materials are usually measured with diffuse/normal (or near-normal) geometry and with the specular component included. The measured sample should be as nearly-opaque as possible. To obtain spectral data, most modern instruments use diffraction gratings to disperse the reflected light.

Instruments must be calibrated according to the manufacturer’s recommendations for reliable results. Instrument calibration procedures, sample presentation, and measurement methods should be standardized within a company or supply chain for reliable results.

Chapter 5 COLOR AND COLOR VISION

1 From Light to Color

1.1 The human color vision apparatus consists of eyes and brain/mind.
Eyes contain the light sensors and produce an electrochemical signal that travels into the brain where the signals end up producing our experiences of vision, including color.

1.2 Eyes are capable of automatically handling widely varying levels of photon flow, from extremely low, at near total darkness, to very high in the brightest sunlight.

The complete process is known as light *adaptation*. There are different mechanisms in the eyes to accomplish this:

- The diaphragm mechanically changes the pupil size in response to the level of photon flow (Fig. 5.1).
- There are two kinds of sensor cells in the eye, *rods* for night vision, and *cones* for daylight vision. The rods are highly sensitive and shut down at higher light levels. The cones are not active at low light levels but become active only at a low-to-medium light level.
- There are electrochemical processes in the eye and brain that change as a result of the light level.

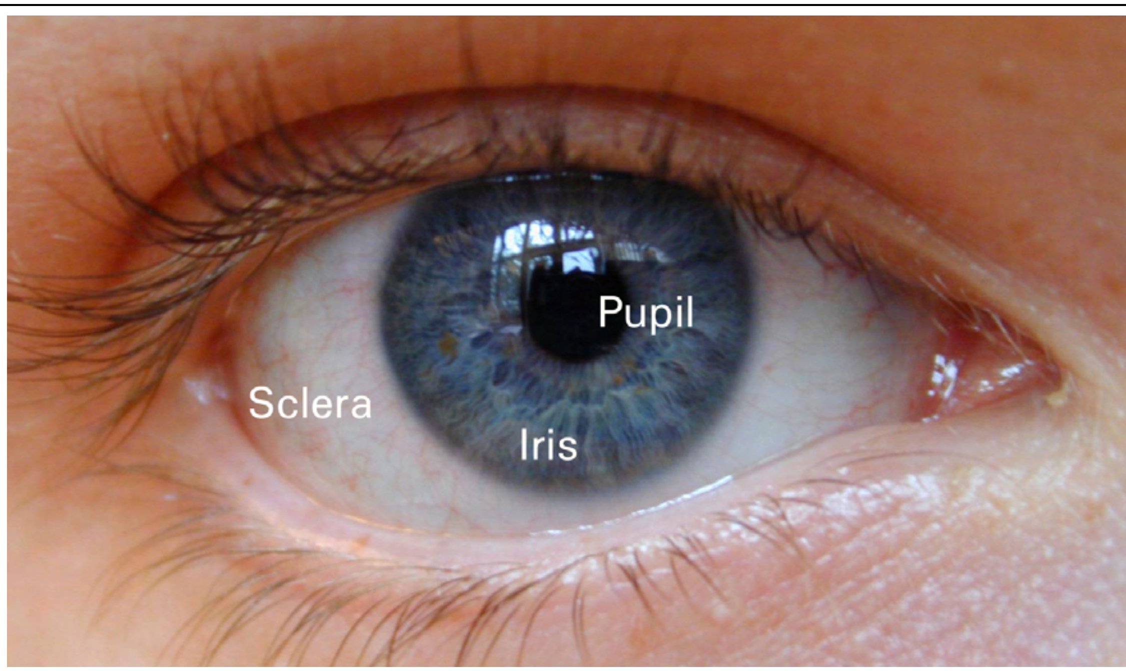


Fig. 5.1. Front view of a human eye.

1.3 The eye has many operating parts. Figure 5.2 shows a cross section of the eye. The light passes through the transparent cornea, the protective surface layer that is exposed to the world when the eye is open. Behind it is an uncolored, jelly-like substance through which the light passes before reaching the lens. The diaphragm forms a circular opening that is smaller or larger depending on the amount of light. The color of the eye is carried by the diaphragm. Muscular fibers change the form of the flexible lens so that the image of the outer world arriving at the back of the eye is always sharp (some people require the help of additional external lenses—contact lenses or glasses). Most of the eyeball is filled with a transparent jelly-like substance called the vitreous humor (glassy jelly). Covering much of the interior surface of the eyeball is the layer containing the sensor cells, called the retina. Behind the retina is a dark layer called the choroid that absorbs all photons not absorbed by the sensors.

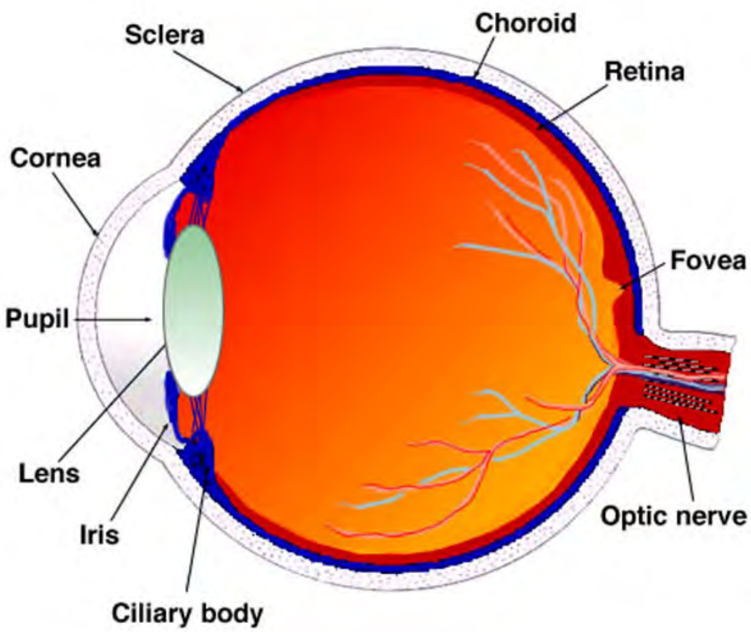


Fig. 5.2. A schematic cross-section of the human eye. Colors are for illustration only. *Courtesy of Helga Kolb, http://webvision.med.utah.edu. Used with permission.*

There is an indentation in the retina at the back of the eyeball, called the fovea. The highest density of sensor cells is here and the optics of the eye are such that the light beam is always focused on the fovea. At another location at the back of the eyeball, the nervous fibers collecting the information from the complete retina pass out of the eyeball and into the brain, forming the optic nerve. The exit of the optic nerve forms a blind spot in our field of vision of which we are normally not aware.

1.4 The layer of the retina is very complex and much information processing takes place in it. Fig. 5.3 shows a cross section of the retinal layer. The rod and cone sensors face the back of the layer and point toward the choroid. The light, therefore, passes through most of the retinal layer before being absorbed. In each eye, there are about 120 million rod and cone cells. The rods and cones connect with various other kinds of cells. They collect and modify the information passed down from the rod and cone cells and pass it along the optic nerve into the brain.

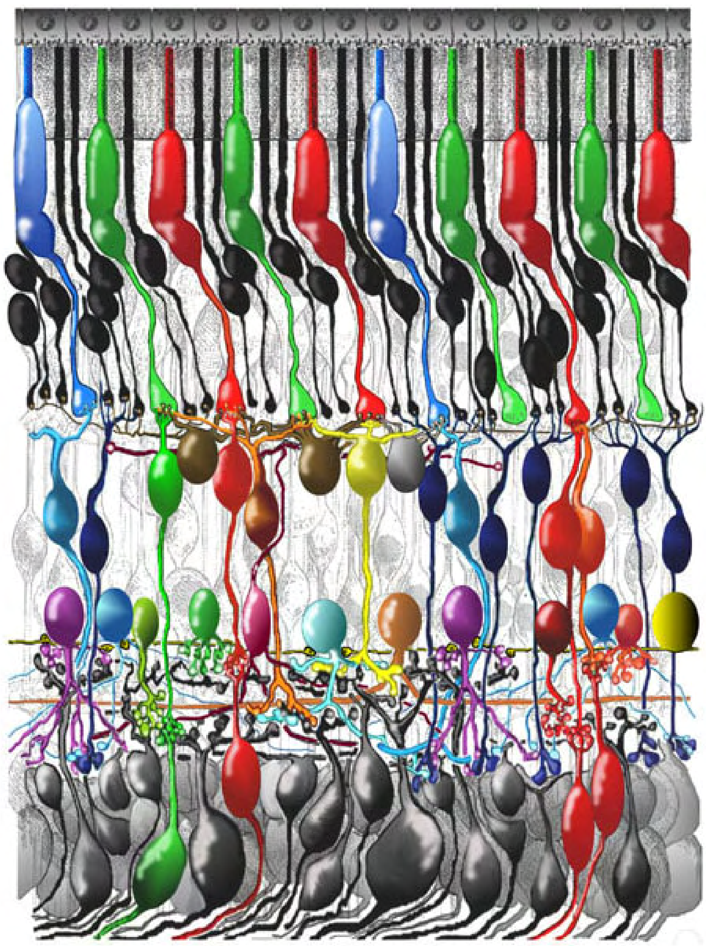


Fig. 5.3. A schematic cross-section of the retina. (Colors are for illustration only.)
Courtesy of Helga Kolb, http://webvision.med.utah.edu. Used with permission.

1.5 What the "eye tells the brain" is different from what it received and what we experience in the end is further modified (sometimes highly) in the brain. It is important to realize that the human visual system does not have the capability to accurately measure light intensity or to determine reflectance curves. The only information the brain obtains (in daylight) is the modified output of three kinds of cones in different locations of the visual field (see Chapter 6). From this information, the eye and brain construct an image of the world in front of us.

1.6 There is additional processing of the information in the brain. Considerable details (but far from all) are known. Much of the processing consists of screening out data that are not of immediate interest to the owner of the system. All of the processing and evaluation of the information is initially done subconsciously. At a given, unknown place, a small amount of the received information is “displayed” to us in consciousness as a colored experience. An “executive” system in the brain decides what the owner of the brain is to experience in consciousness and, to a degree, how. What we experience consciously is what we pay attention to, either because it is novel and interesting, desirable, or possibly dangerous.

2 Defining Color

2.1 Colors are perceptual experiences made possible by our sense of vision. We experience colors in the awake condition as well as in our dreams.

2.2 The true nature of colors is not known. There are two main competing ideas about the nature of colors:

- Colors reside in objects. We commonly assign colors to objects—This red tomato is ripe; I want to buy a green sweater. According to this idea, the eye/brain/mind apparatus simply decodes the color of the object from the “negative” image of it arriving at the eye in form of the spectral power of reflected light.
- Colors are not in objects, but something our brain assigns to spectral power distributions arriving at the eye according to some rules developed by nature.

3 Rods and Cones

3.1 The light-sensitive cells in the retina, rods, and cones, contain different natural chemicals that, when exposed to photons, cause the generation of an electrochemical signal passed down to connecting cells, as mentioned above.

3.2 There are three kinds of cones, with three slightly different chemicals, each with a different sensitivity across the spectrum. The abbreviations designate their range of sensitivity: L for long wavelength sensitive, M for medium wavelength sensitive, and S for short wavelength sensitive. The spectral sensitivity of the three cone types is shown in Fig. 5.4. There is considerable overlap in the sensitivity curves of L and M cones. Together, they provide a degree of information about the spectral nature of the light in a certain location of the visual field.

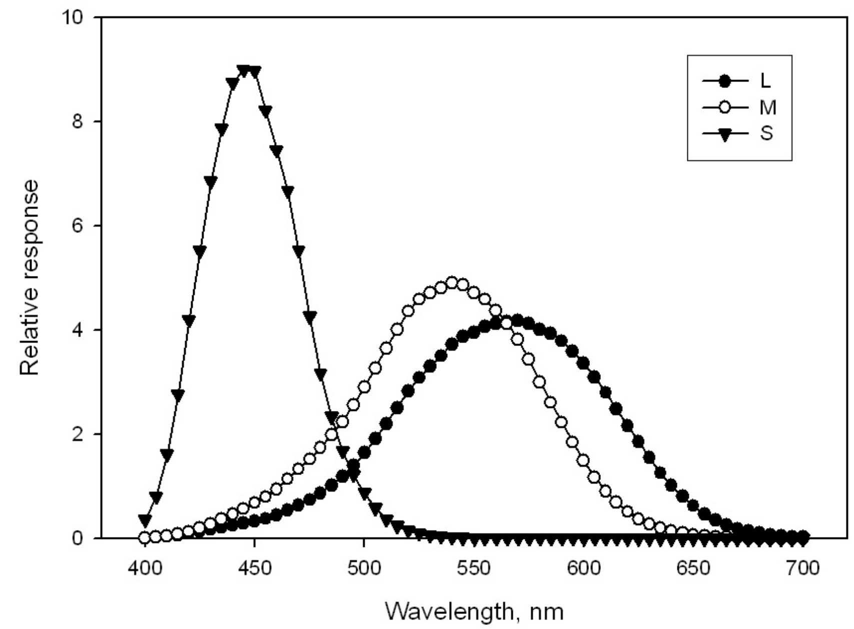


Fig. 5.4. The spectral response of L, M, and S cone types. The area under each curve is identical.

3.4 A given cone type cannot identify the wavelength of the light that makes it respond. The curves merely indicate that, for example, the chances that a photon of 550 nm will trip one of the L cone's light sensitive molecules are about ten times higher than for a photon of 470 nm. Photons in the range of 400 to 550 nm can trip any of the three cone types, but with different likelihood.

3.5 Cone absorption reduces the complexity of the information in the light that arrives at the cones (Fig. 5.5).

Cones are said to "filter" light beams in a certain way. In this process, a certain amount of the original spectral power distribution information about the light arriving at the eye is lost. However, differences in the cone responses from a specific area in our visual field are detailed enough that we can have many different color experiences.

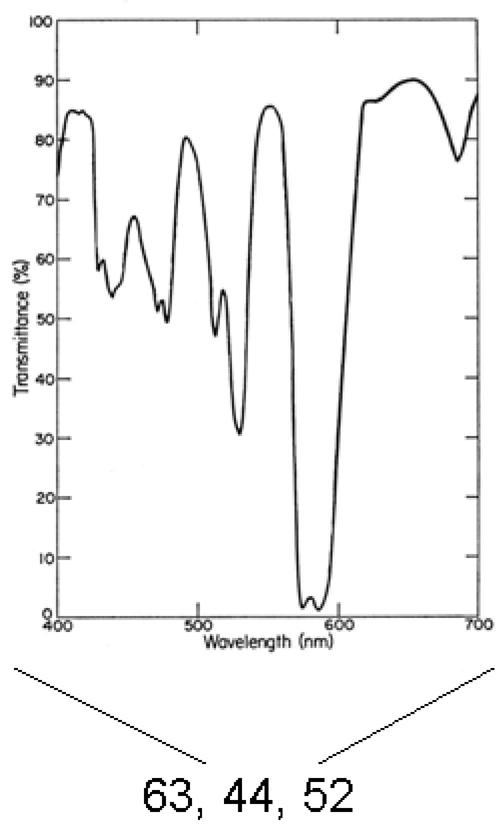


Fig. 5.5. The complex and detailed information of a spectral curve representing a field of color is reduced by the cones to three values: the response of each of the cone types.

4 The Number of Colors

4.1 The number of different color stimuli that can arrive at the eye is unlimited. We cannot distinguish all from each other, so the number of different color experiences from objects is probably about 1 million. Makers of color display units often claim that the display can produce over 16 million different colors. It can produce this number of different color stimuli but we cannot distinguish all of them. Color display units have, for each pixel, three different minute light sources that are perceived as one tiny light. Its color depends on the relative amounts of the three light sources. If you look with a magnifying glass at your display, you can see the horizontal and vertical lines that separate the pixels. Each of the three light sources of one pixel can be adjusted in intensity in 255 different steps. As a result the pixel can have 255×255×255, or 16.58 million different states.

4.2 Comparably, reflectance curves of natural or artificial objects can differ in many ways. As a result, the spectral power distributions of the lights reflected from them can differ in many ways. This can be demonstrated with idealized reflectance curves. We assume a spectral grid with 2 divisions (3 equal regions) along the wavelength scale and 2 divisions (3 regions) along the reflectance scale (Fig. 5.6). Reflectance can have the values 0, 0.333, 0.667, or 1.0. There are 64 different reflectance curves that are possible in this system (see Fig. 5.7 for two examples).

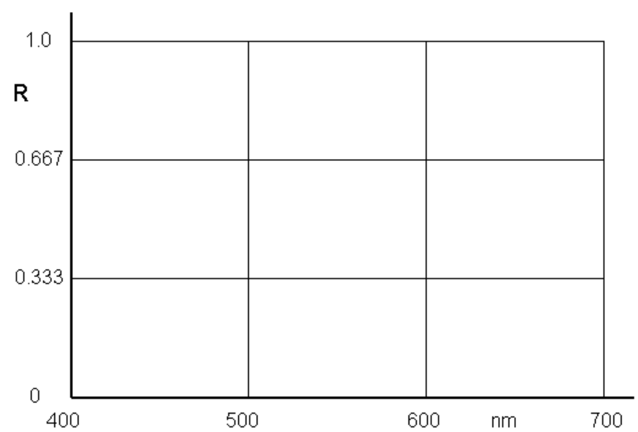


Fig. 5.6. A grid with four possible reflectance positions (0, 0.333, 0.667, and 1.0) and three wavelength divisions (400-500 nm, 500-600 nm, and 600-700nm).

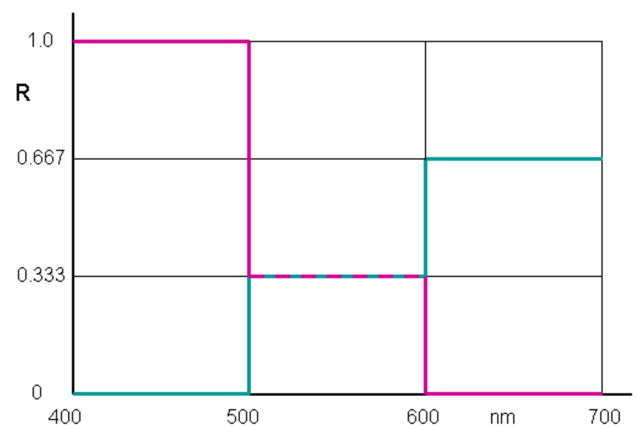


Fig. 5.7. The grid of Fig. 5.6 with two of the 64 possible reflectance functions.

By narrowing the division along the reflectance scale from 0.333 (33.3%) to 0.1 (10%) and along the wavelength scale from 100 nm to 50 nm, we end up with 1.77 million different reflectance curves. There are no problems in accurately measuring these unique curves. By going to 5% increments and 25 nm width (still accurately distinguishable by measurement), we end up with over 7 quadrillion (7, with 15 zeros!) different reflectance curves. It is important to realize that we can visually distinguish only about 1 million different reflectance curves. The ability of a spectrophotometer to measure color stimuli is much higher than the ability of humans to distinguish all stimuli.

5 Putting Color Experiences in Order

5.1 How to order colors systematically has been of interest to humans for the last 2000 years or so. Before going into details, there is a need to discuss the ways in which we can describe how color experiences differ from each other. There have been two important proposals in the last 150 years:

- Munsell system (ca. 1905)
- Hering's natural color system (1878)

American artist Albert Munsell was interested in ordering colors so that he could develop rules of color harmony for multiple color arrangements. He wanted his system to be perceptually uniform, meaning that the visual distance from a given sample to all its nearest neighbors is the same. At the same time, the order had to follow three kinds of scales: the *hue* scale, the *chroma* scale, and the lightness (*value*) scale (Fig. 5.8).

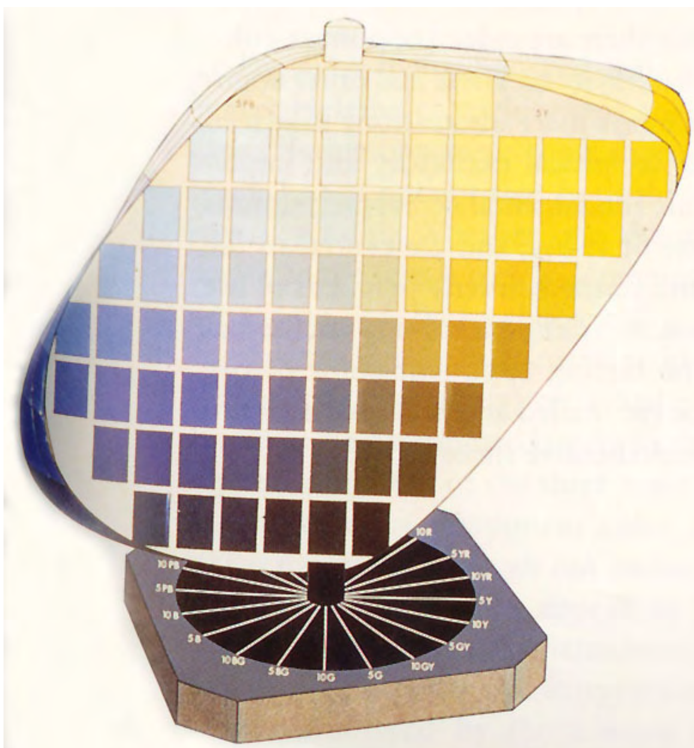


Fig. 5.8. A cross-section of the Munsell color system. The central vertical axis is the gray scale from white to black. To the left side are blue colors of the same hue but differing in lightness (vertical) and in color intensity (chroma, horizontal). The right side shows the same for a yellow hue. *Courtesy of Munsell Color, part of X-Rite Inc. Used with permission.*

German color scientist Ewald Hering also thought in terms of a hue scale but his other two scales are whiteness content and blackness content (Fig. 5.9).

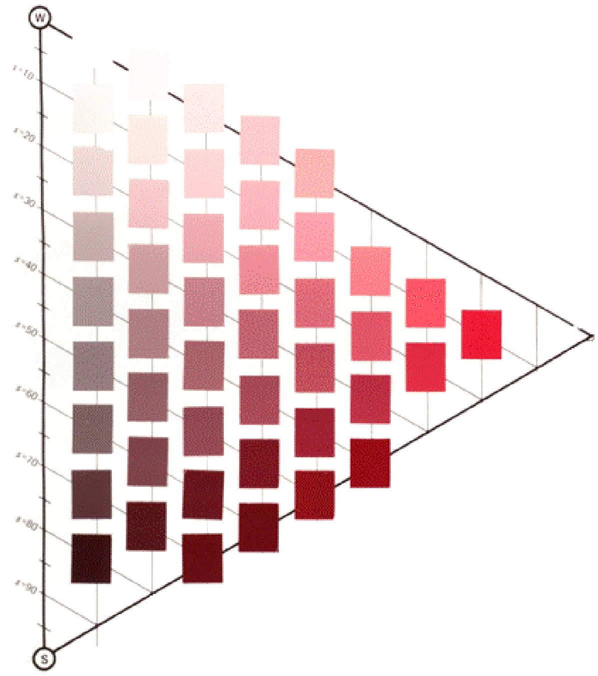


Fig. 5.9. A single hue from a modern version of Hering's system. Between white on top and black on the bottom is the (not shown) gray scale. The most intense color is center right. Along the down-slanting lines are colors of equal blackness. In the opposite direction are colors of equal whiteness. Courtesy of the Scandinavian Colour Institute AB. Used with permission.

Both kinds of systems will be further described in Chapter 7.

5.2 Hue refers to a property for which we have certain color names—yellow, green, blue, violet, purple, red, etc. There is no more objective way to define hue; we cannot describe the nature of red without referring to the term red.

5.3 The hue scale follows the arrangement of colors in the spectrum (Fig. 5.10). The spectrum is open at both ends. However, there is a logical continuation that results in a hue circle. By proceeding on the short-wavelength end in the direction of redder hues and on the long-wavelength end in the direction of bluer hues eventually we arrive at the same hue from both ends and the hues form a circle (Figs. 5.11 and 5.12).

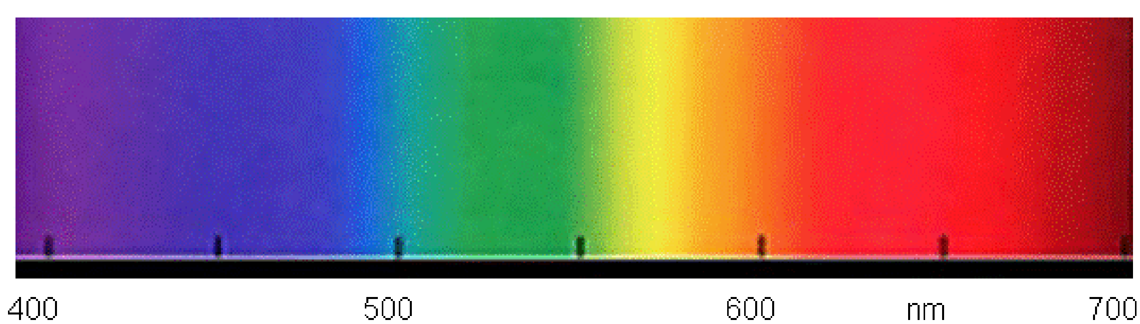


Fig. 5.10. The visible spectrum.

Fig. 5.11. A hue circle formed by the spectrum, with purple colors added to complete the circle.

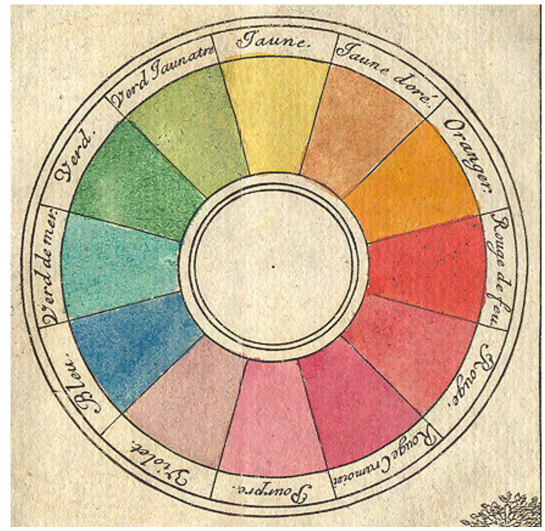


Fig. 5.12. The first printed and hand-colored illustration of a hue circle.
Anonymous, Traité de la peinture en mignature, 1708.

5.4 Chroma expresses the intensity of coloration in the color of objects (see Fig. 5.10). The term chroma applies only to object colors. It is somewhat comparable to the term *saturation* for lights. Munsell's chroma scale is open-ended (there is a theoretical limit to chroma that depends on hue). Achromatic colors have no chroma. The maximum chroma of hued colors shown in the atlas of the system depends on the pigment used to color the chips.

5.5 Lightness ("value" in Munsell's terms) applies to object colors only. It refers to the perceived lightness of an object color compared to that of a perfect white. Munsell's value scale has 11 grades, white, black, and nine grays of varying lightness where the steps from one to the next are seen to be of approximately the same size.

5.6 Hue, chroma, and lightness are called *attributes* of color. They are not the only attributes possible. For example, Hering's attributes are a special form of hue, whiteness, and blackness. Other attributes have also been proposed. A question (to be discussed below) that arises is how the attributes of one system relate to those of another.

6 The Fabric Store Experiment

6.1 Let's assume a fabric store has 500 rolls of solid-color fabric, each with a distinct color. We have small cuttings from each roll and our task is to sort these in some sensible fashion. Most fabrics have a hue but there are a few that do not, they are achromatic: a white, several gray, and a black fabric. First, we sort out the achromatic samples and order them according to their lightness.

6.2 Next, we sort the remaining samples by hue category. This requires some discussion: how many red categories, for example, should we have? For simplicity's sake we limit the categories to the following (starting with red): red, orange, yellow, yellow-green, green, blue-green, blue, violet, and purple. Many samples will be easy to place into these categories; others, such as browns, olives, pinks, and beiges, will be more difficult (Fig. 5.13). In the end there will be nine piles.

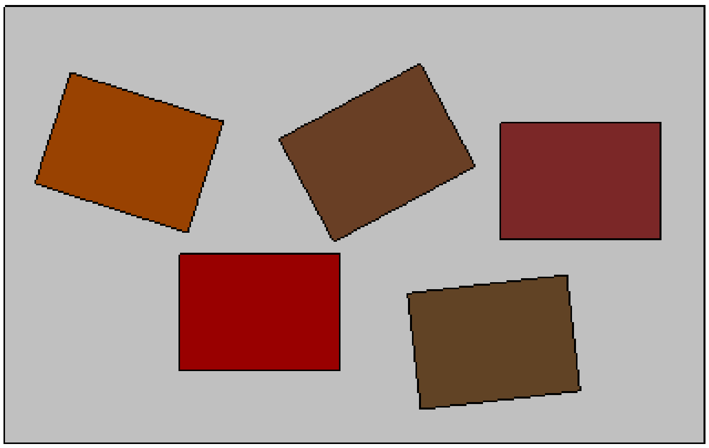


Fig. 5.13. Five different brown samples. What are their hues?

6.3 In each of the piles there will be samples of the same hue, but differing in chroma and lightness. The next task will be to separate the samples of a given hue according to their differences in chroma and lightness. This task takes some practice. Especially in the case of lower chroma samples it is not always obvious if the difference is in chroma or in lightness, particularly if the difference is small (Fig. 5.14).

6.4 For a given hue, the samples are arranged in two dimensions: chroma and lightness.

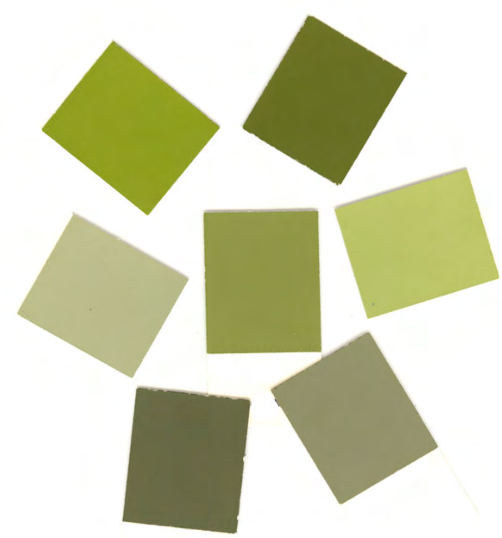


Fig. 5.14. Which samples differ in lightness and which differ in chroma from the central sample? (Some differ in both lightness *and* chroma.)

6.5 To arrange all samples into a system requires three dimensions. One possible arrangement is a cube, with one of the attributes along length, width, and height (Fig. 5.15). In this arrangement there is no hue circle. (However, most color order systems are based on the hue circle.)

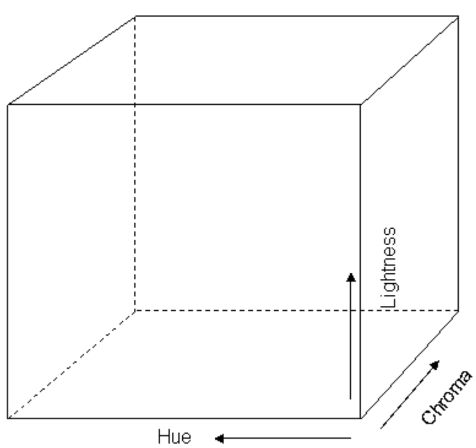


Fig. 5.15. All color samples designated by hue, chroma, and lightness might be arranged in a cube, but without the continuity of the hue circle.

6.6 Use of the hue circle results in a system that has the form of a cylinder. Munsell placed his system into a cylindrical arrangement. In the center of the hue circles is the achromatic color of the same lightness. All hues in a given circle have the same lightness and the same chroma. Chroma increases from the achromatic point in the center in steps (forming hue circles) out to the maximum that differs by hue (Fig. 5.16). Such planes at different lightness are stacked on top of each other, beginning with black and ending in white. The arrangement is cylindrical but the cylinder is filled irregularly with samples of the Munsell system (Fig. 5.17). The cylinder, like the cube, allows for systematically placing all possible object colors

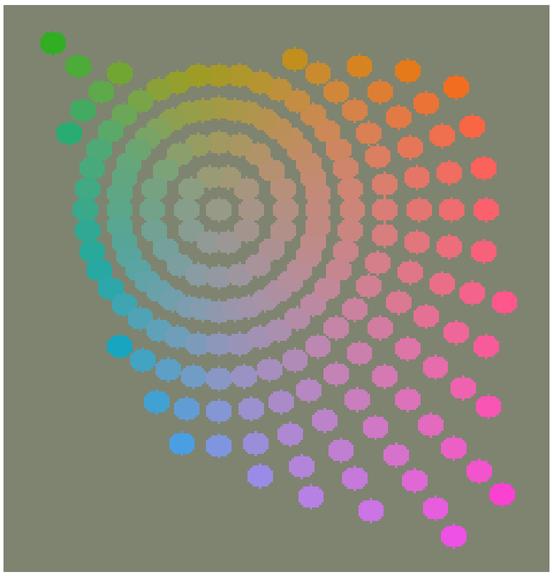


Fig. 5.16. An arrangement of samples of constant value (lightness) in hue circles of constant chroma. *Courtesy of Hans Irtel, University of Mannheim. Used with permission.*

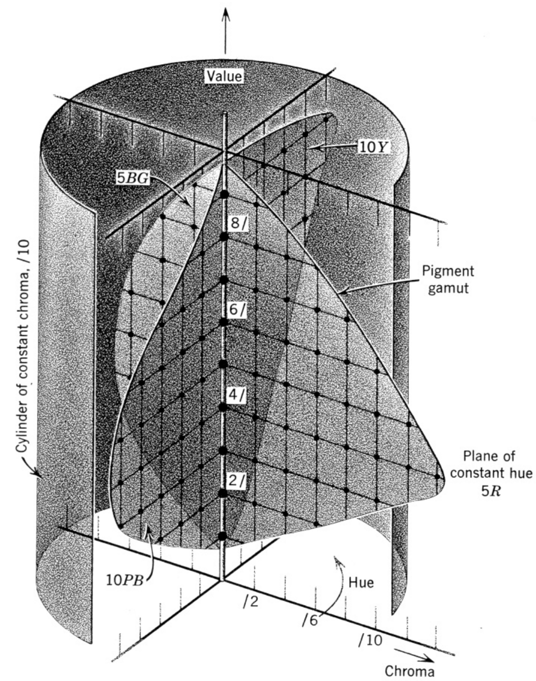


Fig. 5.17. Schematic sketch of the arrangement of the Munsell system. Only four hue planes are shown. *Courtesy of John Wiley & Sons Inc. (Wyszecki, G. and W. S. Stiles, Color Science, 1982). Used with permission.*

6.6 Our fabric samples, not being exactly of the same hue in a category and not being perceptually of equal distance from nearest neighbors, fill the cylinder even less uniformly but fit logically into the system. Each sample can be identified with a designation in the system consisting of a hue, a chroma, and a lightness grade.

6.7 Although fluorescent samples can exceed the maximum chroma and lightness achievable with non-fluorescent colorants, they can fit into the general scheme of the system.

6.8 Dyes can fill a larger portion of the cylindrical space than pigments. For most hues the "brightest" dyes can produce dyeings of higher chroma than pigments because they have sharper transitions from low to high reflectance than pigments.

7 Color Space and Color Solid

7.1 The terms “color space” and “color solid” are often used interchangeably. It is better to make a clear distinction between the meanings of the two terms.

7.2 *Color space* refers to a geometric space of three dimensions in which the *color solid* is located (Fig. 5.18).

7.3 The color solid is the usually irregular three-dimensional solid resulting from the orderly arrangement according to attributes of real or theoretically possible object colors, sitting in the color space. Depending on the chosen attributes, color solids have different forms.

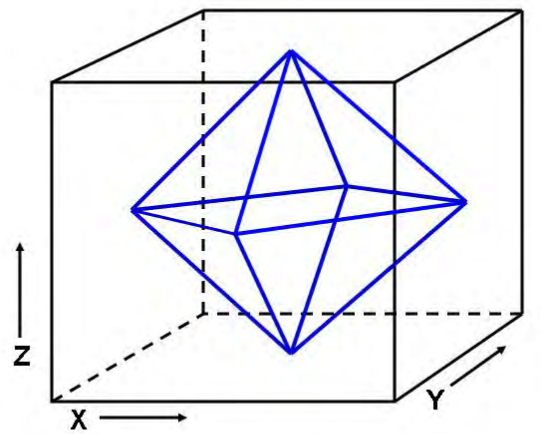


Fig. 5.18. A space in which a theoretical—in this case, regular—color solid is located, with white at the top point and black at the bottom.

7.4 The distances between individual colors in a color solid model carry different levels of information. Of particular interest are two levels: *ordinal* and *interval*.

7.5 At the ordinal level, the distances indicate only steps of order without indicating anything about the perceptual magnitude of the step. An ordinal gray scale places the grays in order of lightness without the geometric distance in the solid being an indicator of the actual perceptual distance between the samples (Fig. 5.19).

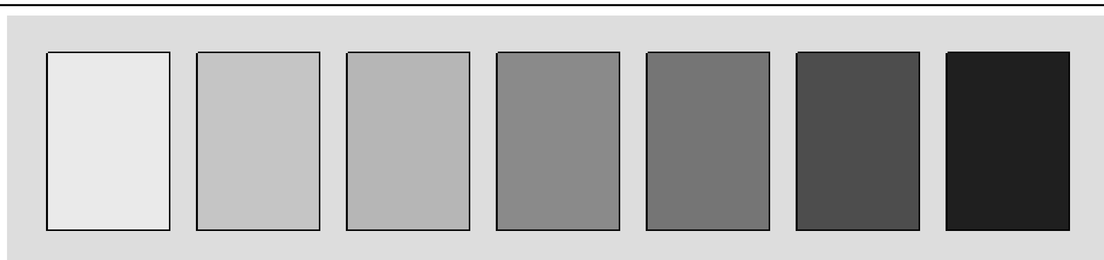


Fig. 5.19. Seven gray samples arranged in ordinal order. From left to right the samples have decreasing lightness but the lightness steps from one to the next are not all of equal size. These samples cannot form an interval scale.

7.6 At the interval level, the geometric distances between the samples located in their solid are in agreement with the perceptual distances between them (Fig. 5.20). Such a color solid contains the highest level of information. An accurate interval-level solid can be used as a basis for a color difference formula.

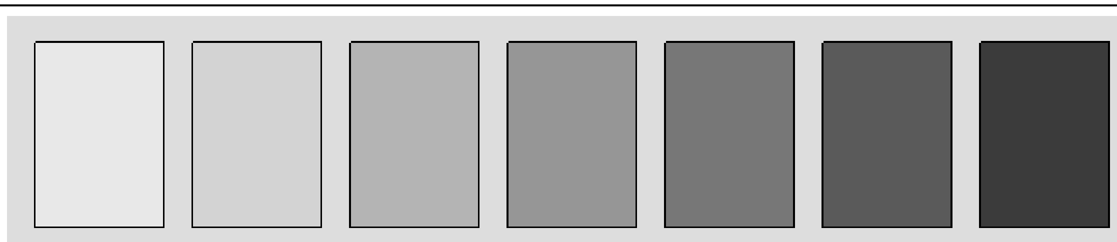


Fig. 5.20. Seven gray samples arranged in interval order. Perceived distances between steps are (approximately) the same.

7.7 Despite Munsell's attempt to make the system perceptually uniform he did not succeed for a number of reasons. The units of his three attributes differ in perceptual magnitude and he was not aware of the *hue superimportance* effect (see Chapter 13). In addition, the cylindrical arrangement does not lend itself to an accurate interval-level system, for reasons discussed in Chapter 7. The actual distances in the Munsell system between neighboring samples have only limited interval meaning and in total it must be considered an ordinal system. Hering's system is even less perceptually uniform as will be discussed in Chapter 7.

7.8 An accurate interval-level object color solid requires four dimensions and complex mathematics and has not yet been attempted. There are a number of reasons for this, to be discussed in Chapter 7.

8 Color Perception Phenomena

Metamerism

8.1 *Metamerism* refers to the fact that it is possible to have samples with often considerably different reflectance curves that, when viewed in a given light by a given observer, have identical color.

When viewed in a different light or by a different observer, the samples can look much different. Perceived color is therefore not directly related to reflectance. Similarly, a yellow light can either be of a particular single wavelength (say, 575 nm) or an appropriate mixture of a red and a green light. Fig. 5.21 shows reflectance curves of two theoretical objects that, for a given observer, are indistinguishable.

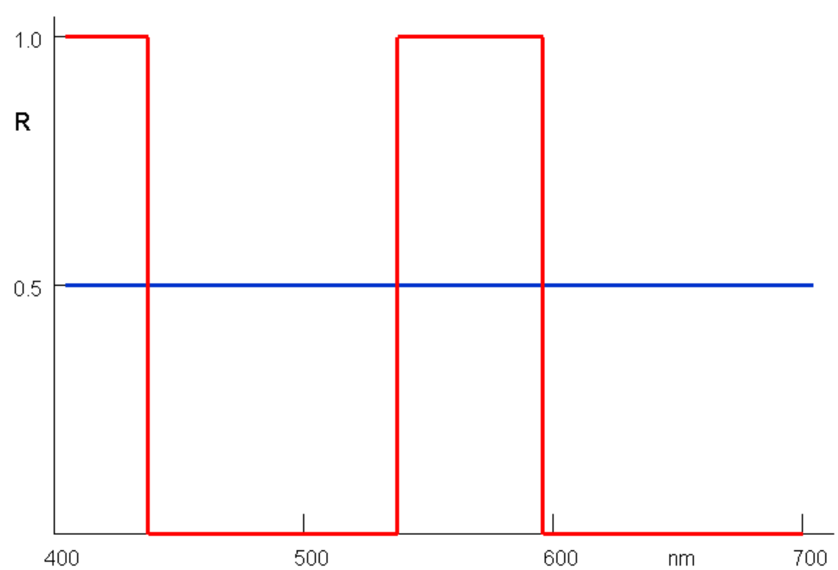


Fig. 5.21. Theoretical reflectance curves of objects that for the CIE standard observer, viewed in a "white" light with equal energy across the spectrum, would both appear indistinguishably middle gray. The reverse of the red curve (values of 1 become values of zero and vice versa) would represent a third indistinguishable metamer.

To understand the reasons behind metamerism requires an understanding of the colorimetric system, presented in Chapter 6. Metamerism and the related issue of color constancy are discussed in Chapter 11. Here, they are briefly mentioned because they are important color perception phenomena.

8.2 Metamerism is a very important aspect of color vision. Without it we would not have color photography, color television, or full-color magazine printing using only four inks. On the other hand, it causes industrial colorists a lot of grief because dye formulations for a given standard are usually metameric to some degree for different lights or different observers (see Chapter 11 for more details).

Complementary Colors and Saturation

8.3 The apparent color of spectral lights can be toned down in two ways—by the addition of “white” light, and by the addition of complementary spectral light.

8.4 Consider an experiment where the total amount of photons in a light beam is always the same, but its composition from a mixture of a spectral light and “white” light changes. With increasing replacement of the spectral light with “white” light, the intensity of color of the light, or its saturation, is reduced until it disappears.

8.5 The same effect can be achieved by replacing the “white” light with another spectral light, the complementary light, or with a purple light that is a mixture of the two lights at the ends of the spectrum. There is light of only one other wavelength that exactly neutralizes the apparent color of the original light. In appearance, the complementary light is much different from the original light, for example, a red light is neutralized by a blue-green light (Fig. 5.22). For every spectral and purple light there is a complementary light that neutralizes it toward colorless. “White” light can be matched with many pairs of spectral and purple lights. This is a special case of metamerism and shows that colorless (or “white”) light can be matched with lights of many different compositions.

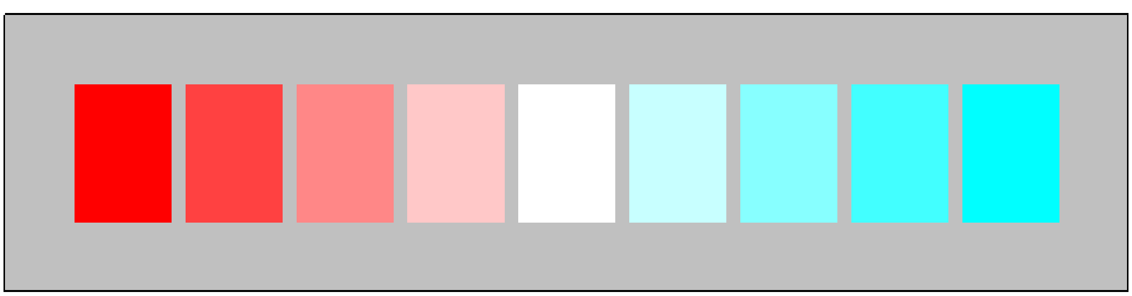


Fig. 5.22. A four-step saturation scale of a red light on the left half of the figure and the complementary blue-green light on the right. The central white can be matched by a mixture of the two most extreme lights or by the two second, third, or fourth lights. The first blue-green light from white can be matched by adding the appropriate amount of “white” light to the full blue-green light or by adding the full amount of blue-green light to the second-from-left red sample. There are other possibilities also.

8.6 Complementary lights are specific to a given observer. Individuals select somewhat different lights as exactly compensatory, that is, resulting in a light that has no hue. In Chapter 6, the complementary lights of the CIE standard observer will be identified.

8.7 A similar process operates with colorants. Figure 5.23 shows idealized reflectance curves of two pairs of dyes that when applied together in both cases form grays of completely flat reflectance at 50%. In reality, reflectance curves of dyes are rounded and irregular. There is little likelihood that one can find a yellow and a violet dye that together exactly produce an achromatic gray color, but it is not impossible.

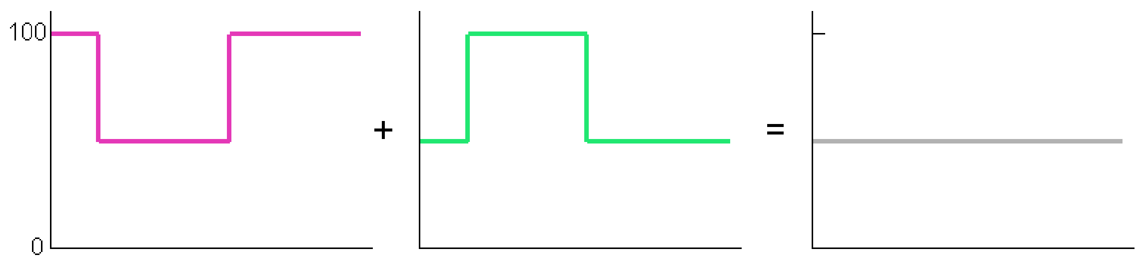


Fig. 5.23. Theoretical reflectance curves from 400 to 700 nm of a bluish red dye on a white fabric and a green dye in certain concentrations on the same kind of fabric. When the two dyes are applied together, a neutral gray (reflectance curve on the right) results. There is an endless number of combinations of two or more dyes with which the same result can be obtained.

Color Constancy

8.8 *Color constancy* refers to the fact that certain objects do not appear to change color when viewed in different lights. Other objects, on the other hand, can change in apparent color quite dramatically when viewed in different lights, including “white” lights of different spectral power distribution (e.g., natural daylight and cool-white fluorescent light). Like metamerism, color constancy will be discussed in more detail in Chapter 11.

Simultaneous Contrast

8.9 *Simultaneous contrast* refers to the fact that the appearance of colored objects can differ dramatically depending on the surrounding conditions in which they are viewed. Figs. 5.24 and 5.25 demonstrate this fact in extreme examples, the first for achromatic, the second for chromatic samples. It is obvious that the appearance of these samples is not directly related to the reflectance. Simultaneous contrast is important in textile and other design. Most objects change color appearance when their surrounding colors change (Fig. 5.26). They change most noticeably if the surrounding color is similar to that of the object. This effect allows us to distinguish objects differing only slightly from neighboring objects or the surround (Fig. 5.27).

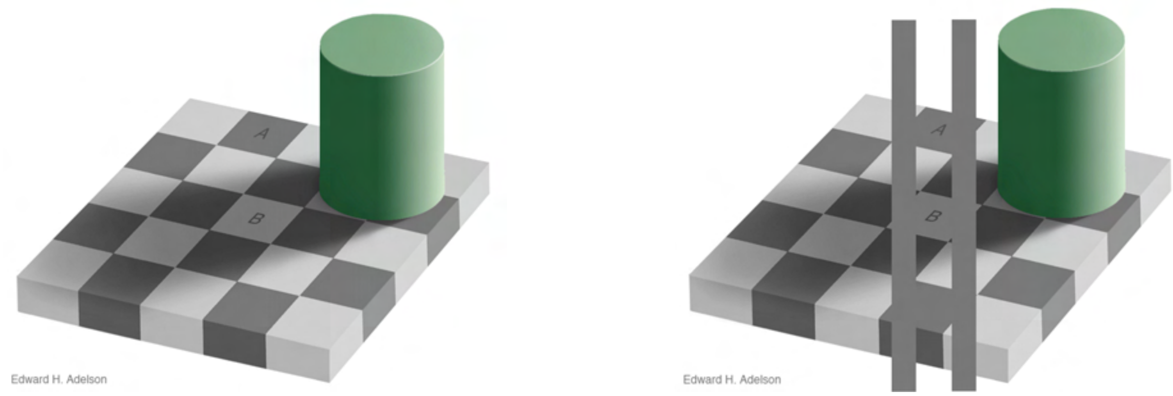


Fig. 5.24. The reflectance curves of the two areas marked A and B are identical. In the second figure, two strips of uniform, identical gray have been added to prove this fact. Note that the strips themselves seem to vary slightly in lightness even though they are uniform.
http://web.mit.edu/persci/people/adelson/checkershadow_illusion.html.

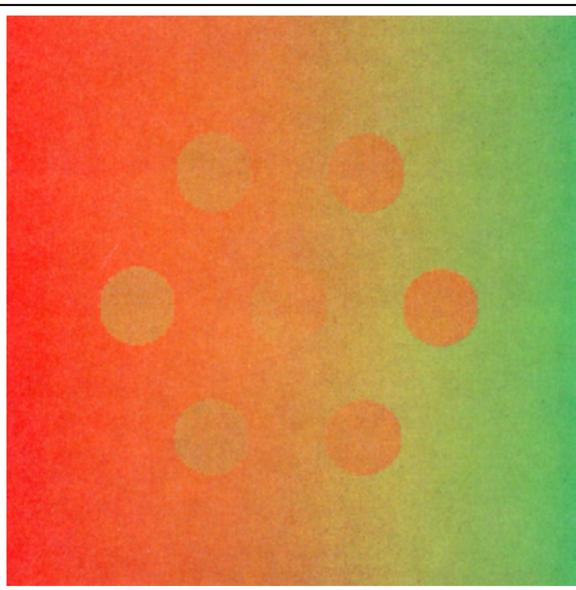


Fig. 5.25. All five circles in this figure have identical reflectance curves. Their difference in color is the result of simultaneous contrast against the surrounding colors. Against the green surround, the circle looks reddish and vice versa.

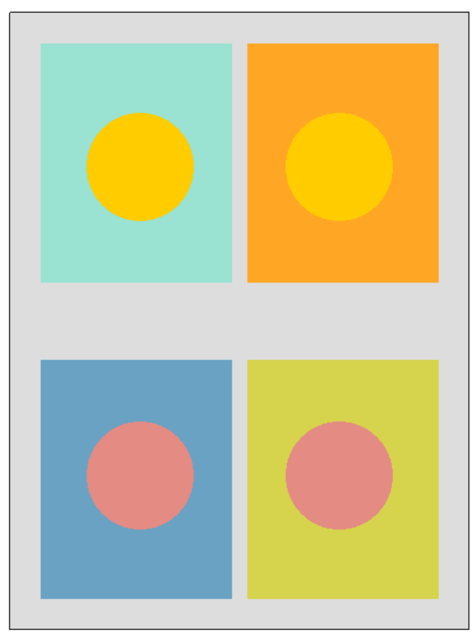


Fig. 5.26. Despite their appearance, the two yellow circles on top and two pink circles on the bottom are physically identical.

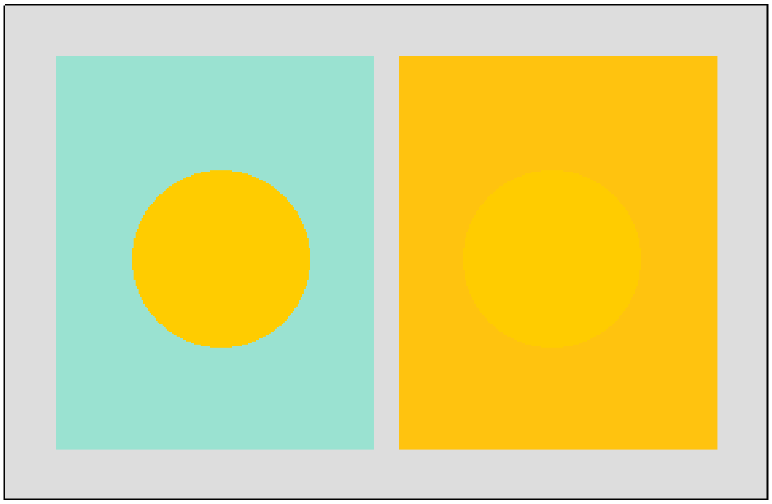


Fig. 5.27. The greener appearance of the yellow circle on the right compared to the circle—identical in reflectance—on the left makes it more easily distinguished against a surround that is very similar.

Successive Contrast or Color Afterimage

8.10 The *successive contrast* afterimage effect occurs when looking for some time at a strongly-colored object or when looking at a strongly-contrasting scene. A well-known example is the image of the American flag in "reverse" colors (Fig. 5.28). When staring at the white dot in this image for some time without shifting the gaze and then changing the gaze to a neutral region, such as a white wall, a fleeting image of the flag in its normal colors appears. Similarly, when in a dark room, looking at a window through which lots of light enters, and then shifting the gaze, we experience the reversal of the image with a light surround and a darker area where the window's image is.

Fig. 5.28. Inverse US flag. Stare at the white dot in the center for about 30 seconds; then shift your gaze onto a white sheet of paper. You will see an image of the flag in its normal colors that will fade away after a short time.

8.11 Afterimages are the results of imperfection of processing in the visual system. Images imprinted on a particular location of the retina will weaken the performance of the cones in that area and can be experienced in negative form until the spot on the retina has recovered its neutral state.

8.12 In the case of hued fields of color, the afterimage hue is the so-called *complementary hue*. Complementary hues are roughly opposite in a color order system like Munsell's from the original hue. This matter will be discussed further in Chapter 6.

Chevreul Effect

Fig. 5.29. Chevreul effect. Even though the bars are all uniform they appear shaded, looking darker against the lighter neighbor and lighter against the darker one as a result of simultaneous lightness contrast.

8.13 The Chevreul effect (named after the 19th century French chemist who investigated simultaneous contrast) refers to apparent changes in the lightness of adjoining bands of colors (Fig. 5.29)

Helmholtz-Kohlrausch Effect (HKE)

8.14 According to the HKE, despite the fact that a gray field reflects in terms of the photopic observer the same amount of light as hued color fields, the gray field looks considerably darker (Fig. 5.30).

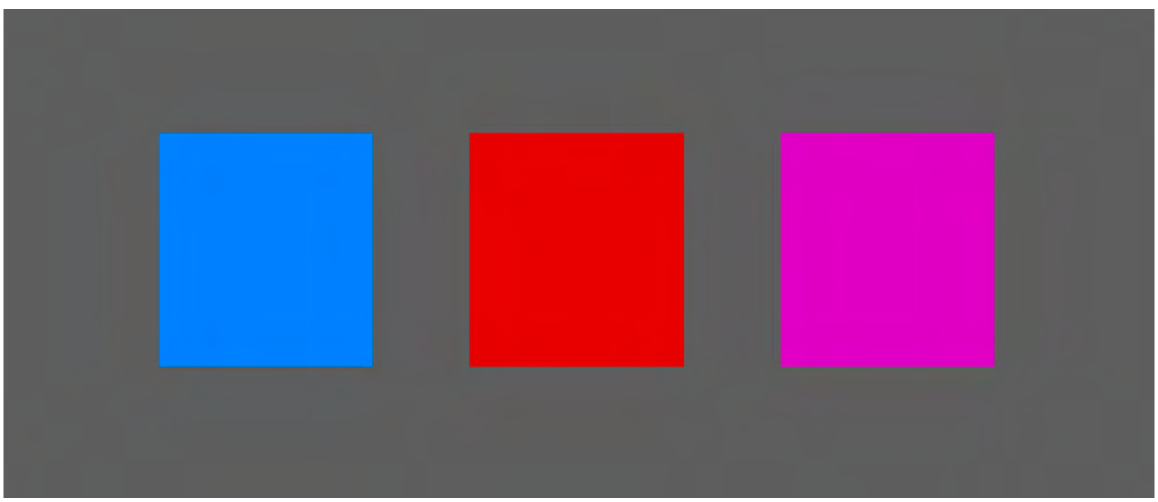


Fig. 5.30. The lightness as measured with a photometer (see Chapter 4) is the same for the three chromatic samples and the gray surround, even though the hued samples appear much lighter.

The implication is that chromatic colors result in some lightness perception of their own. This effect is important when arranging colors in a system according to lightness. For example, in the Munsell system the samples are arranged according to uniform lightness according to the photopic standard observer and not to perceived lightness.

Lightness and Chromatic Crispening

8.15 These are contrast effects related to perceived differences between color fields, such as a standard and sample pair. Lightness crispening refers to the fact that a lightness difference between two samples looks largest if the surround has a lightness that falls between those of the two samples and smallest if the surround lightness is far away from those of the samples (Fig. 5.31). As a result, the surround has a significant impact on the judgment of perceptual lightness differences between samples. To have a better chance at obtaining comparable results at different locations of testing, the surround conditions must be the same (say, in light booths).

Fig. 5.31. Examples of lightness crispening. The six gray fields in both parts are physically identical, but their apparent lightness differs in the two surrounds. The biggest difference between two neighboring samples on top is between the first and second samples from the left; on the bottom it is between the fourth and fifth samples. In both cases, these samples are nearest in reflectance to the surround, one higher, the other lower. The reason in both cases is the lightness crispening effect. Note that on top, the darker samples look more similar than on the bottom, and vice versa.

8.16 Another way of expressing this is to say that in order to perceive a lightness difference of a given magnitude, the reflectances of the samples require the least amount of difference if the surround lightness falls between the lightness of the two samples.

8.17 *Chromatic crispening* refers to the comparable fact that in order to see the same perceived magnitude of difference between two samples against a gray standard surround their difference in reflectance is smallest for a near gray pair and largest for high-chroma pairs (Fig. 5.32).

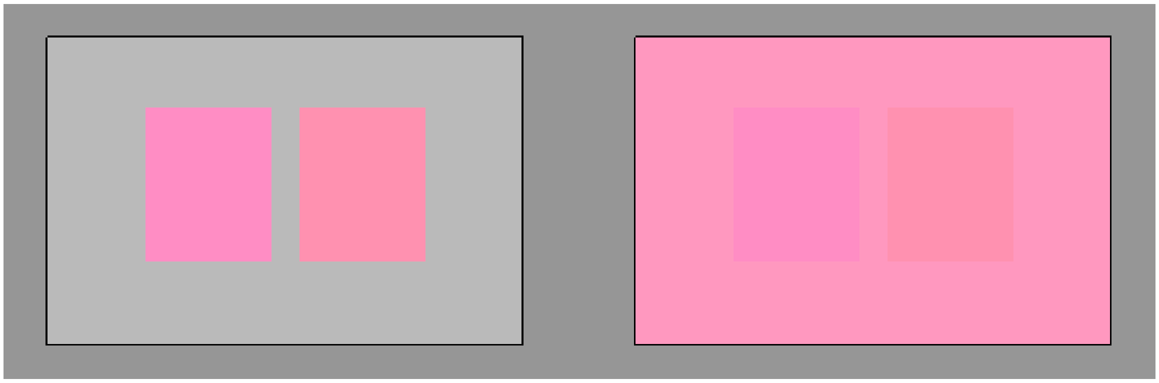


Fig. 5.32. The inset pink samples in the left field are identical to those in the right, even though the difference between those in the right field appears much larger. The cause is the chromatic crispening effect that makes differences between a field and its surround larger if the two are similar, and in this way helps us to distinguish between them. The visual effect depends to some degree on the quality of the monitor and the level of illumination in the room when viewing it.

8.18 These are important facts to consider when creating a mathematical model of color difference based on reflectance data (see Chapter 13).

Color Assimilation

8.19 *Color assimilation* is an effect where, contrary to simultaneous contrast, certain fields of color are “taking on” color from neighboring fields (Fig. 5.33). In this figure, the reddish spirals have identical reflectance curves despite the fact that one appears orange and the other bluish red. The red fields assimilate yellow from neighboring fields in one case and blue in the other. Color assimilation is an effect opposite to chromatic contrast. When larger fields of color are next to each other the result is contrast, when the fields are small and multiple the result is assimilation.

Fig. 5.33. Assimilation effect illustrated by the Munker illusion. The two red spirals are physically identical. Note that the red color on one becomes bluer as the spiral nears the center point and the other yellower. The smaller the neighboring fields, the stronger the assimilation. *Copyright Akiyoshi Kitaoka, 2002. Used with permission.*

Color Spreading and Fill-in Effects

8.20 Color spreading and fill-in effects refer to the curious situation that in given situations, our visual system generates apparent color where there is no directly related light stimulus.

8.21 The neon color spreading effect creates apparent "fluorescent" (slightly glowing) fields of pale color where there is no corresponding stimulus (Fig. 5.34 a and b).

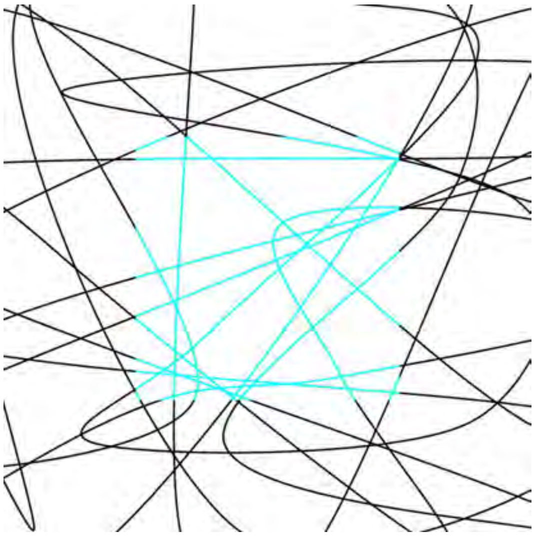


Fig. 5.34a. Neon spreading effect. Note that the outline of the milky bluish square disk is an illusion. Physically, there is nothing there but the blue segments of the lines.

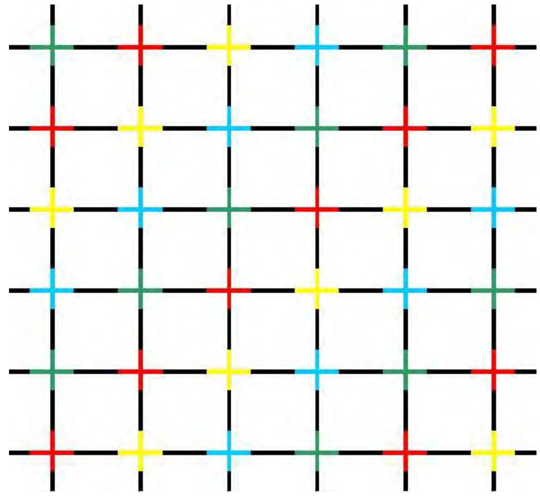


Fig. 5.34b. The apparent little color circles are illusions. Physically there are only color segments in the black bars.

8.22 Of similar nature is Pinna's recently discovered watercolor effect (Fig. 5.35). It requires that the fields in which a color spreads without a stimulus present are enclosed.

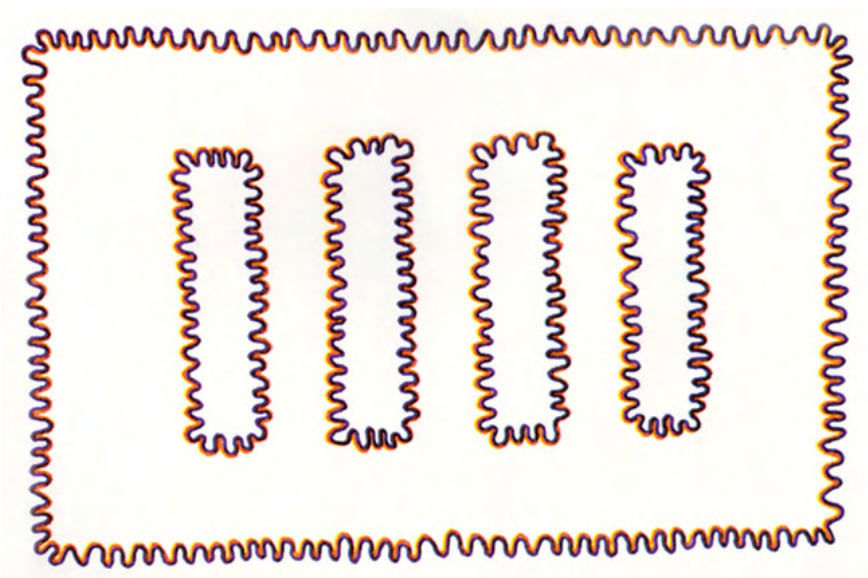


Fig. 5.35. Pinna's watercolor effect. The faint orange coloration of the area between the outside and the four interior contours is an illusion. Physically, the reflectance of this area and the white surround is identical. *Courtesy of Elsevier, 2001 (B. Pinna, G. Brelstaff, L. Spillmann, Vision Research, Vol. 41, pp2669-2676). Used with permission.*

There are several more kinds of color perception effects. Those discussed here are of importance either in regard to textile design or in regard to color quality control of textile materials.

9 Same Stimulus; Different Experience

Color Impairment

9.1 So-called color-impaired or color-blind persons are known to have different color experiences from those of so-called color-normal persons. Color impairment results from:

- Lack of one, two, or all three cone types in the retinas of the affected persons
- Light absorption by cones that have a more or less abnormal sensitivity curve
- Malfunctions of the visual system in the brain. These are usually caused by genetic variation or by neurological problems.

9.2 Missing or non-normal expression of cones is genetically caused. Males are more affected than females because males have only one set of related genes (inherited from the mother), while females have two sets (from both father and mother), making errors less likely. The rate of incidence is about 8% of the male population and about 0.5% of females.

9.3 Persons with three cone types are known as *trichromats*, those with only two as *dichromats* and those with one as *monochromats*. Trichromats with non-normal cones are known as anomalous trichromats.

9.4 Many tools are available today to detect color impairment. Such tests are usually in the form of color charts (Fig. 5.36). Testing usually takes place in early school grades. Persons with impaired color vision can operate largely normally in life but should avoid training and employment for jobs that require normal color vision.

Fig. 5.36. A test chart for impaired color vision. Observers with a certain type of color vision impairment cannot identify the number in the image.

Super-normal Color Vision

9.5 Genetic DNA analysis of females has shown that some have the genetic potential to have four or perhaps even five different cone types. Females actually having more than three cone types have not been identified with certainty. It is not evident how their color vision experiences would differ from those of normal trichromats, because the result depends on how the additional cones are "wired" in the color vision system of such persons.

Different Experiences

9.6 There is a common assumption that all trichromats have the same color experience from given spectral power distributions of light, but we have no tools to compare our color experiences. Since we cannot describe our color experiences in a quantitative manner, such comparisons are verbal and vague. As children, we have learned that adults call certain fields of color by certain names but this does not show that we all have the same experiences when looking at them.

9.7 A peak behind the curtain is possible with the concept of unique hues. Unique hues are part of Ewald Hering's theory of color perception (see section 5). Hering's idea was that humans have four basic hue experiences: yellow, red, blue, and green. All hue experiences are either of unique hues or mixtures of two of them (Fig. 5.37). Unique red is a red hue that is experienced as neither having a yellowish nor a bluish component in it, but is "just plain red." A comparable situation applies to the other three unique hues. In Hering's arrangement, the four unique hues are placed in opposing pairs. This implies that there is no reddish green and no yellowish blue, and this agrees with our normal experiences. This arrangement places all hues into the conventional arrangement in a hue circle, as indicated in Fig. 5.37.

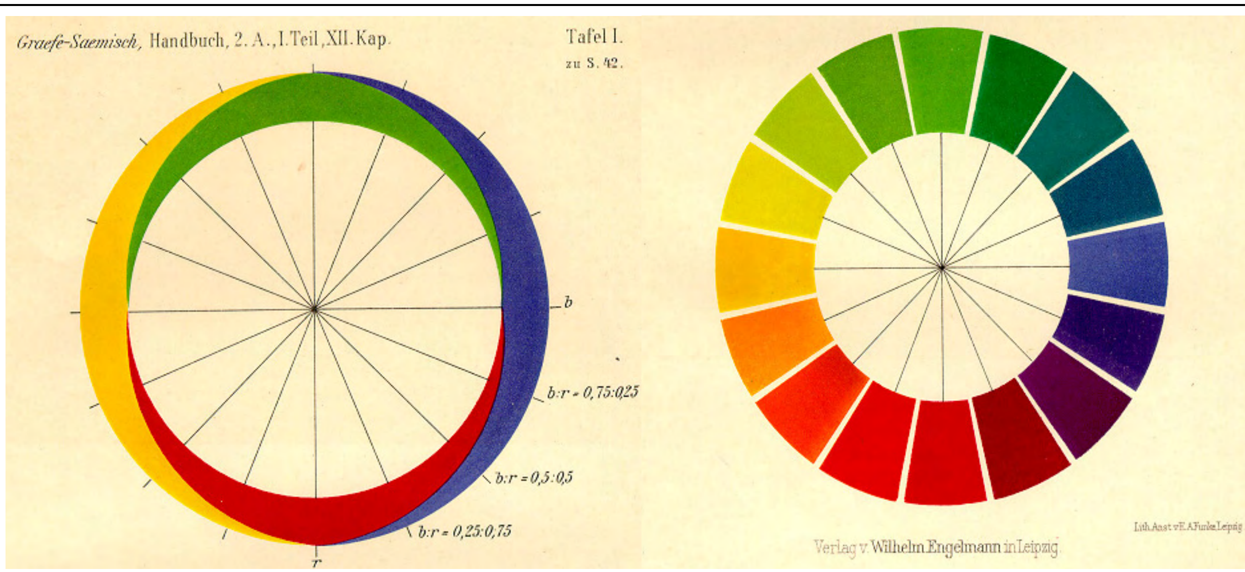


Fig. 5.37. Hering's color circle (right) and an illustration of how the circle colors are created from the four unique hues (left). Each color is a unique hue or a mixture of two neighboring unique hues (three ratios are shown on the right). *Hering, E., Grundzüge der Lehre vom Lichtsinn, 1920.*

9.8 If all color-normal persons have the same hue experiences when looking at given samples they should agree which samples in a hue circle, that is which color stimuli, result in perception of the unique hues.

In this manner, there is a tool that lets us in a limited way compare the hue experiences of individuals. We can still not know that they are the identical experiences; we only know that a given sample is identified by a given individual as having a red hue without any yellowishness or bluishness in it.

9.9 Experiments requiring individuals to pick samples that for them represent the four unique hues indicate considerable variability in the selection of the samples. In a given visual situation (samples, light, and surround) most observers pick their choices reliably from one time to the next. Similar differences have been found when using lights rather than samples.

9.10 If the samples used in the experiment are the 40 samples of a Munsell hue circle at the same chroma and value, the total extent of the four ranges of samples having been picked as representing unique hues encompass approximately 65% of the complete hue circle (Fig. 5.38).

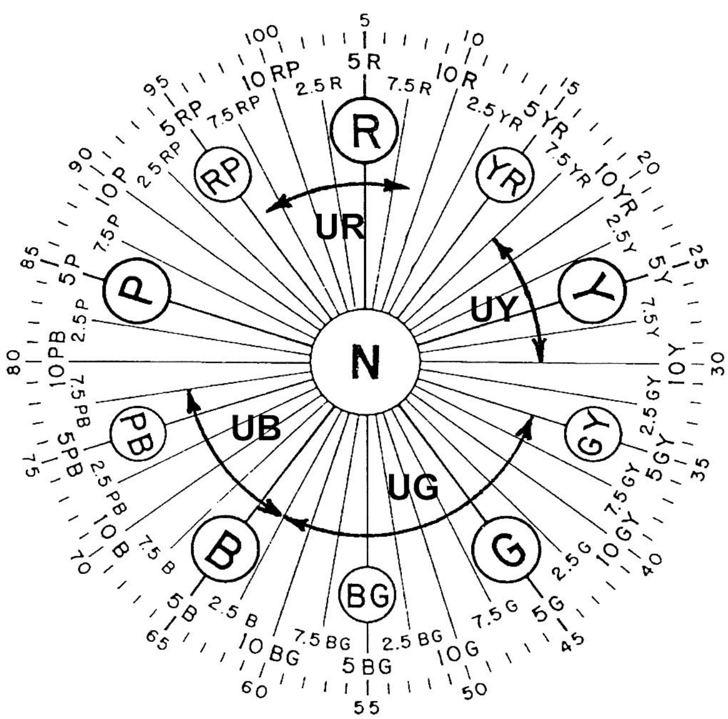


Fig. 5.38. The Munsell hue circle with the ranges of samples people with normal color vision have picked as representing unique red (UR), yellow (UY), green (UG), and blue (UB). Note that the range of green samples is the largest. *Courtesy of Brill Academic Publishers (Kuehni, R. G., Journal of Cognition and Culture, Vol. 5, Nos. 3-4, 2005, pp 387-407. Used with permission.*

9.11 It is evident from these results that color-normal individuals can experience the hues of samples with given reflectance curves, or lights with given spectral power distributions, quite differently. There is no absolute standard by which one result can be judged to be true and the others in error.

9.12 The impact of this matter on visual color difference judgments is unknown at this time.

10 Color Judgments

Threshold Determinations and Color Difference Judgments

10.1 Threshold determinations are determinations of the minimal changes in the flow of photons to the eyes necessary for the observer to detect a perceptual difference between the two different stimuli.

Examples of threshold determinations are:

- Threshold of light versus no light: It measures how many photons of a given wavelength are necessary for an observer to detect them as light in complete darkness.
- Chromatic threshold: The change in spectral power distribution and intensity of a light required so that the resulting color experience is no longer achromatic (gray), but chromatic in the direction of all the hues of the hue circle.
- Color difference threshold: How does the reflectance of a test sample (and with it, the resulting spectral power distribution of the reflected light) have to change so that the observer experiences a *just noticeable difference* (JND) compared to the reference sample? As discussed in section 4 above, we can reliably measure different spectral power distributions in the billions, but we can only distinguish about one million object colors. In a piece of equipment where the observer can change the spectral power distribution of light at will, a JND is represented by the change in spectral power distribution from a certain point (or the change in reflectance of a dyeing) required for the observer to perceive a difference. A smaller change does not result in a perceived difference and a larger change results in an obvious difference. Differences larger than JND are known technically as *supra-threshold differences*.

Such thresholds can be measured at any place in the solid of all object colors and in any direction in three dimensions away from the reference sample.

10.2 *Judgment* refers to making visual estimates of distances larger than thresholds, of supra-threshold differences. Supra-threshold differences can be from small to large. Small supra-threshold differences are those of interest in color quality control. Differences in color atlases are often about 10 times the size of JNDs. Perceived differences between a saturated yellow and a saturated blue dyeing are huge, but only of theoretical interest.

Absolute and Relative Judgments

10.3 Absolute judgments refer to judgments made in the absence of a reference. These are the most difficult judgments and often nearly impossible to make. In the case of a light, the question might be, “How strong is this light?” For a sample, “How blue is this sample?” Like the question by the medical doctor, “How strong is your pain?” such questions are difficult to answer in a meaningful way.

10.4 In color quality control, a question asking for an absolute judgment is, “Is this sample an acceptable match to the standard?” The answer to this question can be based on the observer’s personal preferences or, more likely, on past positive and negative experiences with a customer.

10.5 Relative judgments are made against a reference sample or a reference pair. For light, the question becomes, “Is this light brighter or less bright than the reference light?” In the case of chroma, “If the reference sample has a chroma of 8, what is the chroma of the test sample?” In the case of a color difference, “If the difference between the two gray reference samples has a value of 2, what value does the difference between the two test samples have?” or “Which of the differences is larger, that between samples A and B or that between samples B and C?”

10.6 While relative judgments are easier than absolute judgments, the question arises whether humans have the built-in capability of reliably make judgments of this kind. As yet, no brain/mind apparatus has been discovered that could be the basis for such judgments. Humans can make judgments quite reliably on an ordinal basis (see section 7, above), especially if the samples only vary along one attribute. Judgments become more difficult if samples differ in all three attributes at the same time.

10.7 The *Farnsworth-Munsell 100-hue test* (FM) is a test of ordinal judgment along the hue attribute (Fig. 5.39). The FM consists of a series of “color plugs,” circular color samples, which differ from each other in hue only. The ordinal judgment is to place the plugs into the correct hue order. Individual observers differ in their ability in this test. Observers with impaired color vision can be identified by characteristic errors in the sequencing. Among color-normal observers, the percentage that can complete the test error-free is small. There are no comparable tests for lightness and for chroma but it has been established that observers have the most difficulties in making ordinal chroma judgments.

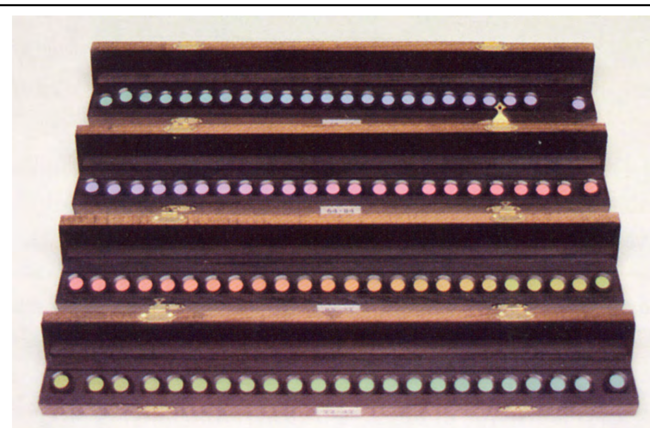


Fig. 5.39. The four boxes with the 85 color plugs of the Farnsworth-Munsell 100 Hue Test. The task is to sort the plugs from a random pile according to hue. *Courtesy of Munsell Color, part of X-Rite Inc. Used with permission.*

10.8 The difficulty of judgment increases in case of general color differences. The problem is that the observer is asked to compare “apples and oranges.” The reference sample pair typically consists of a pair of gray samples with a given difference between them. The test pair can display a lightness difference, a hue difference, a chroma difference or, as in most cases, some combination of the three.

10.9 Judgments are not measurements. The dictionary definition of judgment related to this discussion is “the process of forming an opinion or evaluation by discerning and comparing” (Merriam-Webster’s Collegiate Dictionary). “Evaluation” is defined as “to determine or fix the value of.” When making judgments, humans subconsciously and consciously include a whole range of factors. Judgments are rarely made value-free. The past experiences on which observers base their judgment vary widely and as a result, it should not be surprising that judgments vary widely.

10.10 The reliability of color judgments varies widely by observer. Some observers, for as yet unknown reasons, make color judgments quite reliably, that is, they repeat themselves well for samples viewed under the same circumstances but at different times. For others, the *intra-observer variability* is greater.

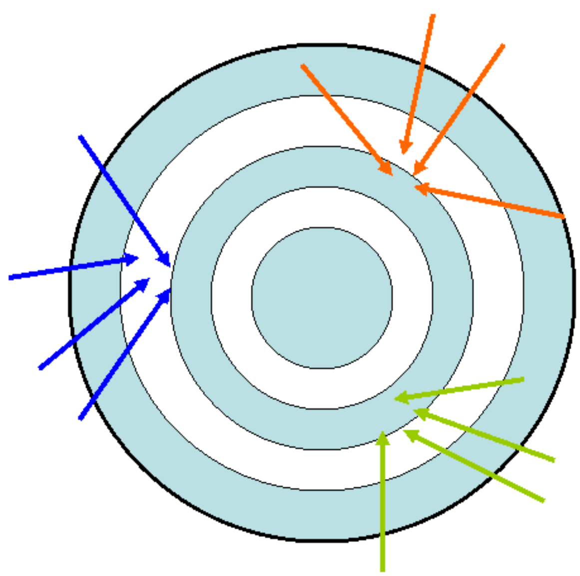


Fig. 5.40. Judgments symbolized as bow-and-arrow shooting results. The three shooters, each with a different arrow color, shoot reliably but their results do not agree and they are away from the center.

10.11 Reliability of judgment does not mean agreement of judgment. Three observers may each make reliable judgments, but there is likely to be a degree of *inter-observer variability*. (Fig. 5.40).

10.12 In case of color differences, there is no objective basis for judgment. There is no physically determined yardstick for perceptual color differences. Thereby it cannot be determined which of the reliable observers in Fig. 5.40 has the true answer. As a result, the procedure has been to calculate average results for a number of observers (usually more than 20) and consider these average results to be the truth. This means, however, that the results of a large percentage of observers would have to be considered in error, a situation that is not factual.

As will be discussed in Chapter 13, color difference formulas have been fitted to average visual results so that the average visual result can be predicted with reasonable accuracy from differences in reflectance measurement. It is evident from sections 8-10 that there is much room for differences between calculated color difference values and the judgment results of an individual observer.

11 Observer, Lighting, and Surround

11.1 The most important factor in regard to the results of color perceptions and judgments is the visual apparatus of the observer and the contents of her/his brain/mind.

11.2 Conditions in which color fields are presented to observers are also important but secondary. Such factors include the spectral power distribution and intensity of the light in which the samples are viewed, the relative positions of light, sample, and observer, and the immediate and larger surround conditions around the samples. For this reason, it has become standard practice to evaluate samples in light boxes with controlled lighting and controlled surround.

11.3 Several professional organizations have issued standards for lighting, geometry, and surround conditions for visual color evaluations. While these aspects are secondary in affecting visual results, they are, unlike the observers, controllable. It is important to assure within a company and a supply chain that these controllable factors are being controlled.

12 Reasons for Color

12.1 The color sense provides much improved distinction of the appearance of objects compared to black and white only. Monochromats see the world in white, grays, and black. They can distinguish perhaps 35 different levels of gray. Dichromats can theoretically distinguish about 100,000 different colors. Trichromats have an approximately 20-fold increase, bringing distinguishable colors in total (lights and objects) to some 2 million.

12.2 Trichromacy is limited to humans and other primates (apes), as well as old-world monkeys (living in Africa and Asia).

12.3 The usual animal dichromatic system consists of S and L cones and is known as the “ancient system.”

12.4 The M cone makes possible much improved distinction between mid-wavelength and long-wavelength photons in the region of the spectrum that results in green, yellow, and red appearances (Fig. 5.41). Trichromatic monkeys have a much better chance of locating yellow and red fruit in green leaves. In certain plants with edible leaves, they are able to distinguish the reddish young leaves, better digestible, from the older green leaves. In addition they are better able to distinguish concealed predators.

Fig. 5.41. Comparison of a natural scene in black and white, and color illustrates the value of color vision and, in particular, the value of being able to make fine distinctions between green, yellow, and red.

12.5 Early humans profited from the same abilities. In addition, the color sense aided developing mental abilities in categorizing objects to be able to remember them and describe them.

12.6 Colors were a major force in the development of works of art, starting with cave painting about 35,000 years ago. Staining and dyeing fabrics with natural dyes became routine activities some 8,000 years ago.

12.7 Like music for the sense of hearing, the ability to experience colors with the visual sense resulted in visual arts, fancily-colored clothing, interior and exterior decorating, cosmetics, and many other distinctly human abilities (Fig. 5.42).


Fig. 5.42. Printed men's wear fashion of the early 21st century.

13 Summary

Colors allow us to experience small spectral differences in photon flows (lights) for the purposes of object identification and distinction and to store these experiences in memory for later mental comparisons.

Much is known about processing of color signals in the eye and certain parts of the brain, but we do not yet have a clear understanding of the nature of colors. Trichromats can distinguish about 1 million different colors of objects that can be ordered in a three-dimensional solid. The human visual system is particularly sensitive to differences in spectral power distributions that result in perceived hue differences.

There are a number of special color vision effects, either for a specific purpose or as the accidental result of the operation of our visual system.

Color-normal humans seem to differ widely in how they experience given spectral power distributions. We have a similarly wide variation in how we judge differences between colors. This makes the development of accurate mathematical models of the color sense difficult.

Chapter 6 THE COLORIMETRIC SYSTEM

1 Color Measurement versus Color Stimulus Measurement

1.1 Sensory experiences cannot be measured in an objective, physical sense; only the stimuli producing the experiences are measurable in such a way. Clearly, the differences between experiences cannot be objectively measured. They can be estimated on a relative basis by comparison with reference examples, as discussed in Chapter 5. Results of such individual estimates tend to vary considerably.

1.2 Color stimuli can be measured objectively, but due to the complex interactions between light and objects, the results depend to some degree on the exact conditions of measurement. For comparable results, measuring instruments must be in agreement with standards, and standard procedures for measurement must be observed. As discussed in Chapter 4, accuracy (how closely the results match those of a certified institute) and repeatability (how closely the results of a given instrument can be repeated on the same instrument) of reflectance measurements are quite high for well-defined samples.

1.3 As discussed in Chapter 5, measured color stimuli are often not directly related to the color experienced. Evidence for this includes metamerism, color inconstancy, and contrast effects. Individual experiences from given stimuli vary much more than generally known.

1.4 To predict color experiences from stimuli requires a theory that, for any given situation, relates the stimuli to the experiences. Mathematical models are used to express such theories.

Because of the variability of experiences among color-normal observers, such models have the highest accuracy for only a small percentage of observers. As a result, they are in some level of disagreement with the results for other observers. Such a theory is expressed in a colorimetric system.

1.5 The term colorimetry means color measurement, but in reality, refers to color stimulus measurement for the reasons given above.

2 A Brief History of the Colorimetric System

2.1 The colorimetric system relies on spectral power measurements of lights and/or spectral reflectance measurements of objects.

2.2 It also relies on a *standard observer*, expressed in terms of a specific kind of experimental results.

2.3 It assumes a very simple and unrealistic color vision system in which color experiences can be predicted from the results of photon absorption in the three cone types.

Three Fundamental Color Experiences

2.4 The idea that all or most colors can be matched, that is, reproduced, with three colorants, yellow, red, and blue, was first clearly expressed in writing in 1664 by the chemist Robert Boyle.

2.5 In 1758, German astronomer Tobias Mayer proposed a system of ordering colors based on a triangle, with the three primary colorants red, yellow, and blue, in the corners (Fig. 6.1). Intermediate steps were obtained by changing the ratios of two or all three colorants in regular steps.

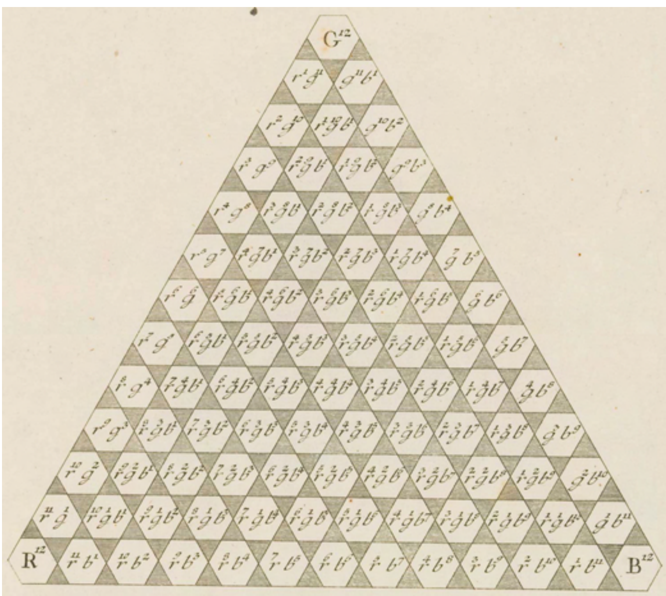


Fig. 6.1. Tobias Mayer's 1758 triangular mixture diagram with the primary colors red (R), yellow (G), and blue (B) in the corners. For all other samples the composition in parts of the primaries is indicated. *Mayer, T., Opera inedita Tobiae Meyeri, 1775. Image courtesy of Edinburgh University Library.*

2.6 That humans may have three "kinds of fibers" with different responses to light of different wavelengths in their eyes was first proposed in 1777, in a book by the English glass merchant George Palmer.

2.7 The idea was next proposed in 1802 before the Royal Society in London by the physicist and astronomer Thomas Young. Experimental work to provide (indirect) proof for the idea was done in England in the mid-19th century by J. C. Maxwell, and in Germany by H. von Helmholtz.

2.8 The technique used by these researchers is based on *metameric color matching*. Maxwell was among the first to use this method. He matched the appearance of spectral lights at different wavelengths with combinations of three lights of different specific wavelengths. He plotted his results in an equal-sided triangle (Fig. 6.2), similar in concept to the one by Mayer (Fig. 6.1) but applicable to lights, where each of the three *primary lights* (the spectral lights A, B, and C which he used to match all others) was located in a corner. He used spectral lights from the beginning, middle, and end of the spectrum. Matched spectral lights are indicated by x's with a number (the number is an abbreviated value for the frequency of the light, rather than the wavelength). For example, light 32 (yellow) could be matched exactly with a certain amount of the red primary light A and a slightly different amount of the green primary light B. The figure also shows that "white" light can be matched with, for example, specific amounts of yellow light 32 and blue light 60 (this situation was already briefly discussed in Chapter 5).

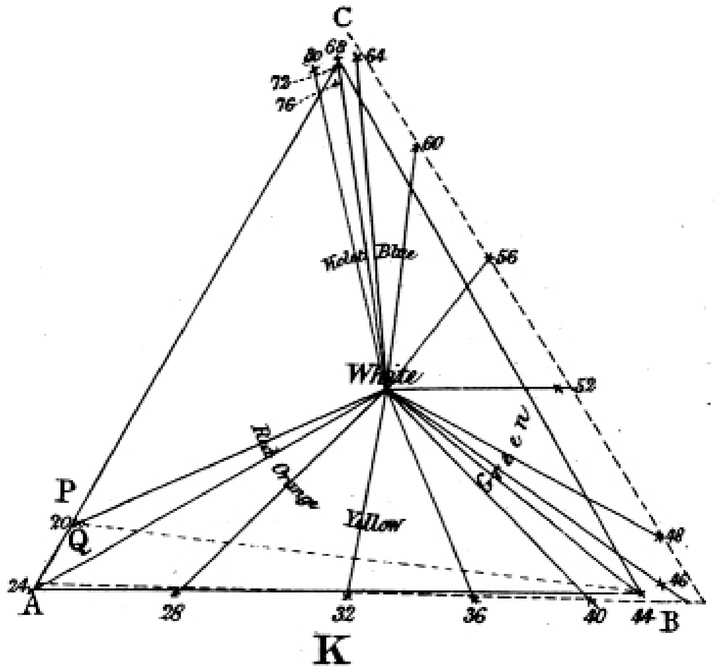


Fig. 6.2. Maxwell's mixture triangle with the primary spectral lights A, B, and C in the corners. Lines from white with "x" at the end indicate the matching results for his wife Kathrine (K) at different wavelengths. *Courtesy of the Royal Society (Maxwell, J. C., Proceedings of the Royal Society (London), Vol. 10, 1860, pU29. Used with permission.*

2.9 The arrangement in the triangle indicates that the central white can be matched with many other combinations of two wavelengths. The implication of the triangle is that the central white can also be matched with appropriate amounts of all three primary lights (that is, lights A, B, and C) and with many other triple light combinations. In fact, the triangle implies that "white" can be matched with an infinite number of different combinations of spectral lights.

2.10 Between the violet (C) and green primary lights (B), the "x"s of the spectral lights are located outside the triangle. This indicates that they cannot be matched exactly in appearance with the two primary lights. They match in hue but not in saturation. The conclusion is that it is not possible to match all spectral light appearances exactly with three primary spectral lights.

2.11 Maxwell plotted the amounts of the three primary lights required to match the spectral lights against their frequency (Fig. 6.3). The resulting three curves are an approximation of the sensitivity curves of the three cone types.

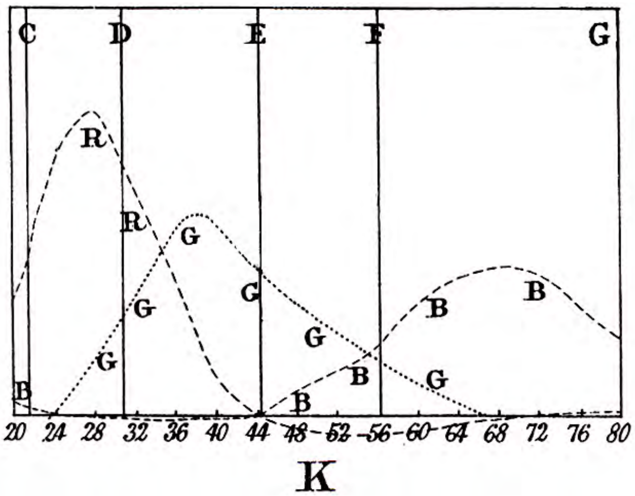


Fig. 6.3. Amounts of the three primary spectral lights needed to achieve matches at different wavelengths. Note the negative amount of red light required for wavelengths between 44 and 68. *Courtesy of the Royal Society (Maxwell, J. C., Proceedings of the Royal Society (London), Vol. 10, 1860, pU29. Used with permission.*

2.12 Quite accurate experimental determination of spectral curves of three “fundamental colors” (the cone sensitivity functions) were produced in the late 19th century by Helmholtz’s assistant Artur König (Fig. 6.4).

These curves are plotted against wavelength and are the approximate reverse of Maxwell’s curves of Fig. 6.3. When properly scaled, they are quite similar to today’s accepted cone sensitivity functions (Fig. 5.5). They show individual differences for two observers, as Maxwell had already found.

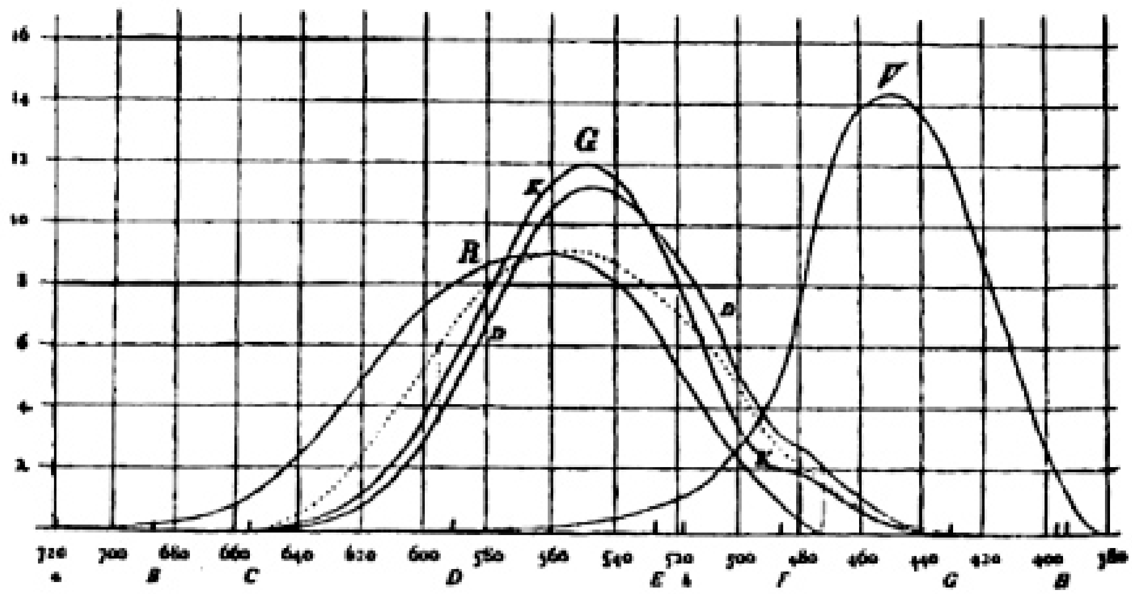


Fig. 6.4. König’s spectral functions from 380 (right) to 720 (left) nm of the three “fundamental colors” (the relative cone functions). R stands for the L cone; G, with different results for two observers, stands for the M cone; and V stands for the S cone. The dashed line indicates the sensitivity of rods. *König, A., Zeitschrift für Psychologie und Physiologie der Sinnesorge, 1892, pp241-347.*

2.13 When the spectral colors are plotted in a Maxwell triangle with the three fundamental colors—the cone functions—in the corners, the resulting curve falls on or inside the triangle (Fig. 6.5). The corners no longer represent spectral lights, but the sensitivities of the cones. The line P shows mixtures of the spectral lights at 400 and 700 nm, the so-called purple colors.

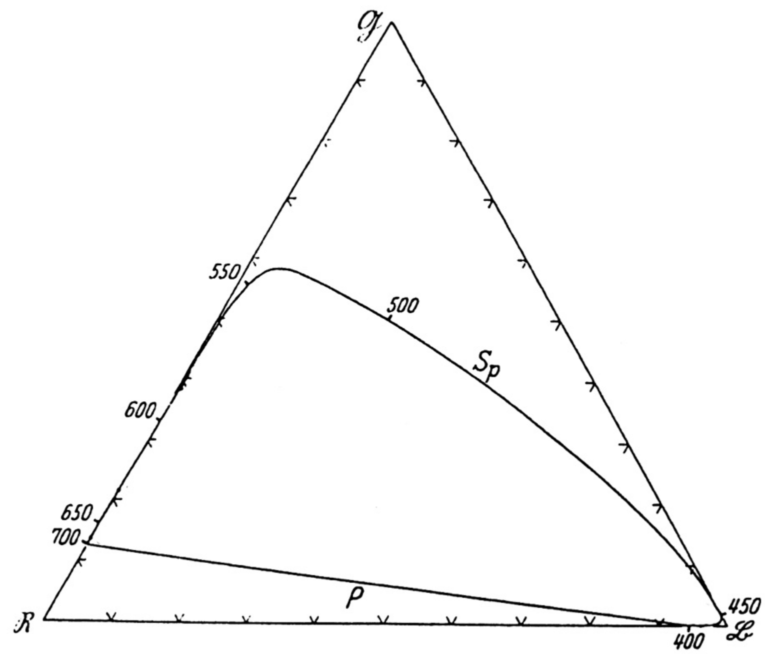


Fig. 6.5. A 1928 image of the Maxwell-type triangle with the three “fundamental colors” (the cone sensitivities) in the corners and the line formed by the points of spectral colors (Sp), as well as the purple line (P). *Rösch, S., Physikalische Zeitschrift, 1928, pp83-91.*

3 Cones Responses to Different Lights

3.1 Cones reduce the amount of information contained in light, that is, they “swallow up” much of the wavelength information in a photon stream. It doesn't matter what the wavelength of the photon was, only whether it is of a wavelength to which the cone can respond. A broadband light with equal energy across the spectrum (Fig. 6.6, top), when striking cones can, on average, be described by multiplying its energy at each wavelength by the sensitivity of the cone at that wavelength (Fig. 6.6, bottom), and summing the values. The result in the example is 100 (because the cone response has been scaled in this manner, see Table 6.1 for the spectral values of cone response from 400-700 nm). The information contained in the light has been limited in the example to one value, 1.0.

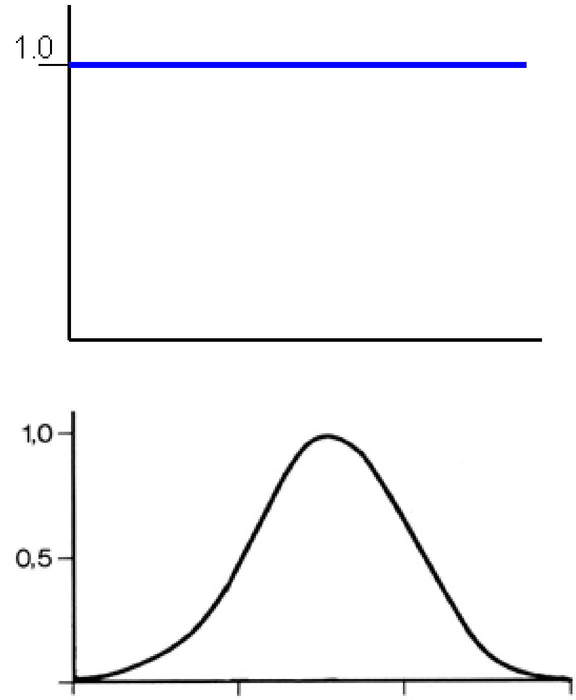


Fig. 6.6. Top: spectral power curve of an equal-energy light source.
Bottom: spectral sensitivity curve of the M cone type.

nm	M
400	0.023
410	0.098
420	0.268
430	0.545
440	0.940
450	1.369
460	1.896
470	2.664
480	3.485
490	4.476
500	5.800
510	7.298
520	8.727
530	9.441
540	9.803
550	9.440
560	8.744
570	7.621
580	6.003
590	4.457
600	2.987
610	1.817
620	1.026
630	0.545
640	0.275
650	0.135
660	0.064
670	0.030
680	0.014
690	0.007
700	0.003
Sum	100.000

Table 6.1. Values of the spectral sensitivity of the M cone.

3.2 The same result is obtained from the cone in response to a number of spectral power distributions of light (metamerism). For light of a single wavelength, say 540 nm, the amount of light energy to obtain the same result of 100 for M cone absorption has to be 10.2 times higher than it is in the light of Fig. 6.6 (10.2 times 9.803 = 100). The value of 9.803 comes from Table 6.1 at 540 nm.

For two lights of wavelengths 490 and 610 nm, the amount of energy can be 13.4 for 490 nm and 22.0 for 610 nm, because $(13.4 \times 4.476) + (22.0 \times 1.817) = 100$. For a band of lights from 540 to 610 nm, the amount of the light has to be only 1.97 times higher than the equal energy light because $1.97 \times 50.87 = 100$ (the number 50.87 is the sum of the function values from 540 to 610 nm in Table 6.1). All these combinations are metameric (for the M cone only!) to the equal energy light—the response value of the M cone is 100 for each combination.

3.3 What applies to one cone also applies to the system of three cones with different spectral sensitivities. A given spectral power curve results in certain values of response in each of the three cone types. Another spectral power curve may (in a metameric match) produce the same response. Two extremely different spectral power curves that are metameric for the standard observer are shown in Fig. 5.22.

An important side-effect of this situation is that once accurate mixture data for one set of three primary lights have been established (for a standard observer) the results for another set of three primary lights can be calculated mathematically. Technically, this is known as *linear transformability*. The conditions are changed (three different primary lights), but the basic information gained from the experiment remains the same. It is as if one looks at a cube from different angles: the view changes, but the cube remains the same. Only one form of the data describes the cone response curves but other forms may be of more practical use as long as they contain the same basic information.

3.4 Once average spectral data for the cone sensitivities are agreed upon, we can predict whether any two spectral power curves are a metameric match or not for the standard observer.

3.5 Since all color stimuli are lights, this is a powerful method to understand color mixture, both of lights and of colorants. However, there are some problems, the biggest being that individuals differ quite significantly in their individual cone sensitivity functions. As a result, it is necessary to define a standard observer, the observer that represents the mean of all individual observers. A match for one person may not be seen as a match by another.

3.6 As mentioned in Chapter 5, there is no clear relationship between a color stimulus and the resulting experience for an individual. The result of calculations in a system can only provide information as to whether lights (or by implication, objects) match, and only for the standard observer. It can only tell in a very loose way about appearance.

While matching or not matching may be determined at the cone level of the visual system, final experiences obtained from a given stimulus are the result of much more complex “calculations” in the brain, as discussed in Chapter 5.

4 The CIE Colorimetric System

4.1 As mentioned earlier, CIE is an abbreviation derived from the French name of an international organization: International Commission on Illumination. This commission, formed in the early 1910s has since provided international guidance on standard procedures dealing with illumination and related subjects, such as color. Its test methods and recommendations provide worldwide guidelines for national standards. Additional information about the organization is available on its website www.cie.co.at. CIE has eight divisions, two of which are of great interest in regard to color, Division 1: Vision and Colour and Division 2: Measurement of Light and Radiation.

4.2 As mentioned in Chapter 3, the CIE defined the photopic standard observer to describe the average brightness response of color-normal observers to light of the spectrum. This made it possible to convert power measurements of light to measurements expressing the average person's response to it.

4.3 In the first quarter of the 20th century, colorimetric systems were established independently in various countries. These were based on different kinds of measurements and were mostly incompatible. It was of interest to develop an internationally-accepted colorimetric system to enable international communication about color stimulus data.

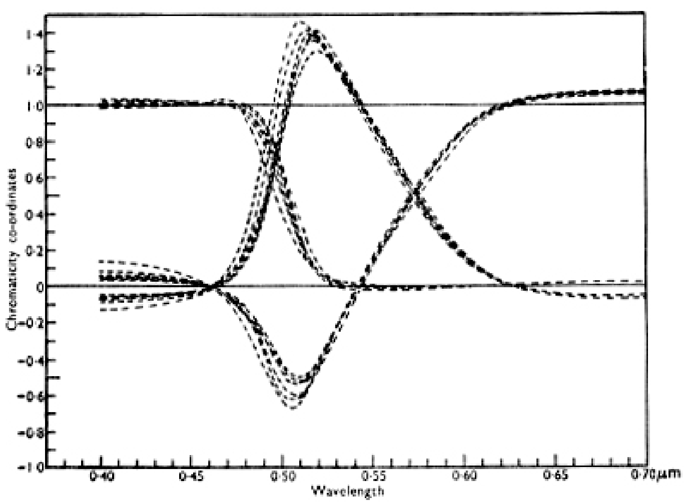


Fig. 6.7. Color matching functions of individual observers measured by Guild in 1930. The wavelengths of the three primary spectral lights used are 460, 540, and 625 nm. Because spectral lights were used some values are negative. *Courtesy of the Royal Society (Guild, J., Philisophical Transactions of the Royal Society (London), Series A, 1932, p158. Used with permission.*

4.4 Setting up a standard system required accurate color-matching data, determined under specific conditions, using the best available instrumentation. Such data were made available by Guild and Wright in England in 1930. The experiment consisted of viewing a circular field in which one half showed the light to be matched and the other half could be adjusted by the observer, changing the amounts of the three primary lights, until a perfect match was obtained for the observer. If a perfect saturation match was not possible, a light could be added to the standard light until a perfect match was obtained. This situation results in negative amounts of light for some of the primaries at some wavelengths (Fig. 6.7). The data for individual observers varied to some degree. They were averaged and recalculated for a different set of primary lights and the CIE issued them as the CIE 1931 2° standard observer (Fig. 6.8).

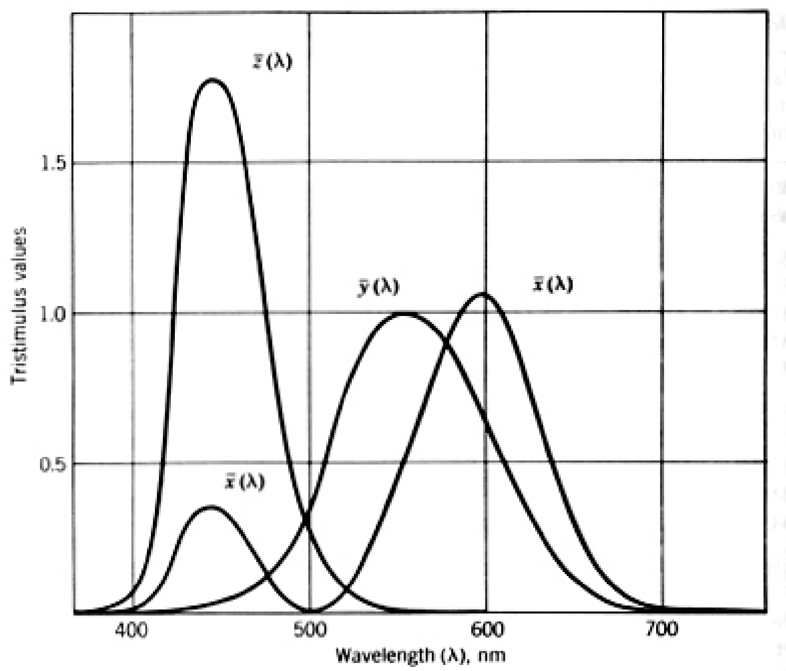


Fig. 6.8. Color matching functions of the CIE 2° standard observer, calculated for the three non-real primary lights **X, Y**, and **Z** from the data by Guild (Fig. 6.7) and data by Wright. *Courtesy of John Wiley & Sons Inc. (Judd, D. B. and G. Wyszecki, Color in Business, Science and Industry, 1975). Used with permission.*

4.5 Why the 2° standard observer? The value 2° refers to the angle at which the image of the circular field impinges on the eye (Fig. 6.9). An angle of 2° was selected so that the image was small enough to fall entirely onto the fovea of the eye of the observer (see Chapter 5). The reason for this was that there are no rod cells in the central fovea that might complicate, and possibly distort, the measurement. (In 1964, a 10° standard observer was also defined.)

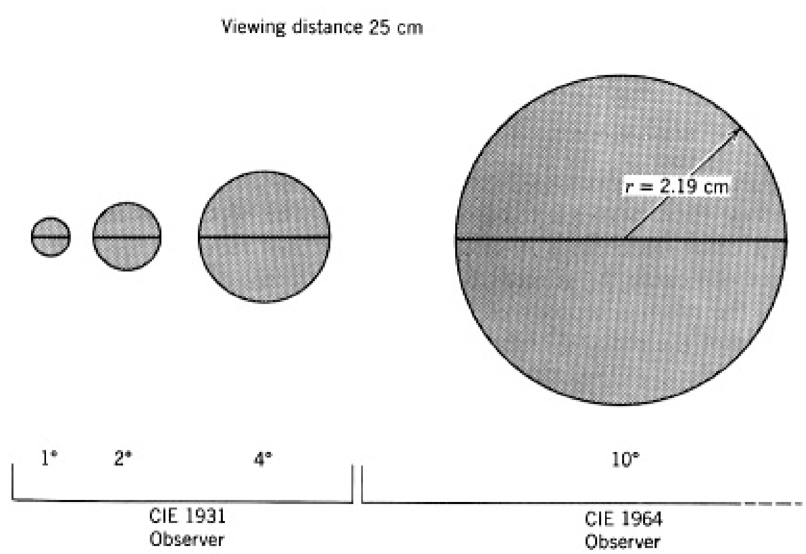


Fig. 6.9. Demonstration of different viewing field sizes. *Courtesy of John Wiley & Sons Inc. (Judd, D. B. and G. Wyszecki, Color in Business, Science and Industry, 1975). Used with permission.*

4.6 The CIE decided to make the standard photopic observer (see Chapter 4) part of the standard colorimetric observer. Object color experiences, as has been described previously, can be considered to have three attributes: hue, chroma, and lightness. If one of the three primary lights can be considered to represent the standard photopic observer it can be taken to represent lightness (although the Helmholtz-Kohlrausch effect demonstrates that for higher-chroma samples, the standard photopic observer is not in good agreement with perceived lightness of highly chromatic colors; see Chapter 5).

4.7 In 1931, computation was still cumbersome and when transforming the average experimental data, the CIE selected primary lights that do not result in negative values. There are no real lights that can meet these requirements, so the CIE primary lights are theoretical only, but they still contain the essential data of the experiment (from a different perspective; see section 3.3, above).

4.8 The theoretical, nonexistent CIE lights are called **X**, **Y**, and **Z**. The results, as expressed for these lights, are the *color matching functions* $\bar{x}$, $\bar{y}$, and $\bar{z}$ (Fig. 6.8). The $\bar{y}$ function is identical to the standard photopic observer function, and the functions only have positive values. The functions are considered linear transformations (see section 3.3) of the average L, M, and S cone response functions.

4.9 The theoretical lights of the standard observer can be placed on corners of a Maxwell diagram for the purpose of calculating mixture results. Because calculations and plotting in this diagram are quite complicated, the CIE decided to use a conventional rectangular diagram. Fig. 6.10 shows the diagram for the 2° observer. The axes of the diagram are labeled *x* and *y* and the values are called *chromaticity coordinates.*

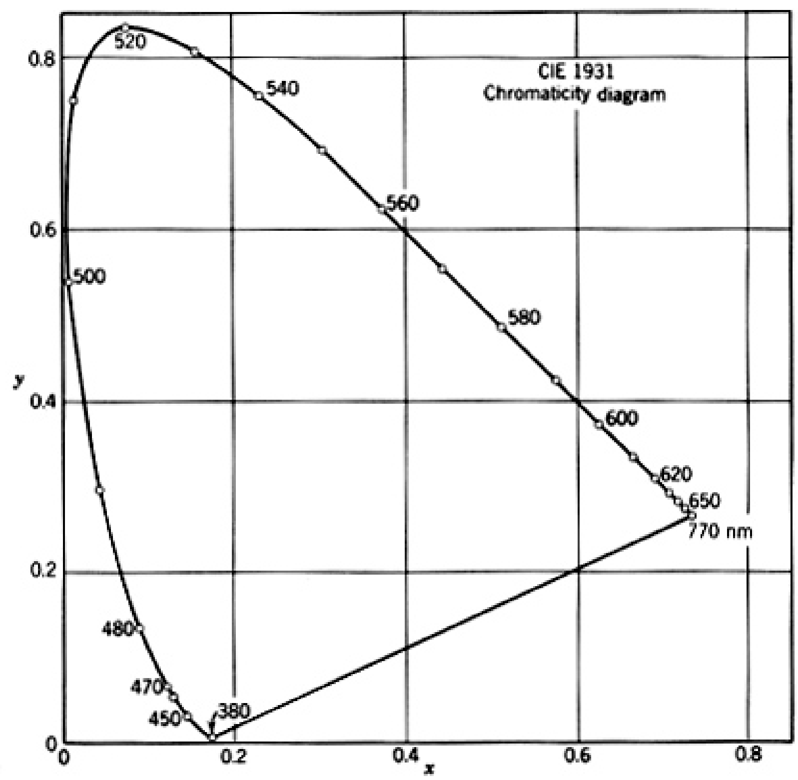


Fig. 6.10. The CIE 1931 chromaticity diagram with the horseshoe-shaped line of spectral colors and the straight purple line closing it off. *Courtesy of John Wiley & Sons Inc. (Judd, D. B. and G. Wyszecki, Color in Business, Science and Industry, 1975). Used with permission.*

4.10 The horseshoe-shaped line connects all points representing the locations of light of a given wavelength. The straight line connecting the two endpoints of the curved line is called the purple line and represents the locations of all possible mixtures of the two lights from both ends of the spectrum. The horseshoe-shaped form falls completely inside the diagram because it is based on theoretical, non-existent lights.

4.11 In this diagram, chromaticity coordinates of x = 0.333 and y = 0.333 apply to a perfectly white object with all reflectance factors equal to 1.0, as viewed in a light with all spectral power distribution values equal to 1.0 (or a corresponding metamer).

As described in section 3, light combinations resulting in colorless light are found by laying straight lines through this central point, and reading the wavelengths off the horseshoe-shaped curve. For some spectral lights, purple lights are required as complements. Their composition from the two spectral lights at the end of the spectrum can be calculated from the position of the required purple light on the purple line.

4.12 Lights that are not spectral, but desaturated (away from the spectral outline, toward the center, such as light S1 in Fig. 6.11), are identified with the wavelength of the spectral light that lies along the straight line connecting the neutral point in the center and the point of the desaturated light (Fig. 6.11).

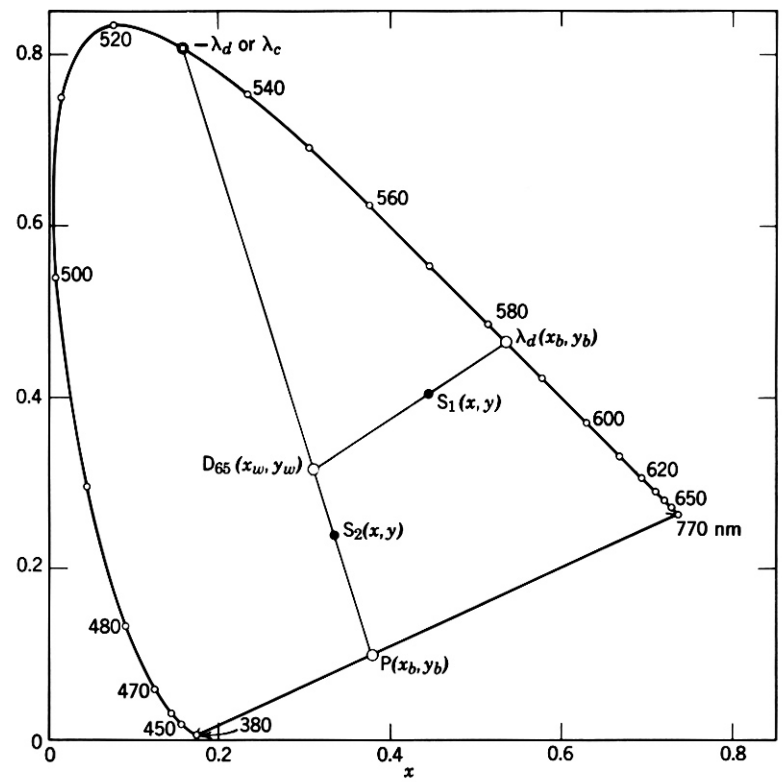


Fig. 6.11. The CIE chromaticity diagram with stimuli of objects S_1 and S_2 as viewed in daylight D_{65}. The dominant wavelength of S_1 is 583 nm; the complementary wavelength of S_2 is 529 nm. *Courtesy of John Wiley & Sons Inc. (Wyszecki, G. and W. S. Stiles, Color Science, 1982). Used with permission.*

The corresponding wavelength is called the desaturated light's *dominant wavelength*. For lights of most wavelengths (and purple lights), the hues of the lights falling along a straight line from the spectral light to the neutral point are not perceived as identical. Lights appearing to have the same hue as a spectral light, but with less saturation, typically fall along a curved line (Fig. 6.12). Dominant wavelength is not an accurate predictor of hue. Lights falling on the purple line are identified by their *complementary wavelength*, that is, the wavelength of the light on a straight line from the purple line through the neutral point to the spectral outline (Fig. 6.11).

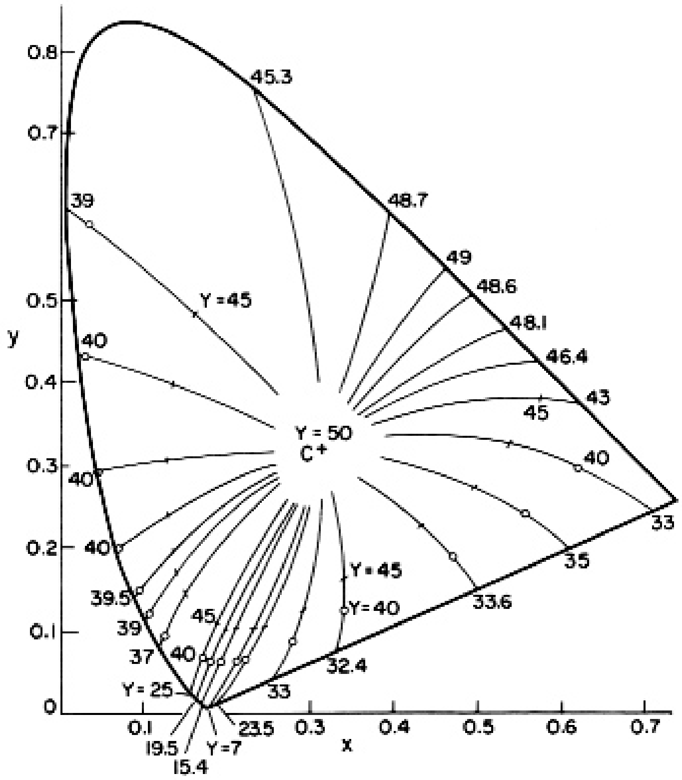


Fig. 6.12. The CIE chromaticity diagram with lines of color stimuli of constant hue from the outline toward the neutral point of CIE daylight illuminant C. Most lines are curved. Different experiments and different observers result in somewhat different curvatures. *Courtesy of Springer Science and Business Media (MacAdam, D. L., Color Measurement, 1981). Used with permission.*

For desaturated lights, the ratio of the distance between the neutral point and the light in question to the distance from the neutral point to the spectral light is called *purity* and is a rough indication of the saturation of the light (Fig. 6.11).

4.13 In the diagram, the result of mixing two lights together in a specific ratio lies on the straight line connecting the two lights Two examples are illustrated in Fig. 6.13. In the first example, spectral light of wavelength 575 nm (yellow appearance) when mixed with spectral light of wavelength 474 nm in the appropriate ratio results in colorless light EE at the center. In the second example, somewhat desaturated light of dominant wavelength 505 nm is mixed with desaturated light of the same but complementary wavelength. The results are located on the straight line connecting the two points. The exact position depends on the ratio between the two lights. All such mixtures are desaturated.

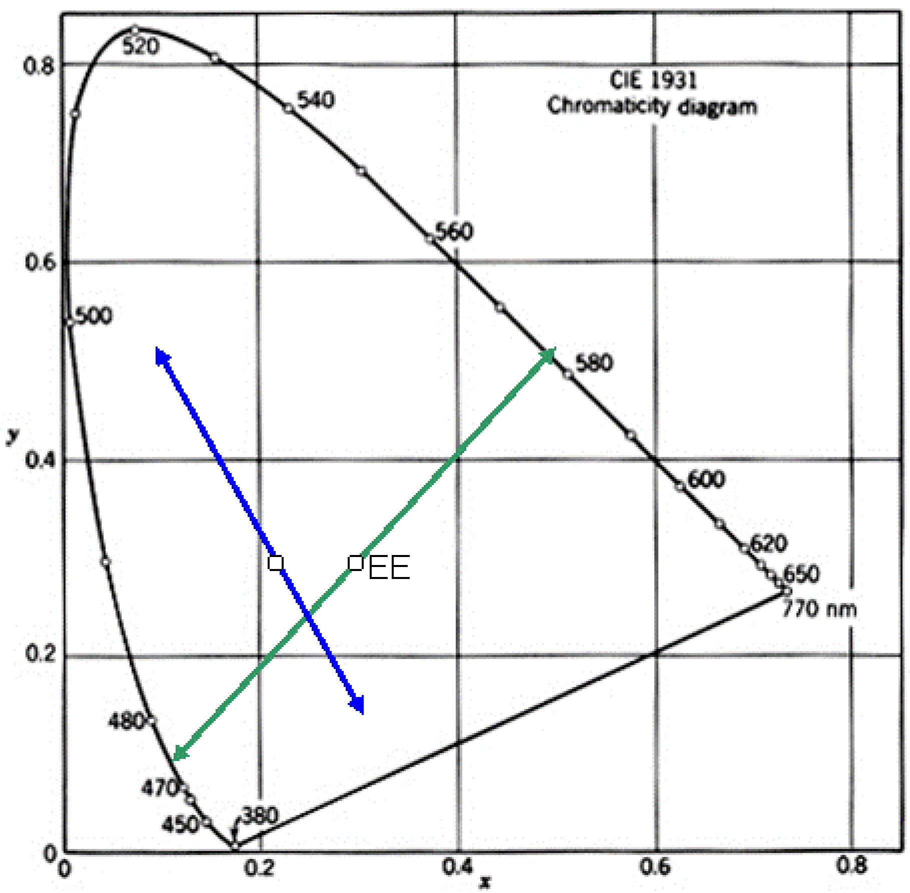


Fig. 6.13. The CIE chromaticity diagram with two examples of results from the mixture of two lights. In the first case (green line) two spectral lights are mixed to form the colorless light identical to the equal energy light source, In the second case (blue line) a desaturated green and a desaturated purple light are mixed to form a desaturated blue light.

4.14 The diagram can be used to predict the result of mixing any number of lights, spectral as well as desaturated, and to determine if mixtures are metameric to other mixtures. The limitations mentioned in sections 3.5 and 3.6 also apply here. A circle around the neutral point represents a complete hue circle, but individual hues are at different levels of saturation.

4.15 In this diagram, the information that exists in complex spectral power distributions is reduced to two values, *x* and *y*. Its advantage is that it represents the totality of lights in two dimensions, like an easily-comprehended map. But, unlike in a map, the distances from one point to another do not express with any reasonable degree of accuracy the perceived distances between the two lights. In addition, the information is limited to dominant or complementary wavelength and saturation and does not express anything about brightness.

Fig. 6.14 shows a typical color illustration of this map. It is not accurate because the colors are generated with three inks. They can neither represent the saturation of spectral lights nor accurately represent the changes in hue along the hue circle.

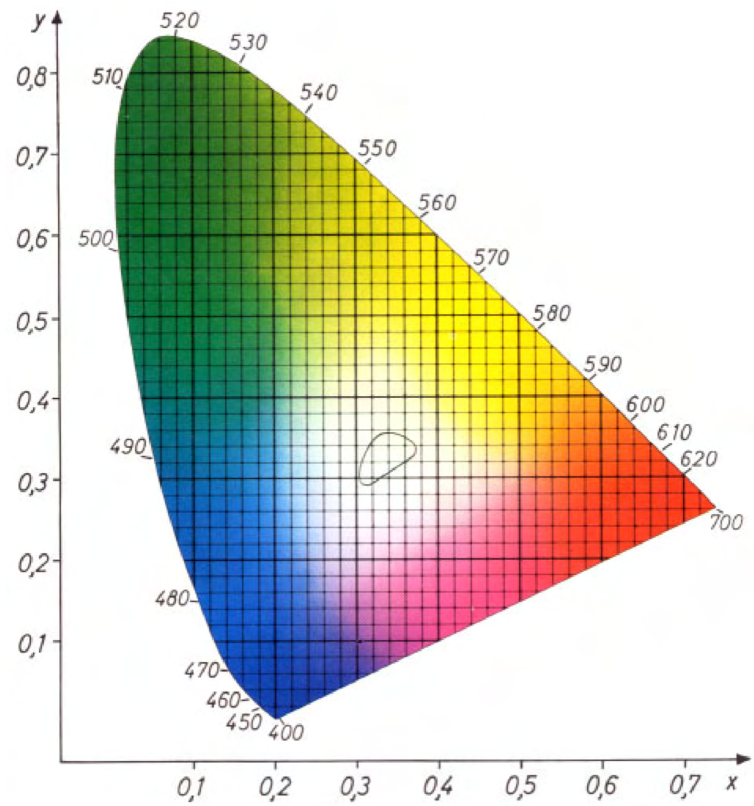


Fig. 6.14. A colored image of the CIE chromaticity diagram. *Courtesy of Bayer Business Services (Brockes, A., D. Strocka, and A. Berger-Schunn, Color Measurement in the Textile Industry, 1989). Used with permission.*

4.16 The *x*- and *y*-values are calculated from the three values that represent the amount of each of the three theoretical lights **X, Y**, and **Z**. As mentioned, the values representing the amounts of the three lights required to make the match are called *tristimulus values* and, in the CIE system, they are named *X, Y*, and *Z.* The letters are the same but the lights are indicated in this text by the bold font, and the amounts (i.e., tristimulus values) are indicated by the italic letters. Calculating the tristimulus values for lights and object colors, and subsequently, the chromaticity coordinates, is the subject of section 6 below.

4.17 In addition to a standard observer, a colorimetric system also requires standard lights. The CIE has standardized a number of illuminants (tables of spectral power distributions) for standardized calculation of tristimulus values. Among these are daylight illuminant D_{65}, and other versions of daylight (see Chapters 2 and 3); tungsten light, abbreviated illuminant A; and a number of different fluorescent lights. Other organizations have calculated illuminant data for other lights of particular interest to its members.

5 Calculating Tristimulus Values and Chromaticity Coordinates

5.1 There are three tristimulus values for a stimulus, one for each of the three color-matching functions. The calculations follow the example given in section 4.1 above. For purposes of calculation, the color-matching functions are represented by three sets of numbers. The numbers for the 2° standard observer are listed in Table 6.2. They are shown in the *normalized* form: the sum of these values in each case is 100.0. It is important to decide for what range of wavelengths the calculations are to be made. Some people calculate for the range of 400-700 nm, others for 380-740 nm, or something in between. It is important that the spectral power data of lights, reflectance data, and color-matching functions are available for the same spectral range. This is usually taken care of by instrument and systems manufacturers, but across a supply chain, differences in spectral range may result in slightly different results for the same basic data. For each spectral range, the color-matching functions need to be properly normalized.

5.2 Color-matching function tables are published by the CIE at 1-nm intervals from 360 to 850 nm and at 5-nm intervals from 380 to 780 nm. In most cases, measurements are made for narrower ranges. Because the values of the color-matching functions are near zero below 400 and above 700 nm, they are often neglected as having little influence on the result. The color-matching functions are abbreviated with lower case letters with a bar above (Fig. 6.15).

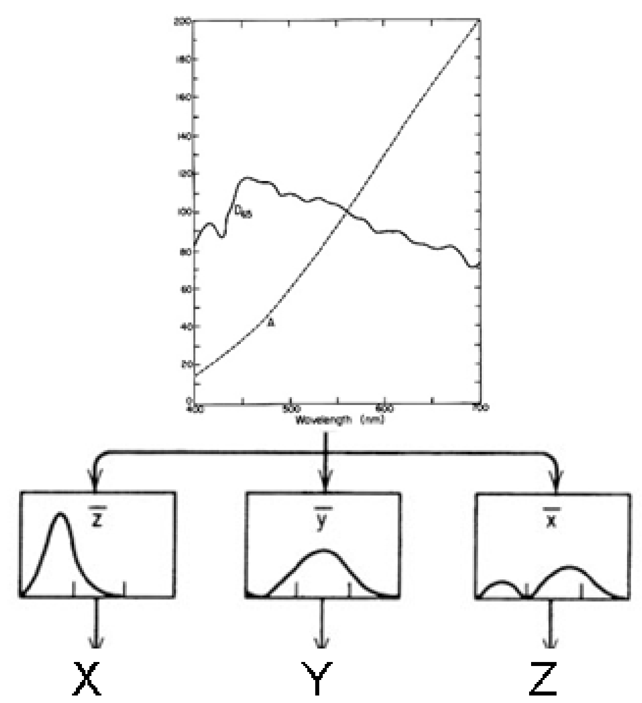


Fig. 6.15. A schematic representation of the calculation of tristimulus values for lights (represented by the illuminants D_{64} and A). At each wavelength, the spectral power of the light is multiplied by the color-matching function values and the results are added up to give the tristimulus values *X, Y* and *Z*.

5.3 For calculation of tristimulus values of lights, the spectral power distribution values at each wavelength are multiplied by the corresponding color-matching function values. All of the resulting products for a given color-matching function are added to find one of the three tristimulus values. This is demonstrated schematically in Fig. 6.15.

5.4 For object colors, the light reflected from the object is calculated first. This is achieved by multiplying the reflectance value by the normalized spectral power value of the light source at each wavelength.

5.5 The tristimulus values for object colors are calculated by multiplying the product of reflectance and spectral power by the color-matching function value at the same wavelength. For each tristimulus value, the corresponding products are added together. In practice, the products of illuminant and color-matching function values are usually pre-calculated in tables and these products are multiplied by the reflectance values. The result is the same. The calculations are demonstrated in Table 6.2 and Fig. 6.16.

nm	D65	Refl	X	Y	Z
400	0.842	0.135	0.134	0.004	0.638
410	0.931	0.121	0.408	0.011	1.947
420	0.950	0.116	1.260	0.037	6.062
430	0.882	0.104	2.662	0.109	13.010
440	1.067	0.101	3.265	0.215	16.404
450	1.190	0.108	3.152	0.356	16.639
460	1.198	0.12	2.726	0.562	15.673
470	1.169	0.152	1.832	0.852	12.090
480	1.179	0.191	0.896	1.301	7.634
490	1.107	0.247	0.300	1.947	4.368
500	1.113	0.311	0.046	3.024	2.554
510	1.096	0.485	0.087	4.709	1.485
520	1.066	0.611	0.593	6.647	0.734
530	1.095	0.592	1.552	8.070	0.396
540	1.062	0.49	2.723	8.931	0.191
550	1.058	0.317	4.063	9.315	0.082
560	1.017	0.272	5.573	9.315	0.037
570	0.979	0.255	7.145	8.913	0.020
580	0.974	0.234	8.590	8.145	0.016
590	0.902	0.211	9.622	7.087	0.010
600	0.814	0.197	9.958	5.907	0.008
610	0.911	0.165	9.399	4.709	0.003
620	0.892	0.148	8.010	3.567	0.002
630	0.847	0.137	6.023	2.481	0.000
640	0.851	0.123	4.199	1.638	0.000
650	0.814	0.125	2.658	1.002	0.000
660	0.816	0.138	1.546	0.571	0.000
670	0.837	0.149	0.819	0.300	0.000
680	0.796	0.18	0.439	0.159	0.000
690	0.709	0.222	0.213	0.077	0.000
700	0.728	0.267	0.107	0.038	0.000
	Tristimulus values		19.423	32.867	15.931

Table 6.2. The relative spectral power of CIE illuminant D_{65} at 10-nm intervals, the reflectance data of a green sample (as factors), and the normalized color-matching functions $\bar{x}$, $\bar{y}$, and $\bar{z}$. The tristimulus values are calculated by multiplying illuminant by reflectance and by the color-matching function value. The values for each color-matching function are added up to result in the tristimulus values on the bottom.

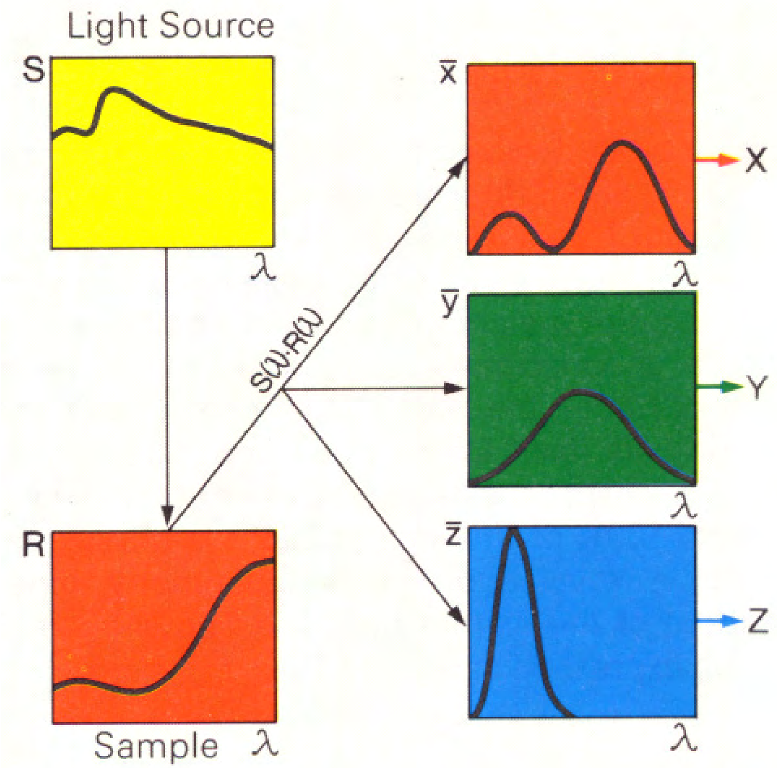


Fig. 6.16. A schematic representation of the calculation of tristimulus values based on the reflectance of an object (Sample) viewed in a given light source. *Courtesy of Bayer Business Services (Brockes, A., D. Strocka, and A. Berger-Schunn, Color Measurement in the Textile Industry, 1989). Used with permission.*

5.6 In this manner, the complex information contained in the reflectance and spectral power functions has been reduced to three values related to the responses of the three cone types. The reflectance or spectral power data cannot be accurately recovered from the tristimulus values.

5.7 The three tristimulus values can be seen as lying on three axes of a three-dimensional space (Fig. 6.17). This space is specific to the standard observer from which it has been calculated.

5.8 Chromaticity coordinates are calculated from the tristimulus values as follows:

$x = X/(X+Y+Z)$

$y = Y/(X+Y+Z)$.

It is possible to calculate a z value in the same manner, but the three values have to add up to 1.0 so when x and y are known, z is easily found. Only x and y are used in the chromaticity diagram.

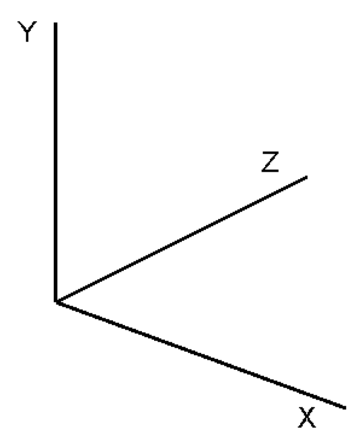


Fig. 6.17. The space formed by the three axes represented by the tristimulus values.

5.9 It is important to realize that, in the chromaticity diagram, the neutral point of lights varies. As mentioned, the neutral point for an equal energy light is at $x = 0.333$ and $y = 0.333$. For lights with different spectral power distributions, the neutral point has different values. Fig. 6.18 shows some examples.

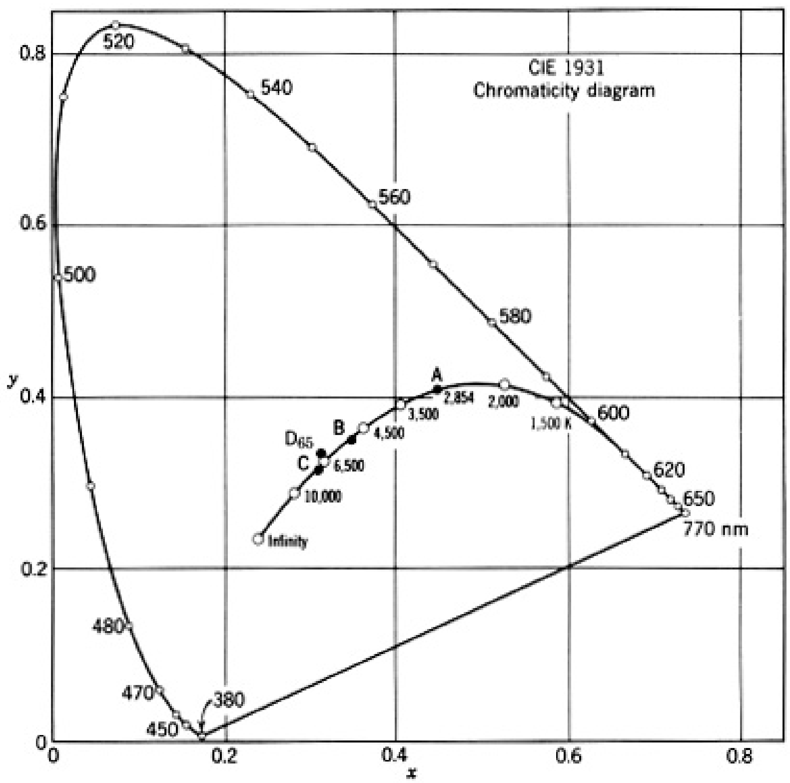


Fig. 6.18. The CIE chromaticity diagram showing the locations of different illuminants: CIE standard illuminants A, B, C and D_{65}, as well as blackbody radiators at different Kelvin temperatures (see Chapter 1). Each of these points is the neutral point for the particular illuminant. *Courtesy of John Wiley & Sons Inc. (Judd, D. B. and G. Wyszecki, Color in Business, Science and Industry, 1975). Used with permission.*

5.10 As discussed earlier, the $\bar{y}$ color-matching function is identical to the standard photopic observer function. As a result, the *Y* tristimulus value represents relative brightness for lights and lightness for objects. The *X* and *Z* values have no similarly specific meaning, but together, they can be considered to contain the chromatic (hue and saturation) aspect of the color stimulus.

6 The Object Color Solid in the Tristimulus Space

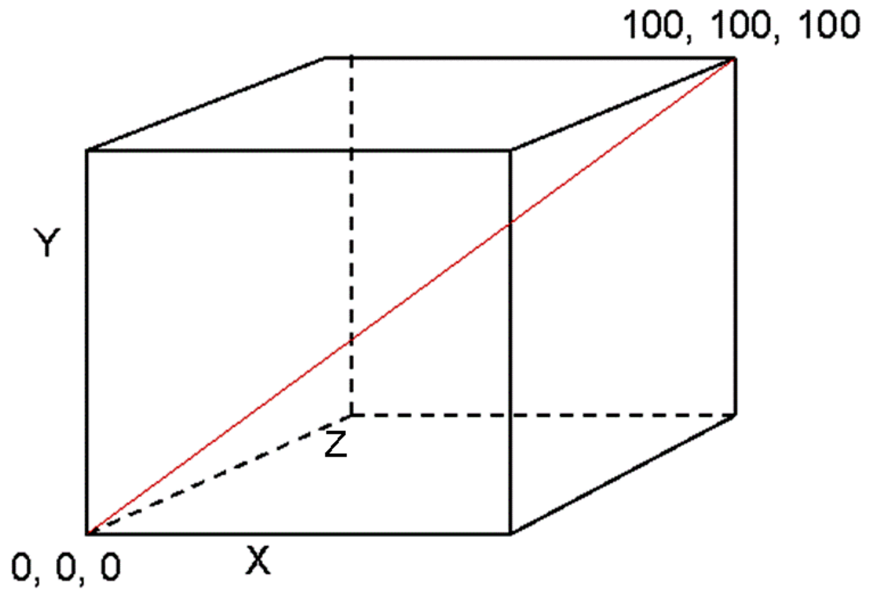


Fig. 6.19. The tristimulus space with the black (0,0,0) point at the lower left and the white (100, 100, 100) point at the upper right. The achromatic (gray) scale falls on the diagonal red line connecting them.

6.1 Each possible color stimulus is represented as a point in the tristimulus space. However, the points representing object colors cannot fill the tristimulus space completely. This is demonstrated by the fact that perfect black has tristimulus values of 0, 0, 0, and perfect white has tristimulus values of 100, 100, 100. The first is located at the origin of the tristimulus space, the second diagonally opposite (Fig. 6.19). Because of the overlap of the color-matching functions (see Fig. 6.8), it is not possible for an object color to have, for example, an *X* value of 0 and *Y* and *Z* values of 100, or *X* = 100, *Y* and *Z* = 0. As a result, the tristimulus space is only partially-filled with the object color solid. The object color solid has a spindle-like form placed diagonally in the tristimulus space (Fig. 6.20). On its surface and inside are the points that represent all possible object color stimuli. Achromatic colors (grays) are located on the diagonal. It is difficult to orient oneself in this solid so it is rarely used.

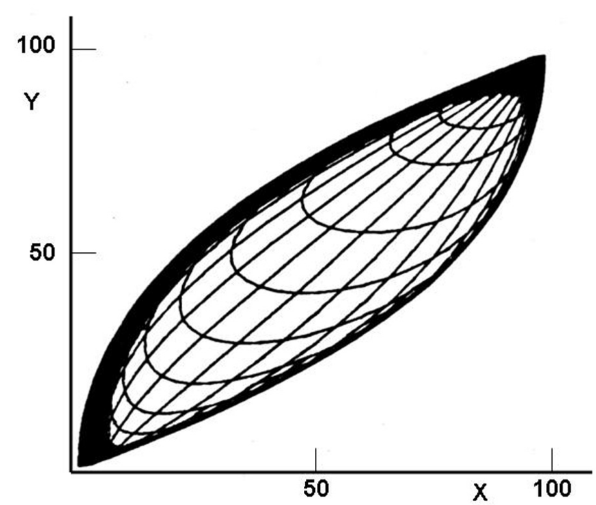


Fig. 6.20. A view of the spindle-like object color solid in the *X, Y* plane of the tristimulus space shown in Fig. 6.19.

7 Object Color Stimulus Solid above the Chromaticity Diagram

7.1 As discussed in section 4.15, the chromaticity diagram does not contain lightness data. Lightness data can be included by erecting a lightness scale from 0 to 100 over the neutral point of the diagram. An object color solid comparable to the solid in Fig. 6.20 can be calculated in this way.

7.2 Object color stimulus solids calculated in this manner are known as Rösch-MacAdam solids. The form of the solids depends to a considerable extent on the illuminant for which they have been calculated.

7.3 Figs. 6.21-22 show schematic views of such solids, looking down from the top, for CIE illuminant C (an early and slightly different version of D_{65}) and illuminant A.

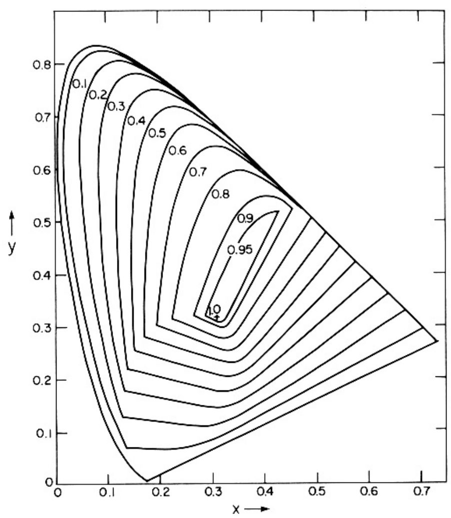


Fig. 6.21. A projection of planes of equal lightness of the object color solid for daylight illuminant C onto the CIE x, y chromaticity diagram. *Courtesy of Springer Science and Business Media (MacAdam, D. L., Color Measurement, 1981). Used with permission.*

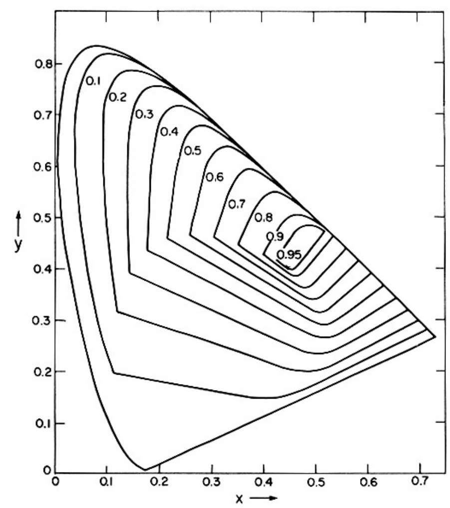


Fig. 6.22. Plane projection as in Fig. 6.21, but for CIE illuminant A (tungsten light). *Courtesy of Springer Science and Business Media (MacAdam, D. L., Color Measurement, 1981). Used with permission.*

Fig. 6.23 is a view of a three-dimensional drawing of the solid for D_{65}.

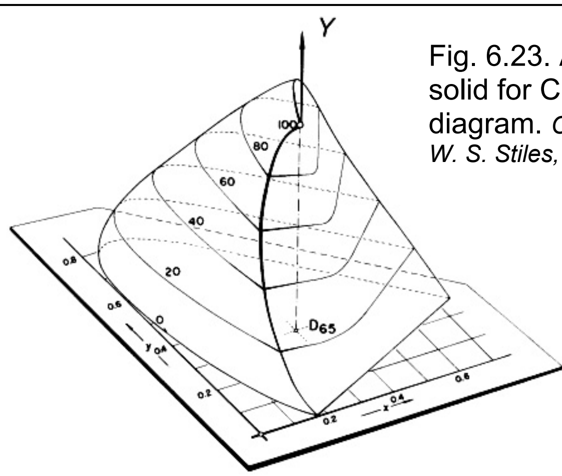


Fig. 6.23. A sketch of the three-dimensional object color solid for CIE illuminant D_{65} over the CIE chromaticity diagram. *Courtesy of John Wiley & Sons Inc. (Wyszecki, G. and W. S. Stiles, Color Science, 1982). Used with permission.*

8 1964 CIE 10° Standard Observer

8.1 In most practical situations, samples are larger than what they should be for the 2° observer to be applicable. The CIE considers the 2° observer to be accurate for a viewing field up to 4°. In 1964, they published an additional set of color-matching functions applicable to larger fields of view and measured at 10°.

8.2 The color-matching functions of the 2° and 10° standard observers are somewhat different and they cannot be used interchangeably (Fig. 6.24). The reason for the difference is that the cone types are not uniformly distributed across the retina. Care should be taken when comparing data to assure that all data were calculated with the same standard observer color-matching functions (as well as the same illuminant).

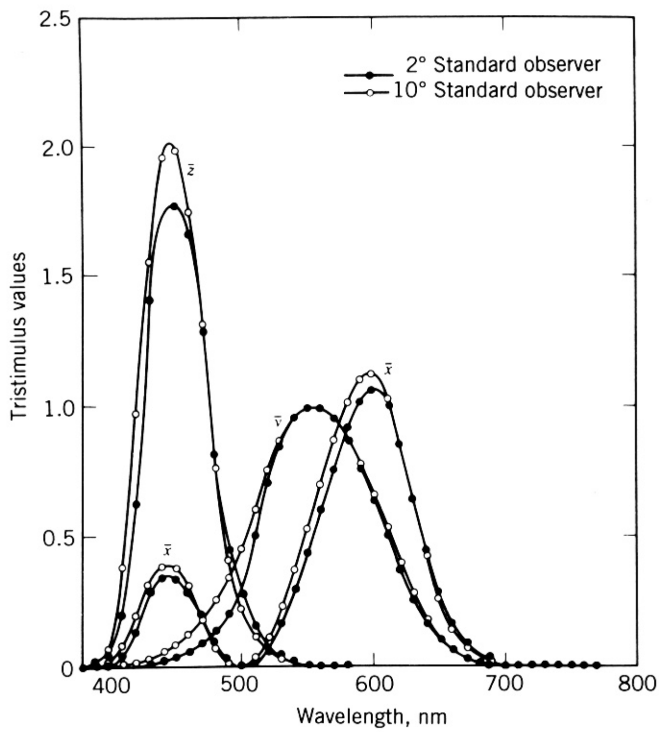


Fig. 6.24. Comparison of the CIE 2° and 10° standard observer color matching functions. *Courtesy of John Wiley & Sons Inc. (Billmeyer, F. W. and M. saltzman, Principles of Color Technology, 2nd ed., 1981). Used with permission.*

8.3 While the $\bar{y}$ function of the 2° standard observer is identical to that of the standard photopic observer, this is not exactly the case for the 10° standard observer. The difference is not large, and the *Y* value is routinely considered to refer to lightness (the exact term is *luminous reflectance*) for the 10° observer as well.

8.4 It has become customary in the textile industry to make calculations for the 10° standard observer.

9 Practical Value of the Colorimetric System

9.1 Absence of a simple, clear relationship between stimulus and color experience limits the value of the colorimetric system to exact specification of stimuli in the system, but not of perceptions.

9.2 The colorimetric system provides clear and simple specifications of color stimuli derived from objects. The specification is in terms of three values, either the three tristimulus values, or the chromaticity coordinates x and y, and tristimulus value Y. The system makes it possible to distinguish and specify an unlimited number of color stimuli. The values are applicable to the specific conditions followed in the measurement. They relate to the standard observer and standard illuminant data only for which they have been calculated.

9.3 Geometrical distances in the object color stimulus space are representative of perceptual experiences only in a very general manner. They are in the correct sequence in regard to hue, chroma, and lightness, but the distances between points do not indicate average perceived distances between the corresponding samples.

9.4 Orientation in the tristimulus space, and the object color solid in it, is difficult. It is somewhat easier to orient oneself in the x, y, Y space.

9.5 The most direct practical use of the system is in the prediction of metamerism for the standard observer (Chapter 11), of the results of light mixture (Chapter 8), and in computerized dye formula calculation (Chapter 9).

9.6 Indirectly, the system has been used to develop mathematical models that predict the color rendering of lights (Chapter 12), degree of color inconstancy (Chapter 11), average perceived color difference (Chapter 13), and the numerical expression of fastness testing results based on reflectance measurements (Chapter 14).

10 Summary

Colorimetric systems specify color stimuli in a manner where the complex information contained in a spectral power distribution of a light (direct or reflected) is reduced to three values by using direct or modified information about the sensitivity across the spectrum of the three human cone types to “filter” it. In the CIE colorimetric system, the color matching functions are the “filters.” They have been experimentally obtained by metamerically matching the appearance of all lights of the spectrum with three selected spectral lights—the primary lights. The averaged results have been mathematically modified so that there are no negative values in the color matching functions and one of them, the $\bar{y}$ color-matching function is, for the 2° observer, equal to the CIE photopic luminosity function representing brightness or lightness under specific experimental conditions.

The CIE developed two sets of color-matching functions, one for a 2° field of view and the other for a 10° field, the latter being commonly used for textile materials.

Because human color experiences are based on much more complex interpretation of the color stimuli than that happening at the cone level in the retina, tristimulus values have only a loose relationship with color experiences. They are useful for predicting the results of mixtures of lights colorants and for specifying color stimuli in terms of physically-measured data from lights or objects.

Chapter 7 COLOR ORDER

1 Defining Color Order

1.1 Color order was briefly mentioned in Chapter 5. It refers to various kinds of orderly, systematic arrangements of color experiences or color stimuli. Because real color experiences obtained from a given stimulus differ significantly among color-normal individuals, color order systems and the related atlases are color stimulus standards and not color experience standards. Color order is a broad subject justifying its own chapter.

1.2 Color order has a long history dating back to antiquity. At first, color order systems were one-dimensional. In the early 18th century, two-dimensional systems appeared. By the mid-18th century, the first three-dimensional system appeared. Since then, dozens of such systems have been developed, each one representing certain ideas of their developers.

1.3 Several classes of color order systems exist:

- Systems representing average uniform visual distances between neighboring samples are often called perceptual or psychological systems. There are different sets of visual attributes that can be used for ordering.
- Another group consists of systems with regular changes in color stimuli, such as tristimulus values (discussed in Chapter 6).
- In a third group, samples vary regularly in regard to the concentrations of three primary colorants (dyes or pigments), or three primary lights. Among modern systems for colorants are systems that show color spacing when printing in the halftone printing process with cyan, magenta, and yellow inks. The best known examples of light systems are the RGB (red, green, blue) systems of color monitors.
- In one group of systems, average perceptual results experimentally obtained from many observers have been modeled (described) mathematically, based on tristimulus values (color space and difference formulas, see Chapter 13).
- A final group of systems orders color stimuli strictly according to mathematical principles based on reflectance functions of samples—without involving the human observer in the form of tristimulus values or perceptual results. (Perhaps such systems should not be called color order systems, colors being human experiences.)

2 Brief History of Color Order Systems

2.1 Color order began in antiquity with linear order systems, systems where colors were placed in a single line. The best known of these is by the Greek philosopher Aristotle (ca. 300 BC), who described a scale of colors beginning with white and continuing through yellow, scarlet, purple, green, and blue, to black. He was aware that there are many more colors but believed the color of his scale to be the major classes. Nothing is implied by Aristotle about the differences between the members of the scale.

2.3 Two-dimensional systems began with Newton's circle of the colors of the spectrum (Fig. 7.1) of 1704.

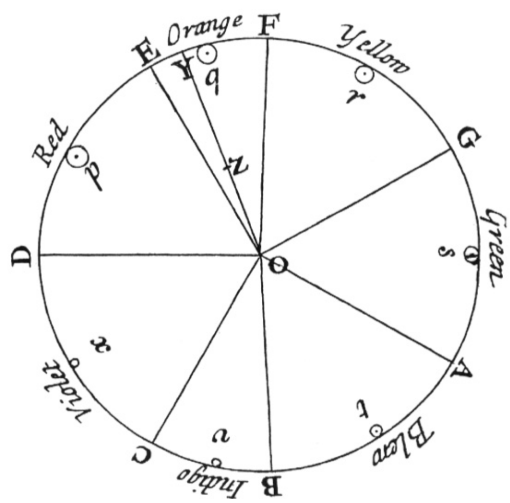


Fig. 7.1. Newton's circle of spectral colors. Compared to today's hue circles, it is missing purple between violet at the beginning of the spectrum, and red at the end. *Newton, I., Opticks, 1704.*

2.4 The first three-dimensional system was proposed in the mid-18th century by the German astronomer Tobias Mayer.

2.5 In the 20th century, dozens of three-dimensional systems were developed representing various ideas about color order.

2.6 The key issue is what the geometric distances in the models of the color order systems are to be representative of in terms of different colors. In other words, what is the relationship between perceived difference between samples and the geometric differences in the model of the system. There may be little or no relationship, or there may have been an attempt to make the relationship perfect.

2.7 Color chips of color order systems are often shown in atlases. The order and geometrical distances of the samples in the atlas may have little or no relationship to the geometric distances between these samples of the system in their color solid, or they may have a reasonably close relationship.

3 Geometric Distances Representative of Perceptual Color Properties

3.1 In a geometric solid, distances from one point to another have geometric meaning. In a solid that represents all possible color experiences, distances between points should have some meaning related to color. The question is what the meaning of the distances should be. Consider all possible color experiences to form a cloud of undefined shape. This cloud can be shaped into different three-dimensional geometric solids: pyramids (regular and tilted), sphere, semi-sphere, cube, and many more regular and irregular ones. When sampled at equal geometric intervals, different color experiences in different solids will be picked as representing the grades in the system. One possibility is that the distances should be representative of average perceived differences between samples in the system. The question arises as to whether the form of such a solid is a simple geometric one or an irregular one.

3.2 In case of perceptual, or psychological, systems the increments are usually in terms of units of general perceived distance or, more often, in terms of units of attribute scales, such as hue, lightness, and chroma. These scales can be in *absolute units* or *relative units*. A typical example is *chromatic intensity*. The Munsell chroma units are absolute units, meaning that one unit of chroma is of identical perceived magnitude for all hues. This means that the maximum number of chroma units differs by hue because the most intense colors of objects have different chromatic intensity depending on hue (Fig. 7.2).

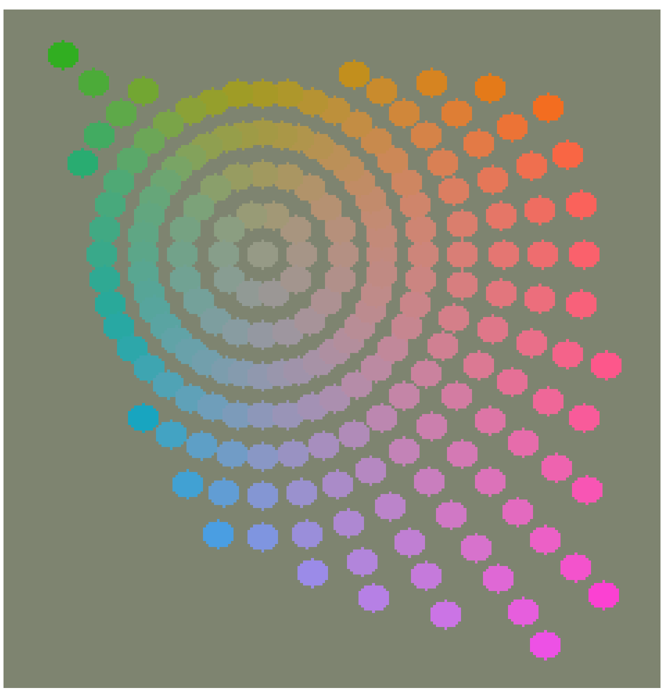


Fig. 7.2. Complete and incomplete Munsell hue circles at value 6 with chroma values increasing from the central gray out to the limit possible on a video display. The number of steps differs by hue (along radial lines from the center). *Courtesy of Hans Irtel, University of Mannheim. Used with permission.*

As a result, the full hues are not located on a circle and the object color solid is not a simple geometric solid, like a sphere or a double cone (as will be shown below) but rather, of irregular form. In the case of systems with relative units of chromatic intensity, all hues have the same maximum number (usually 10 or 100) but the size of each unit differs by hue. In this case the full hues form a circle. It can be expanded to three dimensions to accommodate lightness resulting in a simple, regular geometric solid, such as a double cone or a sphere.

3.4 There are also absolute and relative units of lightness. Absolute units are units of a lightness scale (they can vary), typically from 0 to 100, such as the Munsell Value scale (shown in only 10 samples in the system). Relative lightness units are the result of placing *full colors* of all hues on the same plane, regardless of their absolute lightness. This is typically done in hue circles, where the colors of highest intensity for each hue are used (Fig. 7.3). They are considered to have the same relative lightness. This, again, makes it possible to place the system into a simple geometric solid.

Fig. 7.3. A modern hue circle with the full colors all on the same plane regardless of their lightness.

3.5 Are absolute units of identical perceptual size for three attributes such as hue, lightness, and chroma possible? Or do they necessarily differ in perceptual size? Munsell designed his system in such a way that units of hue, value, and chroma differ in perceptual magnitude. The value (lightness) scale has 100 units, with only 10 shown in the atlas. As mentioned, the chroma scale is open-ended. The number of chroma steps from gray to (non-real) *optimal object colors* vary from 16 to 38 (the color samples of the Munsell atlas have maximum chromas of up to 20). The hue scale has 100 grades, of which 40 are represented in the atlas.

The perceptual magnitude of each of the three units is different, however. In addition, the size of the hue unit depends on the chroma of the colors compared. This is the automatic result of the circular arrangement of the system (see Fig. 7.12 later in this chapter). The geometric distances between lines of constant hue differ along the chroma scale (Fig. 7.4). Geometrically, the distance between points indicating neighboring colors of the same chroma, but differing in hue, at chroma 2 is ten times smaller than that at chroma 20. Perceptually, the two distances are less different than what geometry indicates. The unit of hue difference in such an arrangement has to be defined for the hue circle at a particular chroma and steps between neighboring grades at higher or lower chroma have larger and smaller hue differences, respectively. It is evident that, as a result of these matters, the attribute scales of the Munsell system do not have units of identical perceptual magnitude and the system is not perceptually uniform.

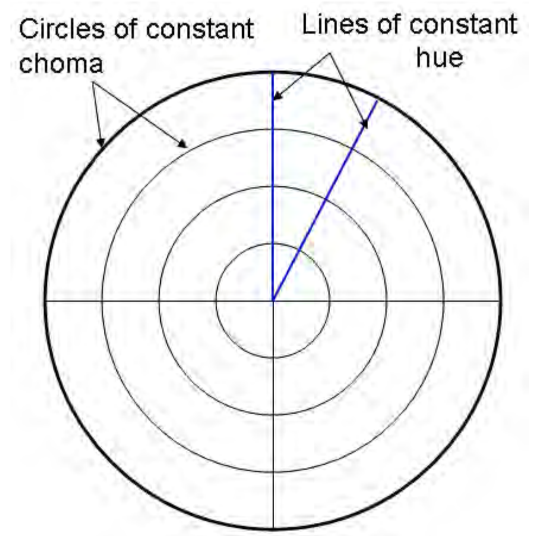


Fig. 7.4. Sketch of a chromatic diagram with circles of constant chroma and two (blue) lines of samples of constant hue. The geometric length of the circle segments between the lines of constant hue depends on the chroma: the higher the chroma the larger the distance, indicating that the hue differences between neighboring series of colors of constant hue depend on the chroma of the colors involved.

3.6 A perceptually completely uniform system, also called an *isotropic system*, would contain the most information. Distances in its geometric model in any direction would be accurate indicators of perceptual distances between the corresponding color perceptions. Such a system, for some of the above reasons and others to be mentioned later when discussing the OSA-UCS system, cannot fit into any solid of our common, three-dimensional Euclidean geometry but would require at least four dimensions. There is no such system in existence.

3.7 The choice of stimuli for each sample in a perceptual color order system atlas is limited by the fact that each sample must simultaneously be a member of at least three different scales, such as the hue, value, and chroma scales of the Munsell system.

4 Geometric Distance Representative of Stimulus Units

4.1 Some color order systems based on color stimuli as they are “filtered” by cone-sensitivity functions or color-matching functions have been discussed in Chapter 6. These include the CIE tristimulus system and the *x, y, Y* system. These systems are not perceptually uniform. The geometric distances between points in these solids have no simple relationship to the perceptual distances for an average observer as represented by the standard observer.

4.2 Widely-used color order systems based on three primary lights are found in computer monitors and color TVs. The three primary lights are usually narrow-band but multi-spectral. This means each light consists of multiple wavelengths (different technologies differ in this respect). The lights are located near the beginning, middle, and end of the spectrum. Such color order systems are often represented as cubes. Most color monitors have screen outputs of the three primaries in 255 units. They can be represented as axes of a cube with each axis representing one of the primaries (Fig. 7.5). The origin, in one corner of the cube, is where all three primaries have a value of zero. The corresponding color, by definition, is black. In the opposing corner all three primaries have values of 255 and the corresponding color is white. All other color stimuli (some 16 million different ones) that can be generated fall somewhere within the cube. This is known as the RGB system.

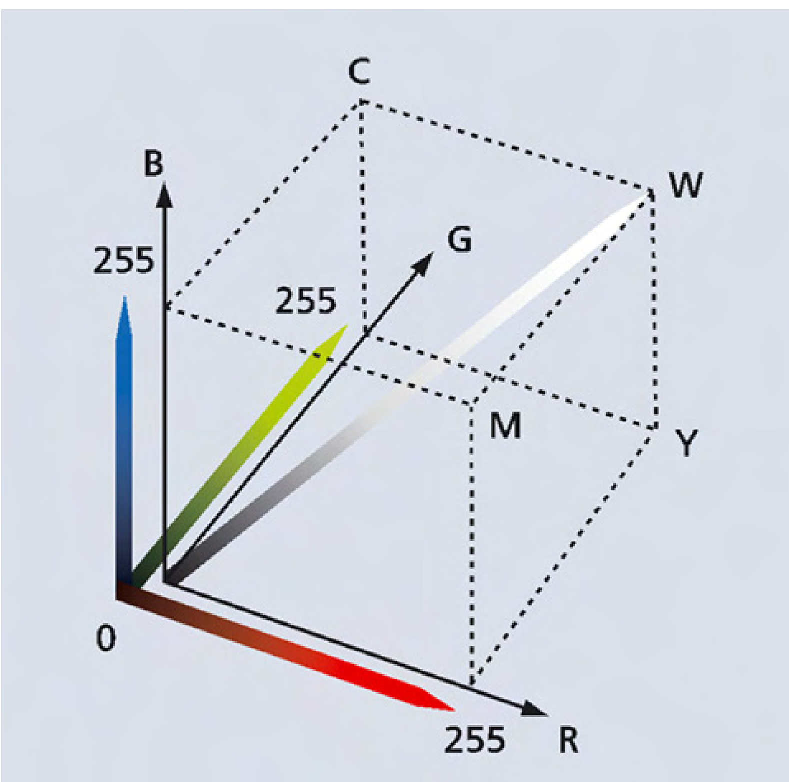


Fig. 7.5. Schematic model of the RGB system with the primaries adjustable in 255 grades each. The central diagonal axis is the gray scale.

4.3 In a similar way, the results of dyeing with three primary dyes or printing by the *halftone process* on paper with three chromatic primary printing inks (yellow, magenta, and cyan) can be represented in a cube. In each case the system depends on the chromatic properties of the primary colorants. The axes represent the concentrations of the dyes or pigments or, in the case of halftone printing, the *screen density* of the halftone screen. In the corresponding cube, white (the color of paper) is in one corner, and black (the result of adding all three primary pigments in full concentration) is in the diagonally opposing one.

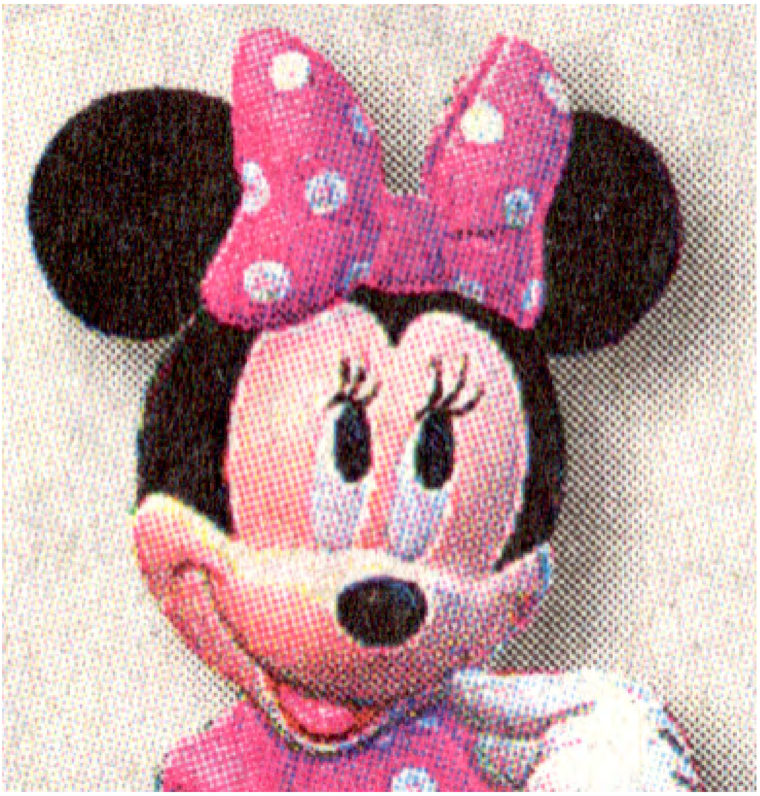


Fig. 7.6. Enlarged newspaper halftone color print showing separate dots of yellow, cyan, magenta, and black. When viewing the monitor from a distance, the dots fuse to a continuous color picture.

In halftone printing, the three inks are printed in dots of varying numbers per inch. The dots may or may not overlap to some degree (Fig. 7.6). The number of dots per inch as well as the size and shape of the dots can be varied by design. With or without overlap, they create a wide variety of color stimuli that can be systematically presented. For purposes of demonstrating the results of halftone printing with particular chromatic process inks (cyan, magenta, yellow; CMY), the screen density is usually varied in 10 steps from 0, meaning paper white, to 10, meaning full coverage of the area by the printing ink. Multiple inks are overprinted in a given sequence, often cyan first, then magenta, and yellow last. Fig. 7.7 shows enlargements of four ratios of the three chromatic inks. The intended color is seen when either squinting the eyes or stepping sufficiently back from the computer screen so that the printed components optically fuse. Black colors produced from overprinting of all three inks at full strength do not appear fully black so, for the past 100 years, a fourth ink—black—has been used in halftone printing (making the printing system CMYK). Fig. 7.8 shows four examples of halftone printing with all four inks.

A cube representing 10 grades each of the three primary inks contains 1,000 different samples. Prints with four inks cannot be represented in a cube but require additional cubes.

There are commercial atlases with as many as 25,000 different halftone printing colors available.

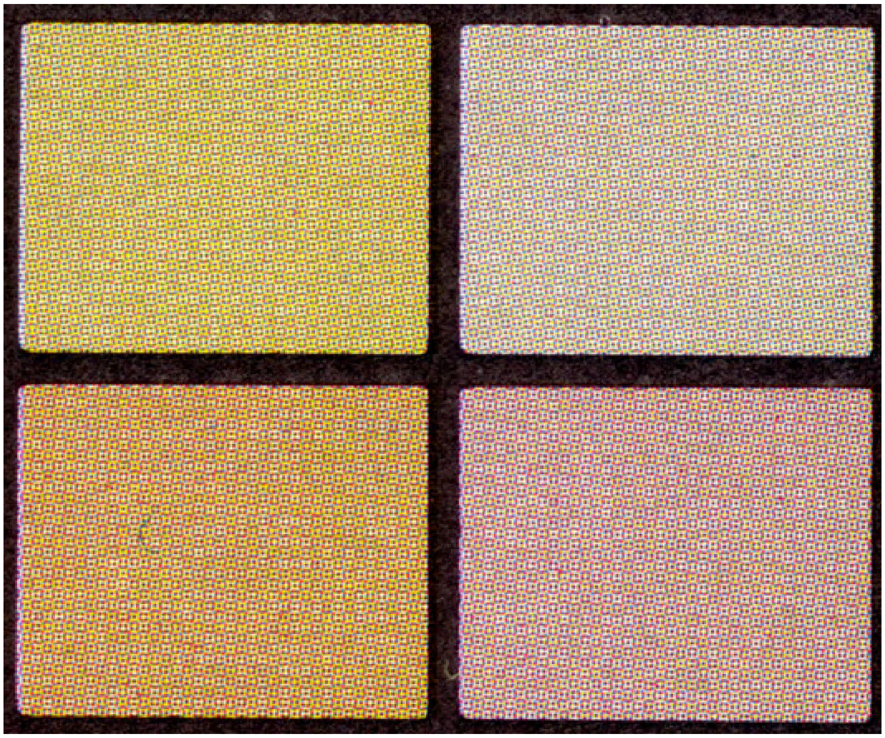


Fig. 7.7. Examples of CMY halftone prints with different screen densities of each of the three primaries. When viewed from a distance, the dots fuse into uniform-appearing color fields.

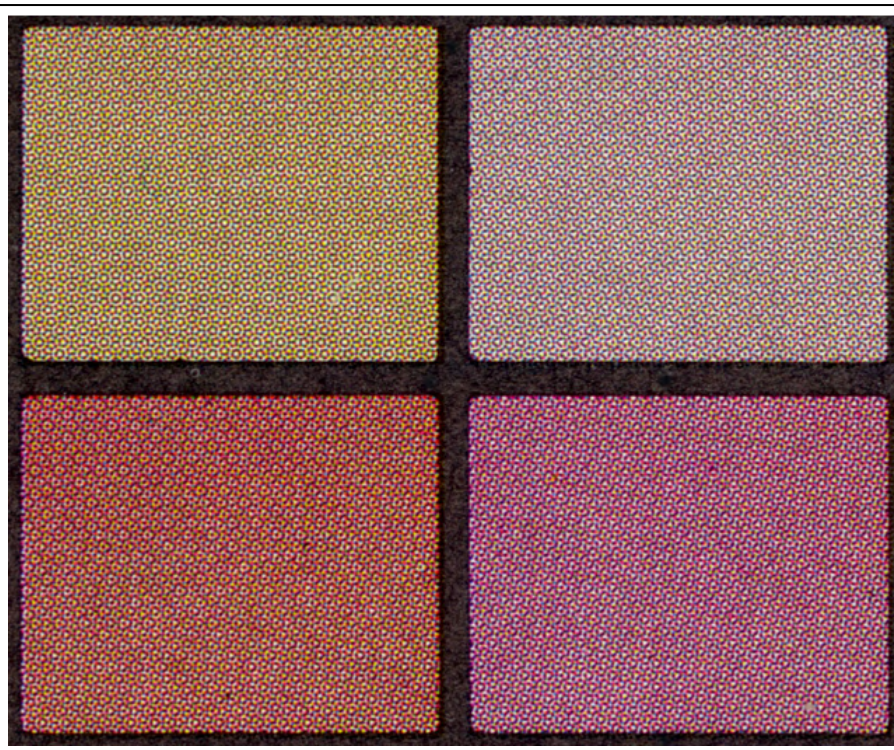


Fig. 7.8. Examples of CMYK halftone prints at different screen densities of the four primary inks.

4.4 Because of the large number of dyes and substrates, similarly complete systems for dyes have not been produced. Dye manufacturers sometimes present recommended trichromatic combinations in the form of triangles where the total concentration of dye for a given sample is uniform but the ratio of dyes used differs (Fig. 7.9). The results depend strongly on the dyes used. Lightness of samples varies widely with one of the nearly-central combinations of all three dyes being the darkest (it is usually not the central sample, but one toward blue as the blue primary is darker than the other two). Such triangles give an idea of the range of shades that can be achieved with the dyes involved.

Fig. 7.9. A textile dye mixture triangle with the primary dyes yellow, red, and blue in the corners. Along the sides are two-color combinations and in the interior, three-color combinations. All squares have an identical dye content of 2% on weight of goods with the ratios changing in regular intervals. Note how large the first steps away from yellow are compared to other steps. The diagram is clearly not perceptually uniform, but only uniform in terms of dye concentrations.

5 Three Color Order Systems

Munsell System

5.1 The Munsell system was originally developed at the beginning of the 20th century by the American artist and educator Albert H. Munsell. After his death, it was further developed in the Munsell Color Co. with the help of scientists from the National Bureau of Standards in Washington, D.C. When measurements of the samples were made in the 1920s and the results plotted in the CIE chromaticity diagram in the 1930s, apparent irregularities in the spacing of the samples were discovered. During the Second World War, a committee of the Optical Society of America investigated the system and recommended changes that were defined in the CIE colorimetric system (Fig. 7.10). The results, known as the Munsell Renotations, have since then been the official specifications for Munsell samples. The system continues to be produced by the Gretag-Macbeth Co. and is available as a two-volume atlas, as well as in the form of individual sheets of painted paper. A textile version, on cotton fabric, has also been issued.

		Greens (*continued*)							
		2.5*G*		5.0*G*		7.5*G*		10.0*G*	
V/*C*	*Y*	*x*	*y*	*x*	*y*	*x*	*y*	*x*	*y*
3/22	0.06555	0.0390	0.7468	0.0340	0.6011	0.0332	0.5206	0.0333	0.4444
20		0.0720	0.7127	0.0620	0.5802	0.0568	0.5082	0.0528	0.4393
18		0.1049	0.6766	0.0882	0.5605	0.0798	0.4954	0.0718	0.4340
16		0.1341	0.6420	0.1120	0.5414	0.1023	0.4818	0.0925	0.4275
14		0.1626	0.6052	0.1382	0.5197	0.1262	0.4667	0.1161	0.4192
12		0.1902	0.5642	0.1660	0.4948	0.1516	0.4505	0.1411	0.4095
10		0.2170	0.5211	0.1935	0.4682	0.1800	0.4310	0.1688	0.3974
8		0.2435	0.4752	0.2228	0.4380	0.2088	0.4101	0.1970	0.3841
6		0.2642	0.4342	0.2471	0.4100	0.2346	0.3901	0.2240	0.3699
4		0.2836	0.3915	0.2711	0.3780	0.2618	0.3667	0.2525	0.3537
2		0.2999	0.3500	0.2935	0.3439	0.2890	0.3391	0.2844	0.3337
2/16	0.03126	0.0329	0.7358	0.0277	0.5986	0.0276	0.5153	0.0285	0.4327
14		0.0820	0.6860	0.0688	0.5691	0.0629	0.4973	0.0599	0.4270
12		0.1307	0.6308	0.1120	0.5358	0.1022	0.4759	0.0934	0.4183
10		0.1773	0.5698	0.1560	0.4981	0.1442	0.4505	0.1321	0.4059
8		0.2192	0.5042	0.1979	0.4583	0.1842	0.4244	0.1705	0.3911
6		0.2493	0.4522	0.2318	0.4231	0.2200	0.3983	0.2092	0.3739
4		0.2763	0.3998	0.2640	0.3845	0.2540	0.3705	0.2442	0.3559
2		0.2978	0.3507	0.2918	0.3450	0.2869	0.3400	0.2820	0.3341

Fig. 7.10. A portion of the Munsell Renotation table defining Munsell color chips in terms of CIE chromaticity coordinates *x* and *y* and luminous reflectance *Y*, expressed as a fraction. The samples are identified by their abbreviated hue name and the value and chroma numbers (leftmost column). *Courtesy of John Wiley & Sons Inc. (Wyszecki, G. and W. S. Stiles, Color Science, 1982). Used with permission.*

5.2 The arrangement of the Munsell system is cylindrical. This is the result of colors of constant chroma falling on a perfect circle. The attributes used by Munsell are hue, value (lightness), and chroma, an attribute invented in its specific form by Munsell. As mentioned above, the atlas shows hue in 40 grades, value in 10, and chroma in up to 10 double steps. Each atlas page contains all samples of a given hue (Fig. 7.11). The 40 hues are 2.5-step intervals of the 100-hue scale. Munsell selected five primary hues—yellow, red, purple, blue, and green, represented by the hue number 5 attached to the hue letter. The hues are named accordingly (Fig. 7.12). For example, 7.5 PB indicates a hue between the purple and the blue primary hues, but slightly closer to purple. The value of the samples is shown in 10 grades, with 0 being black and 10 being white. Chroma of the samples is shown in double steps of the chroma scale as far as can be obtained with the pigments selected to produce the system. As discussed earlier, the chroma scale is an absolute scale and different hues in the system have different maximal chroma. Fig. 7.13 is a schematic view of the cylindrical system showing four opposing pages of constant hue. Fig. 7.14 is a view of what is known as the Munsell Color Tree, a three-dimensional assembly of some of the samples in the Munsell system.

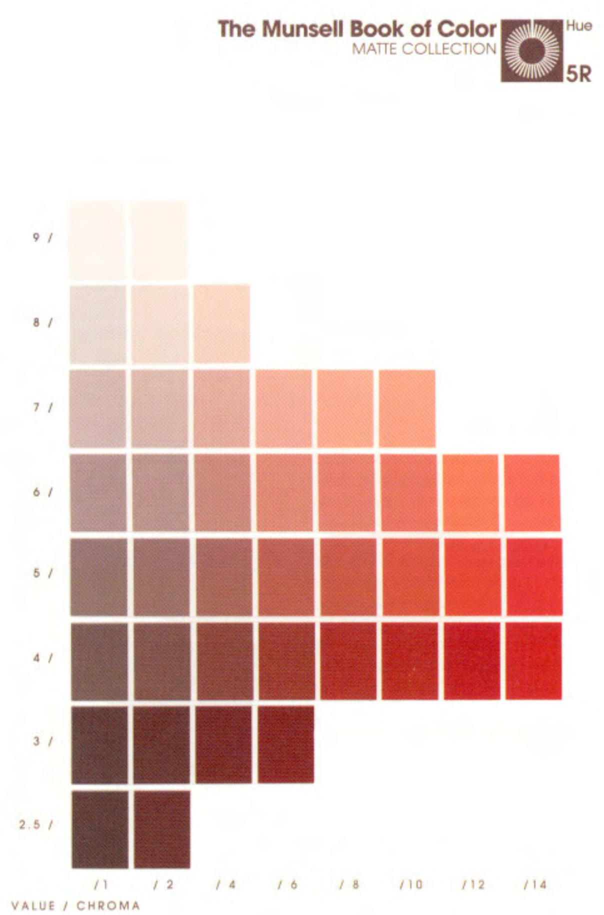


Fig. 7.11. Page 5R of the Munsell color atlas. All color chips have the same hue and differ only in chroma (columns) and in lightness (rows). *Courtesy of Munsell Color, part of X-Rite Inc. Used with permission.*

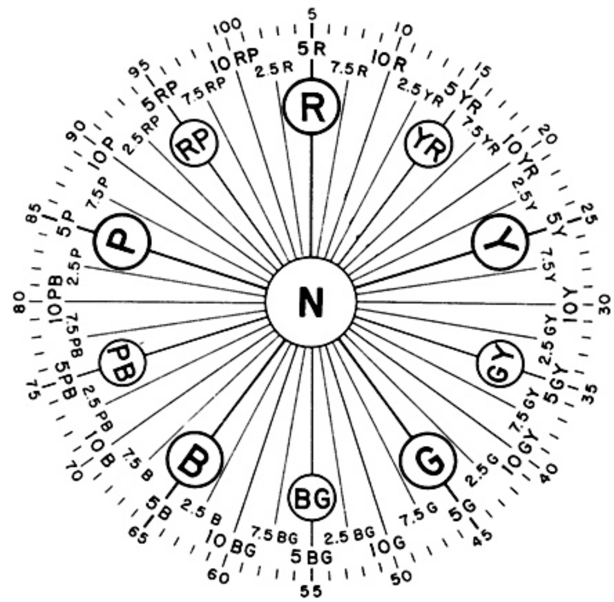


Fig. 7.12. Schematic view of the Munsell 100-grade hue circle with identification of the 40 hues of the Munsell atlas. *Courtesy of Munsell Color, part of X-Rite Inc. Used with permission.*

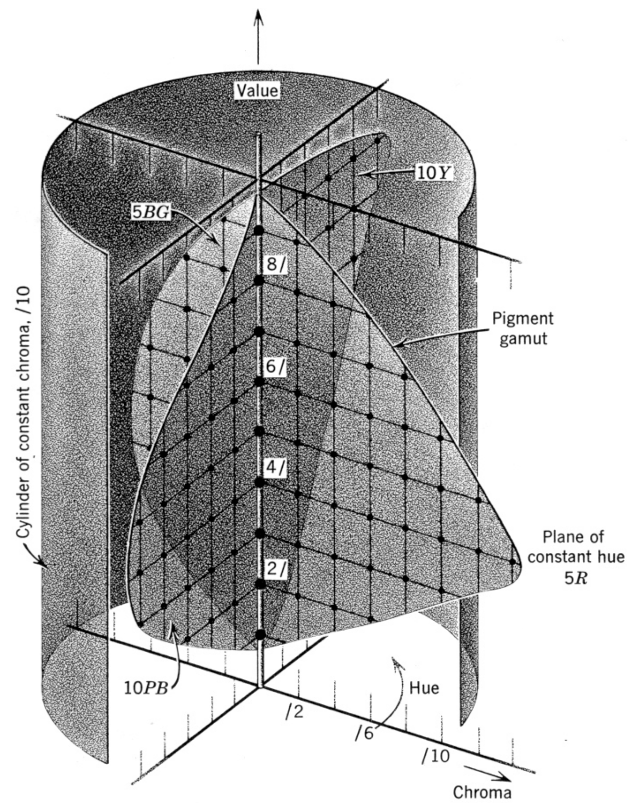


Fig. 7.13. Schematic view of the cylindrical structure of the Munsell system. Four constant-hue planes and their organization in terms of chroma and value are shown. *Courtesy of John Wiley & Sons Inc. (Wyszecki, G. and W. S. Stiles, Color Science, 1982). Used with permission.*

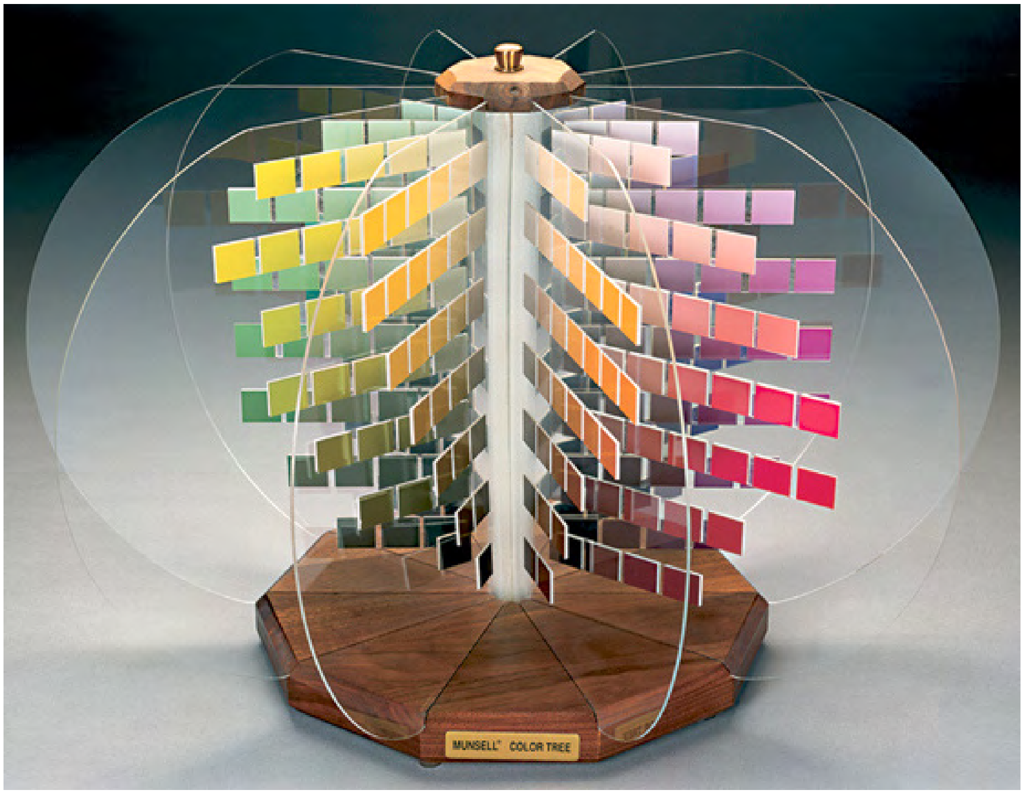


Fig. 7.14. The Munsell color tree, showing the systematic arrangement of 10 of the 40 hue planes. *Courtesy of Munsell Color, part of X-Rite Inc. Used with permission.*

5.3 Advantages of the Munsell System

The Munsell system is based on the three relatively easily-comprehended attributes of hue, lightness, and chroma. Its samples are defined in a colorimetric system. In newer editions, care has been taken to use comparatively color-constant pigment formulations, that is, the appearance of the samples remains relatively constant when viewed in different ”white” lights. The system is an approximation of a uniform system, but with some limitations as described in previous sections of this chapter.

Problems with the Munsell System

The system is not isotropic (generally uniform), as demonstrated in section 3.5 above. Reflectance curves of the samples are not officially established. The appearance of the samples (as with those of any other system) changes significantly, depending on the color of the surround. Depending on the observer, the perception of uniformity of the hue circle or the chroma scales at different hues differ. The lightness scale does not consider the *Helmholtz-Kohlrausch effect* (see Chapter 5). The scale is an average of gray scales determined against a white, a black, and a mid-gray surround.

Natural Color System of the Scandinavian Colour Institute (NCS)

5.4 The NCS system is a representation of Ewald Hering's ideas about perceptual color order (see Chapter 5, section 5). It was developed in the 1960s by researchers of the Scandinavian Colour Institute and is marketed by this organization. Its samples are specified in the CIE colorimetric system. It is a Swedish standard.

5.5 The NCS system fits into a double-cone solid (Fig. 7.15).

Hering placed his samples of a given hue in an equal-sided triangle with white, black, and the full chromatic color in the corners (Fig. 7.15). The set of triangles of different hue have the gray scale in common and, when arranged around the gray scale, they form a double cone. Following Hering, colors of constant whiteness lie in each triangle on parallel lines away from white, those of constant blackness on parallel lines away from black. All full colors are taken to have the same chromatic content. Colors of constant (relative) chromatic content lie on vertical lines parallel to the gray scale line.

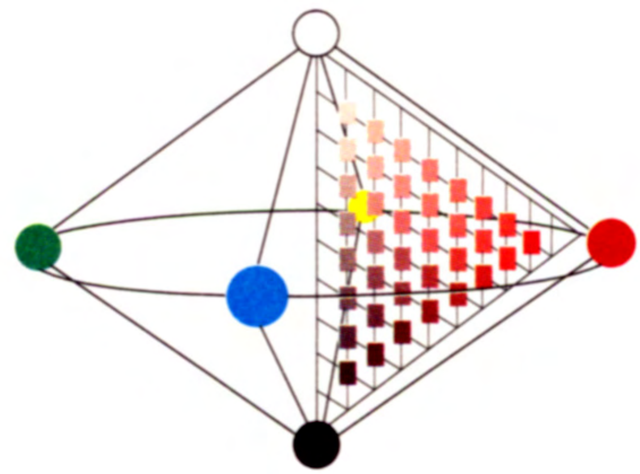


Fig. 7.15. Schematic view of the double-cone structure of the NCS system based on the six Hering primaries—white, black, yellow, red, blue, and green. A constant hue plane is shown. *Courtesy of the Scandinavian Colour Institute AB. Used with permission.*

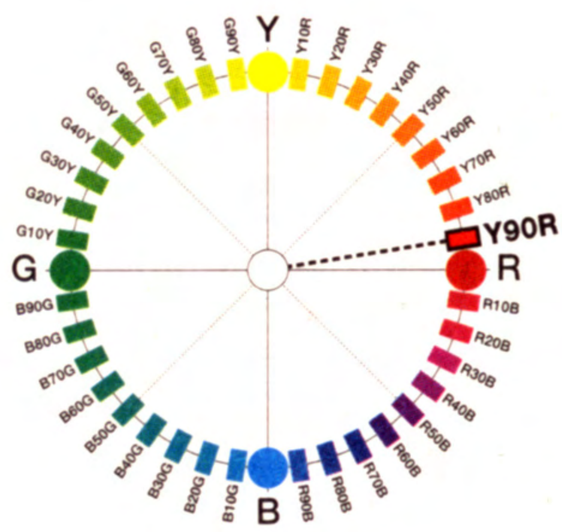


Fig. 7.16. The NCS hue circle with average Hering unique hues stimuli on the axes, with nine intermediate hue grades between pairs of primary hues. *Courtesy of the Scandinavian Colour Institute AB. Used with permission.*

In the hue circle, the unique hues of the system are located on the four semi-axes (Fig. 7.16). The hue circle has a total of 40 hues, with nine between each two neighboring unique hues. All full colors reside on the same plane. As a result, there is no general lightness scale, only a central gray scale that is different from the Munsell value scale.

According to Hering, every color experience is the sum of three or four separate experiences: a chromatic experience—a unique hue or a mixture of two neighboring unique hues, white, and black. He assigned a value of 100 for the total for each color. NCS is based on average choices of a group of observers of samples representing the unique hues, as well as estimates of the amounts of full colors with the unique hues, white, and black in a number of color samples. Since, in the view of the NCS developers, full colors can usually not be realized with pigments or dyes, the full color positions are often not occupied in the atlas pages (Fig. 7.17). Because of market needs, most pages include additional light and bright samples. Colors are identified in a system that has three independent scales, each with a maximum value of 100. Color 3050-Y90R is a color with a hue consisting of 90 parts unique red and 10 parts unique yellow, with a blackness content of 30 and a chromaticness of 50.

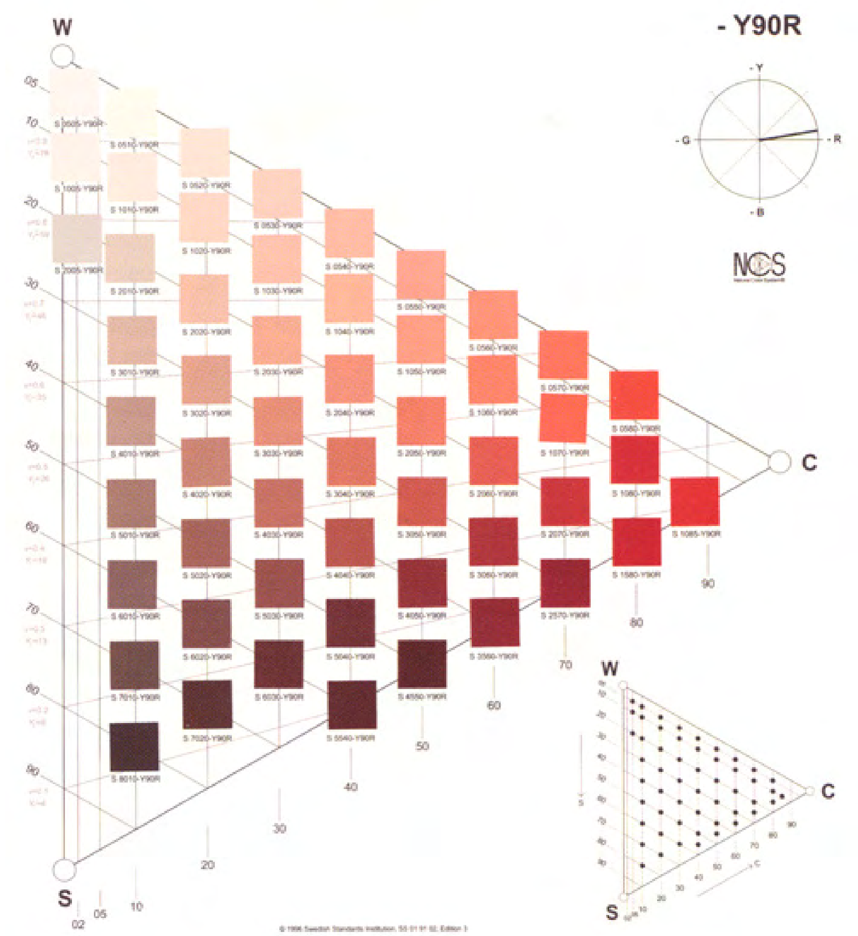


Fig. 7.17. The Y90R constant hue page, showing the organization of samples according to constant whiteness, blackness, and chromaticness. The slanted lines in the main figure converging on a (not shown) point above and right of C are lines of approximately equal to CIE luminous reflectance values Y. The angles of these lines differ for each hue. *Courtesy of the Scandinavian Colour Institute AB. Used with permission.*

5.6 Advantages of NCS

NCS is claimed to be universally applicable because it is based on the presumed reasonably uniform experiences of observers when looking at color stimuli, independent of their source. Its samples are defined in a colorimetric system. They are available in atlases as well as in loose format.

Problems with NCS

The system is far from perceptually uniform in the sense of being isotropic. Placing the unique hues on the semi-axes and dividing the distances between them into 10 equal parts creates a hue scale that is much different from the Munsell approximately uniform hue scale. Uniformity in terms of blackness and whiteness content does not mean perceptual uniformity in terms of perceived distance. As discussed in Chapter 5, the magnitude of each of 10 whiteness steps from white to the full color is much different than the magnitude in case of blue. In case of blackness, the situation is the reverse.

The fact that, as mentioned in Chapter 5, individual observers make widely-differing choices of samples that represent for them the unique hues means the example implemented in the NCS may be reasonably valid for 10%-20% of observers and more or less inaccurate for all others.

Optical Society of America Uniform Color Scales (OSA-UCS)

5.7 OSA-UCS was an attempt to create a system as uniform in all directions as possible. OSA-UCS was published in 1974 after more than 30 years of development. Its structure is not based on a hue circle, but on a geometric principle. In a perfect system, samples equally different in any direction from a central standard form a sphere, but such spheres cannot fully pack a space without leaving gaps (Fig. 7.18). The question to be answered was: What is the maximum number of lines of equal length, from a central color, that result in a geometric solid that can fully pack a space and comes closest to a sphere? The answer found by geometrists and implemented by the OSA committee is the *cubo-octahedron* (Fig. 7.19). This means that from the outset a geometric space fully uniform in all directions is not possible and in the cubo-octahedron, the number of directions from any color in the system in which there is full uniformity is only 12.

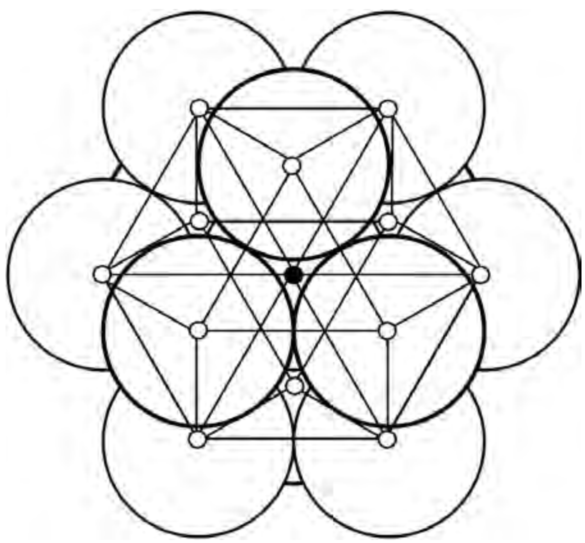


Fig. 7.18. Schematic view of twelve samples (small open circles) that are located at equal geometric distance from the central sample (black dot). Each of the samples has a sphere of equal size around it (some hidden). On the surface of the spheres are all samples equally distant from the central sample. It is evident that the spheres do not fully pack the space in which they are located. Only where the spheres touch is their uniformity of distance and full packing of space.

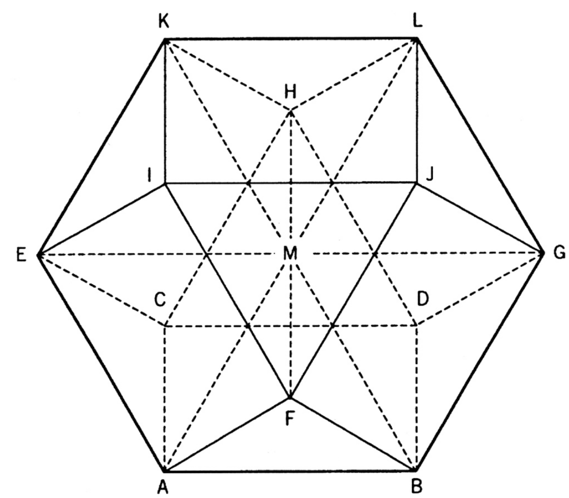


Fig. 7.19. The cubo-octahedron formed by the samples of Fig. 7.18, with central color M and the 12 locations of colors geometrically at equal distance from M: A to L. Cubo-octahedra can be fitted together so that they fully pack a space.

There is an additional problem resulting from the hue superimportance effect. This effect was discovered in the 1930s from study of the Munsell system. When attempting to make the perceptual units of the three attributes of the system equal in size, an important effect was discovered—the change in *stimulus intensity* required to produce a unit chroma difference is approximately twice as large as that required to produce a hue difference of the same magnitude. This means that our color vision system is more sensitive to changes in reflectance that are interpreted as a hue difference than to those that are interpreted as a chroma or lightness difference. As a result, a perceptually uniform system cannot be accurately represented in a geometric model based on our common three-dimensional geometry. A four-dimensional space is required. The Munsell system can be represented in a three-dimensional model (Fig. 7.13, above) because geometric distances in the model are not representative of the perceptual distances between the samples. As a result, in regular three-dimensional geometry, perceptual unit difference contours (the outlines of all possible samples that are perceptually equally distant from a central standard) are always ellipses rather than circles in the constant-lightness plane and ellipsoids rather than spheres in the space, as will be further discussed in Chapter 13. The UCS committee encountered this effect in its own experimental data also. They decided to disregard it and to produce a Euclidean system with an atlas of samples because the system offers six different kinds of approximately uniform color scales, four of which are not available in any other system (Fig. 7.20).

Fig. 7.20. Three-dimensional model of the OSA-UCS system showing its internal structure. Some of the internal planes (horizontal and slanted) are shown. Along each of these are color samples approximately uniformly different from neighbors on the scale. *Courtesy of Springer Science and Business Media. (MacAdam,D. L., Color Measurement, 1981). Used with permission.*

The system is the only one that incorporates the *lightness crispening* effect and the Helmholtz-Kohlrausch effect in its lightness scale.

5.8 OSA-UCS has a square organization but with the solid filling the corresponding space irregularly. The cube has three internal axes, a vertical lightness axis, *L*, and the chromatic axes, *g* and *j* (Fig. 7.21). In the system, samples are identified by these coordinates. The atlas, still available from the Optical Society, is not arranged in an intuitive manner and orientation in the system is somewhat difficult.

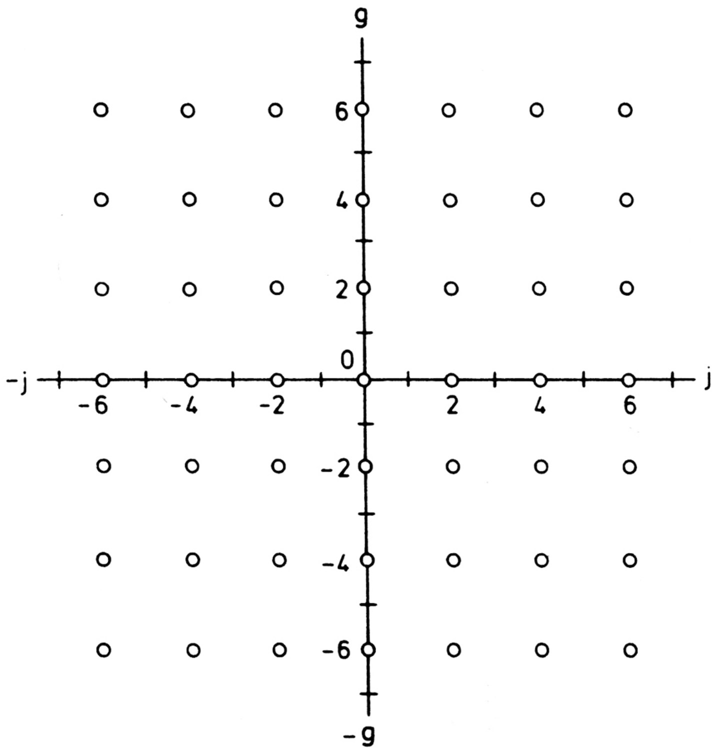


Fig. 7.21. A portion of the chromatic plane, showing the square organization. The lightness scale is arranged at a right angle to the plane in the center of the diagram. The locations of the samples on the planes above and below the one shown are offset by one unit. *Courtesy of Springer Science and Business Media. (Agoston, G. A., Color Theory and its Applications in Art and Design, 2nd edition, 1987). Used with permission.*

5.9 Advantages of OSA-UCS
The system is more uniform and has more approximately uniform directions than any other system. It has a better treatment of lightness than any other system and samples are specified in the CIE colorimetric system.

Problems of OSA-UCS
Because the hue superimportance effect has been disregarded and uniformity would be limited to 12 directions around each sample, the system is less than uniform.

The organization of the system makes orientation in it more difficult than in a hue circle-based system. Not being strongly marketed, the system has found scant acceptance in the field.

6 General Issues with Color Order Systems and Their Atlases

6.1 Color order systems are collections of real or numerically specified color stimuli. Many color order systems are collections of color samples that, when illuminated with a given light, produce a given reflected stimulus. The experience that this stimulus causes depends on the surround in which the sample is viewed and on the specific implementation of the color vision apparatus in a given observer. If a color order system is to represent a specific plan, such as uniformity of perceptual distance between samples, or equality of whiteness or blackness content, it can do so only for specific conditions of viewing and for a limited percentage of observers that experience stimuli similarly to the average observer participating in the perceptual experiments behind the system.

6.2 Depending on the colorants used, the samples of a color order system can be more or less color-constant in appearance. The appearance of its samples can vary to a smaller or larger extent depending on the spectral power distribution of the “white” light that is used to view it in.

6.3 Color chips in atlases are subject to deterioration due to handling. They may fade as a result of the influence of light or chemicals in the air, or be contaminated by handling. As such, they are fragile and should be treated with care.

6.4 Color chips represent the aim colors (the specified color stimulus) only within certain manufacturing tolerances. Two copies of the same system may differ noticeably, at least when the chips are measured. Measurement can be used to determine if the samples have deteriorated.

6.5 Often, color atlases are used as convenient, systematic collections of color stimuli, for example by designers, and the design idea behind them is of less interest and importance. In this case, it may matter little which atlas is used. When specifying a color for design purposes using an atlas designation, it is important to ensure that the chip is close to its specification. Alternately, chip measurement data should be supplied with the designation.

7 Summary

Color order systems have been developed to show orderly arrangements of the world of color stimuli. At least three dimensions are needed to place the stimuli or samples without major discontinuities. Such arrangements are based on different plans, usually meaning that perceptual differences between samples of the system are supposed to represent particular ideas. In one example, they are meant to represent uniform (different per attribute) changes in perception for an average observer along scales of hue, lightness, and chroma. In another one, they are meant to represent uniform changes in mixtures of unique hue perceptions along the hue circle and equal relative increments of whiteness and blackness.

An accurate three-dimensional solid of a system where the geometric distances are proportional to average perceived distances between the samples is not possible.

Some color order systems are based on increments in color stimuli, such as the RGB system of light monitors, or systems representing systematic results of halftone printing.

When color chips from a color order atlas are used to specify a color in design, care must be taken that the actual chip used is representative of its specification or it must be measured and the measuring data supplied also.

Chapter 8 ADDITION OF LIGHTS AND COLORANTS

1 Color Mixture

1.1 The term *color mixture* is a general and loose description for the mixture of light stimuli or the effect of a mixture of colorants in materials on light stimuli. This subject has been briefly mentioned in Chapter 6.

1.2 The difference between the results of light mixture and colorant mixture was a source of confusion from antiquity to approximately 150 years ago, when scientific understanding of the similarities and differences between light and colorant mixtures began.

2 Mixture of Lights: Additive Color Mixture

2.1 When two lights are mixed together—for example, two projector beams of light that have passed through differently colored filters and are focused to overlap on a white screen—the sum is always brighter than either of the two single beams. Quantitatively, the absolute spectral power distributions of the two beams are added together at each wavelength to create the absolute spectral power distribution of the summed light, thus the name *additive color mixture*.

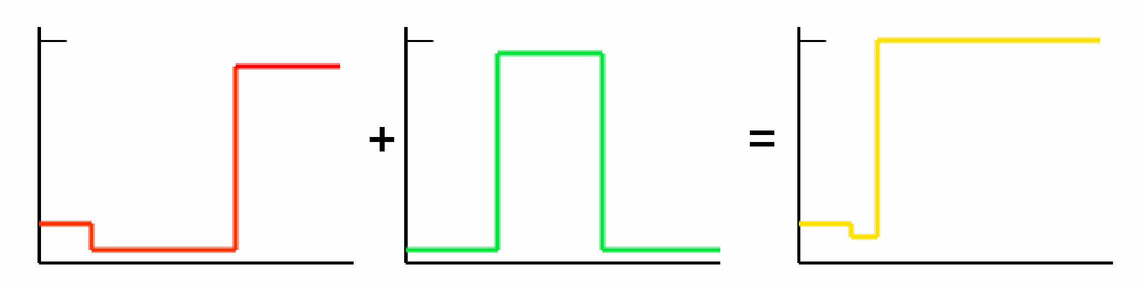


Fig. 8.1 Schematic illustration of the result of mixing a red and a green light with broadband spectral power distributions. The vertical scale represents absolute light intensity, the horizontal scale represents wavelength.

2.2 The color experience resulting from viewing the screen (or the summed lights directly) can be much different from that experienced by viewing either of the two component lights alone. The most dramatic example is the result of mixing a green light (dominant wavelength of 550 nm) with a red light (dominant wavelength of 700 nm). Depending on the relative intensity of the two lights (the amounts), the result can be experienced as anywhere from a yellowish green to a yellowish red. At a certain ratio of the two beams, the appearance is that of a bright yellow (Figs. 8.1 and 8.2).

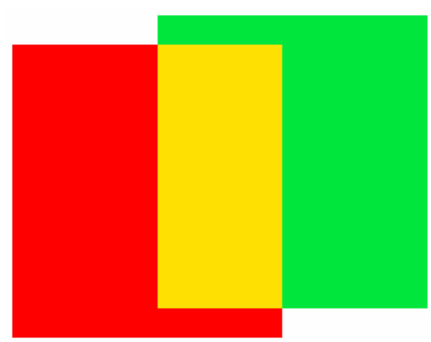


Fig. 8.2. Illustration of the result of overlap of red and green beams of light.

2.3 The result of mixtures of lights is directly proportional or linearly additive (within a limited range of light intensity). This means that their effect on the three cone types is proportional and, as already discussed in Chapter 6, the result can be calculated for a given observer, say the standard observer, from knowledge of his/her cone functions or color matching functions.

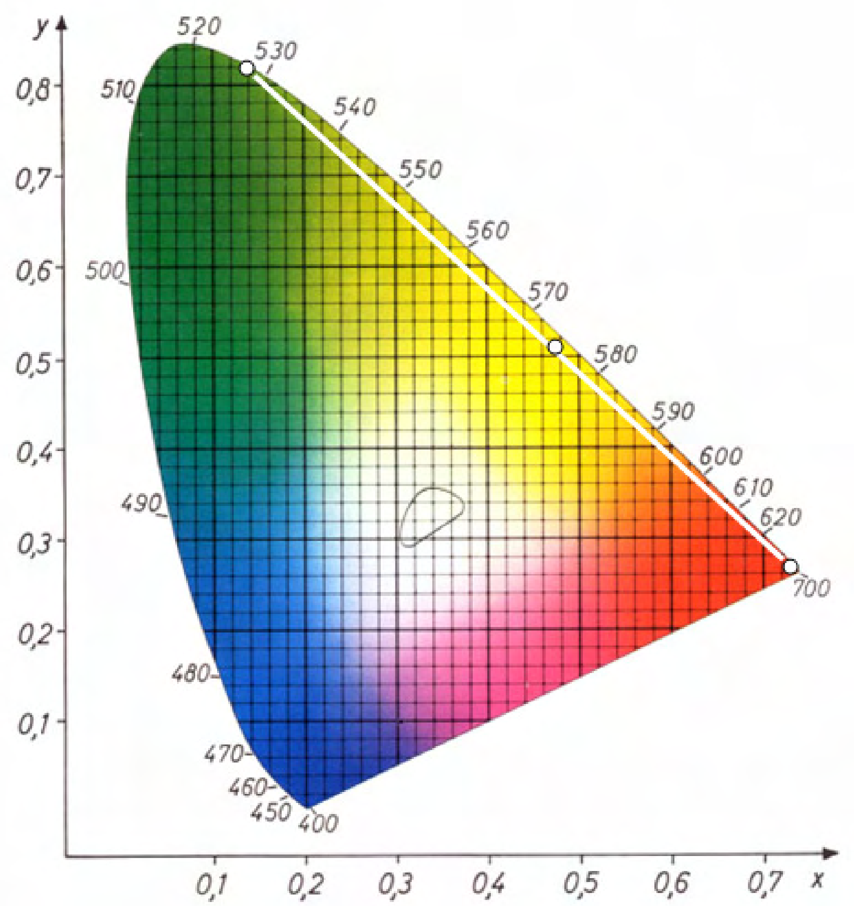


Fig. 8.3. Illustration of the result of mixing a green spectral light of wavelength 528 nm and a red spectral light of wavelength 700 nm, resulting in a given ratio in a near-spectral yellow light of dominant wavelength 576 nm. *Courtesy of Bayer Business Services (Brockes, A., D. Strocka, and A. Berger-Schunn, Color Measurement in the Textile Industry, 1989). Used with permission.*

As shown in Fig. 8.3, the chromatic results can be shown in the CIE chromaticity diagram. Results for two lights fall on straight lines connecting their locations in the diagram. Results for three or more spectral lights or for broadband lights can also be shown geometrically in the chromaticity diagram by calculating the tristimulus values of the mixture and the corresponding chromaticity coordinates (Figs. 8.4 and 8.5).

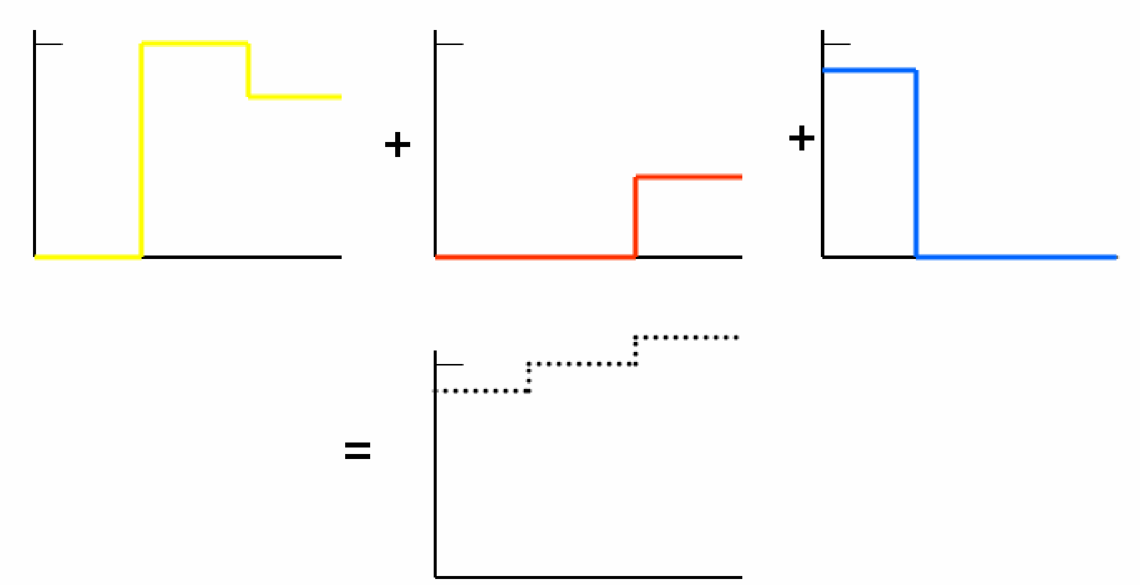


Fig. 8.4. Schematic representation of the addition of broadband yellow, red, and blue lights. The summed light is “off-white” (slightly orangeish) when viewed reflected from a white screen before the visual system of the observer is adapted to it. After adaptation, the appearance is white.

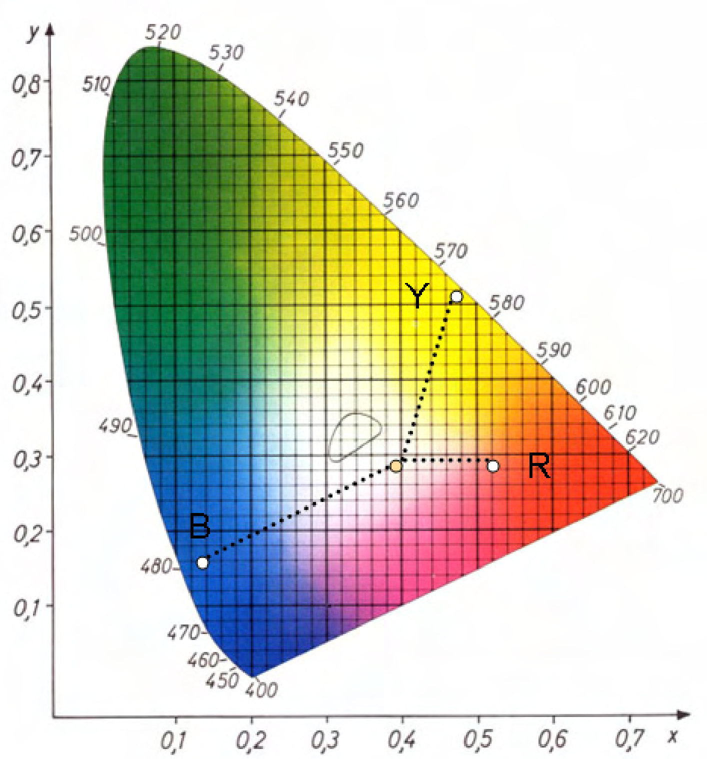


Fig. 8.5. Representation of the mixture of the three lights of Fig. 8.4 in the chromaticity diagram. *Courtesy of Bayer Business Services (Brockes, A., D. Strocka, and A. Berger-Schunn, Color Measurement in the Textile Industry, 1989). Used with permission.*

2.4 As shown in Chapter 6, achromatic (colorless) light can be mixed from an unlimited number of combinations of two, three, or more spectral lights or broader bands of light. In a general sense, this also applies to any other light, but the number of possible combinations becomes smaller as the light to be matched approaches a spectral light.

2.5 The largest chromatic range of mixed lights is possible when the three primary lights are from the beginning, middle, and end of the spectrum (Fig. 8.6). All hues can be generated from a mixture of these three lights but in most cases not at the saturation of spectral lights. As discussed in Chapter 6, most spectral lights cannot be matched at full saturation using other spectral lights.

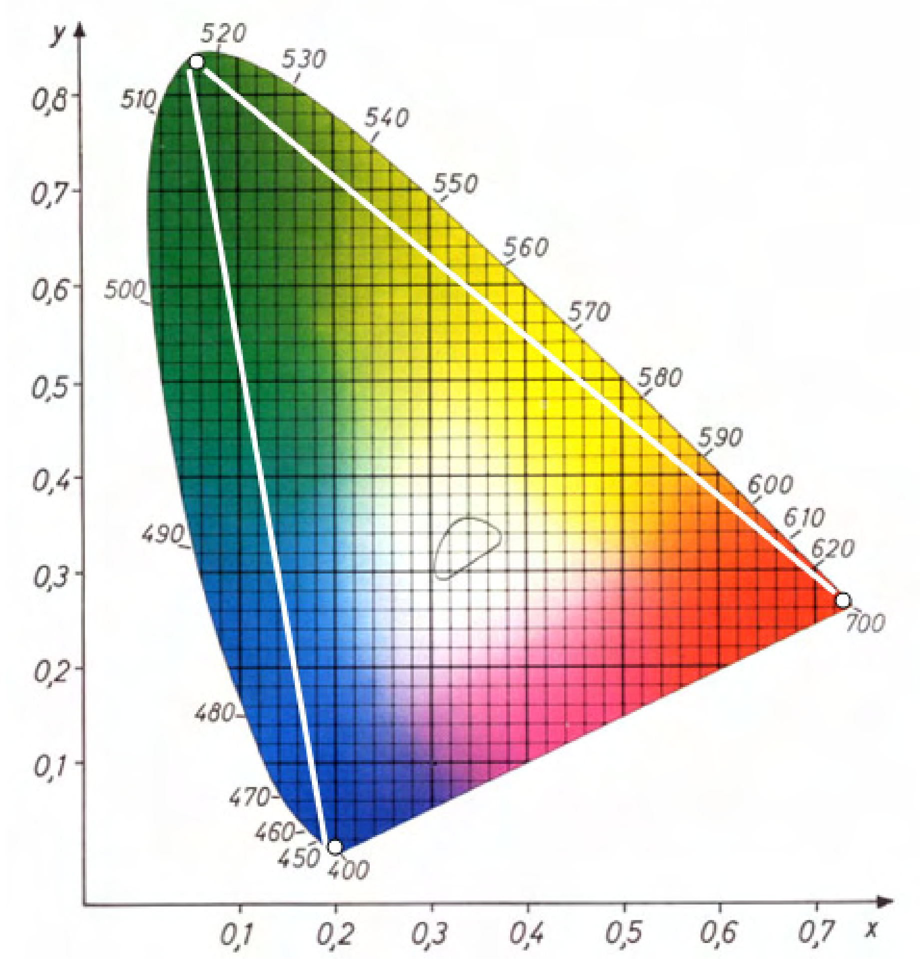


Fig. 8.6. The so-called *chromatic gamut* of lights that fall on and within the triangle and which can be produced from spectral lights from the beginning, middle, and end of the spectrum. With exception of the primary lights themselves none of the spectral lights can be matched at full saturation. *Courtesy of Bayer Business Services (Brockes, A., D. Strocka, and A. Berger-Schunn, Color Measurement in the Textile Industry, 1989). Used with permission.*

2.6 In additive light mixture, it is comparatively simple to predict the results of mixing different lights. In textbook discussions, a light mixture is typically illustrated with three partially superimposed lights, usually from the beginning, middle, and end of the spectrum (Fig. 8.7).

Fig. 8.7. Image of three real lights consisting of broadband spectrum “white” light filtered through a red, a green, and a blue filter, partially superimposed on a white screen in an otherwise dark room. The combination of red and green results in a brighter yellow light, that of red and blue in a brighter magenta light, and that of green and blue in a brighter cyan light. All three, superimposed (in the correct intensities), result in “white” light at the center.

2.8 Additive light mixture is the source of colors that can be viewed on a video monitor. At each pixel, there are micro-sources of three primary lights that each can be adjusted to 255 levels of intensity. We cannot separately resolve the three micro lights and they appear as if additively mixed. Some color appearances from a monitor, such as black, are further influenced by contrast effects.

3 Mixture of Colorants: Subtractive Color Mixture

3.1 When mixing a green dye and a red dye, the result, depending on the dyes, is a dark brown, olive, or gray, or even a blackish color. This is much different from the effect of mixing green and red lights. When mixing dyes, the resulting appearance is always darker than that from either of the two dyes used in the mixture.

3.2 When mixing dyes, their light absorptions are added up. This is best demonstrated by placing transmission filters of different colors on top of each other and observing the effect on the light passing through the filters and reflected off a white screen.

3.3 As discussed in Chapter 4, absorption is the inverse, but not by a simple proportion (not linear), of the transmittance function of the filter (Fig. 8.8).
Adding the absorptions in a mixture means subtracting (in a general sense, not directly) the transmittance values, thus *subtractive color mixture*.

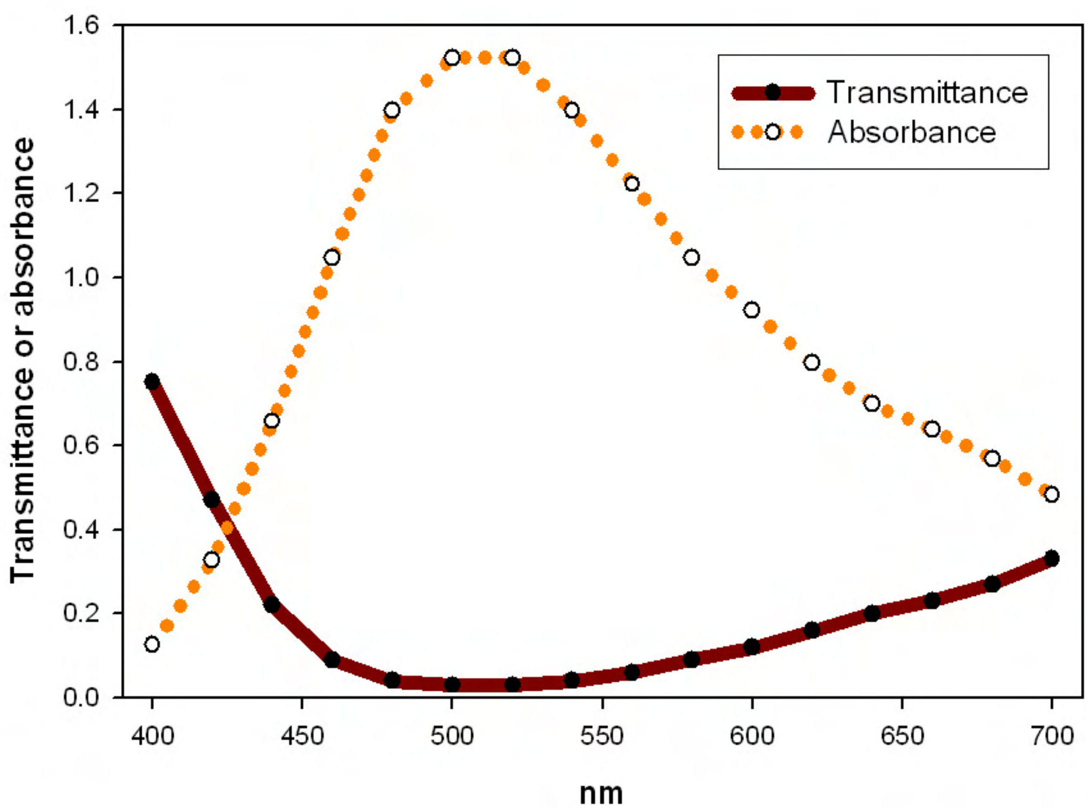


Fig. 8.8. Spectral transmittance function showing the light transmitted through a broadband purple glass filter and the corresponding absorbance function, showing the light absorbed

Fig. 8.9 shows the result of dissolving certain amounts of yellow and blue dyes in a given volume of liquid. The separate curves of blue *a* and yellow *b* are those of individual solutions of these dyes in the volume of solvent. Curve *c* is the result of both dyes in the same amount of liquid. The appearance of the mixture is green. As is evident, the transmittance of the mixture at every wavelength is lower than that of either component dye.

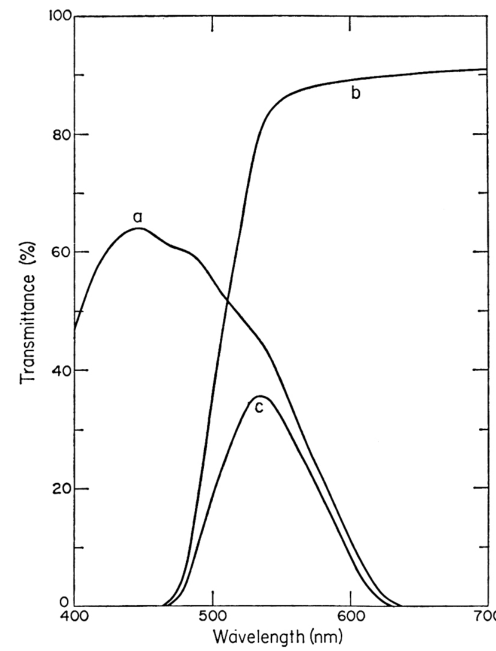


Fig. 8.9. Transmittance curves of a blue dye *a* and a yellow dye *b*, dissolved in water and the transmittance curve *c* that results when both dyes in the same concentrations are dissolved together. *Courtesy of John Wiley & Sons Inc. (Grum, F. R., Physical Methods of Chemistry, Vol. I, Part 3B, 1972). Used with permission.*

3.4 Superimposing certain yellow, red, and blue filters result in black appearance, that is, very little light can penetrate the three filters, because at each wavelength most of the light is absorbed by the colorants in the filter (Fig. 8.10).

This so-called subtractive color mixture, or colorant mixture is often demonstrated by the partial superimposition of a yellow, a red, and a blue filter.

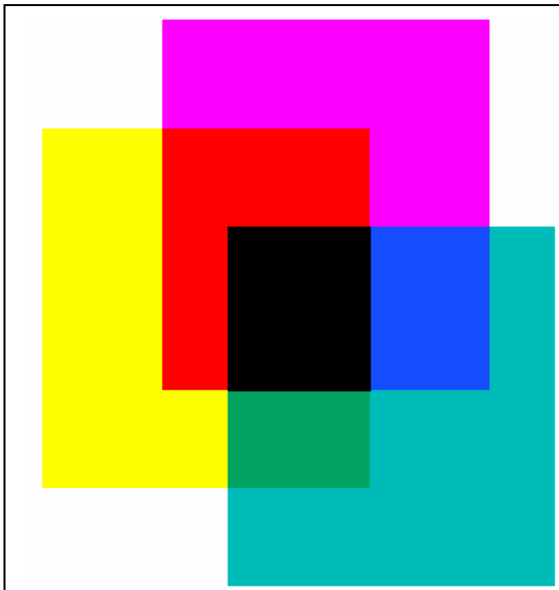


Fig. 8.10. Result of broadband "white" light transmitted through partially superimposed yellow, magenta, and cyan filters. The two-filter combinations produce red, blue, and green appearance. Where all three overlap the result is black. When using filters with duller dyes, the appearance of all fields (except black) is darker and duller.

3.5 In the case of a mixture of dyes or pigments on textiles, matters are complicated by the effects of scattering, as discussed in Chapter 4. The interplay of absorption and scattering has been modeled by Kubelka and Munk and the relationship between them and reflectance is explained by their equation, already discussed in Chapter 4:

$K/S = (1-R)^2/2R$

where *K* is the absorption constant, *S* the scattering constant, and *R* is the reflectance expressed as a value between 0 and 1. When mixing dyes on textiles or when mixing pigments, it is the *K/S* values of the individual colorants that are added up, together with the *K/S* values of the textile substrate, at each wavelength. But recall the limited accuracy of the Kubelka-Munk law in practical conditions. Figure 8.11 illustrates the effect on reflectance of a yellow and a blue dye, applied to a textile substrate, singly and in combination.

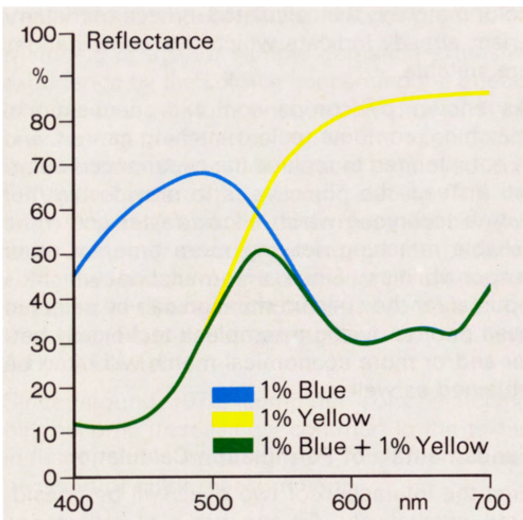


Fig. 8.11. Reflectance curves of dyeings of a blue and a yellow dye individually and of both dyes together. *Courtesy of Bayer Business Services (Brockes, A., D. Strocka, and A. Berger-Schunn, Color Measurement in the Textile Industry, 1989). Used with permission.*

3.6 For various reasons, real colorants change the relative shape of their reflectance and corresponding *K/S* functions somewhat as a result of their concentration.

There are several possible reasons having to do with agglomeration or other uneven distribution of dye molecules in the substrate, interaction between dye molecules, as well as, in the case of pigments, scattering effects.

Fig. 8.12 shows reflectance curves of an acid dye in various concentrations on wool fabric. It is evident that with increasing concentration, the curve shape broadens, with more light being absorbed, and more broadly, at higher concentrations of dye. This makes prediction of the results of dye or pigment mixtures from knowledge of the relationship between concentration and reflectance at one concentration unreliable. As will be shown in the next chapter, usually several dyeings of a given dye in different concentrations are measured as an information basis for that dye. Such dyeings are often called *calibration dyeings*.

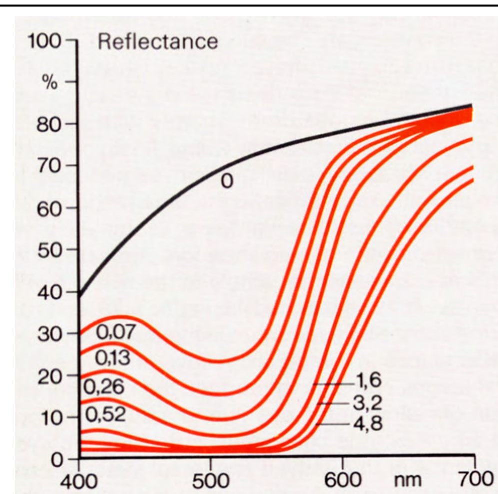


Fig. 8.12. Reflectance curves of a red acid dye dyed in various percent concentrations on weight of goods on the wool fabric with reflectance O. The wool fabric was exposed to the dyeing process in a blank dyebath resulting in yellowing of the wool (light absorption at lower wavelengths). *Source: Courtesy of Bayer Business Services (Brockes, A., D. Strocka, and A. Berger-Schunn, Color Measurement in*

3.7 Colorants can result in different appearances depending on the substrate. This is particularly true if the substrate and the colorant chemically interact. For example, basic dyes generally have a different hue and chroma when applied to acrylic fibers compared to when they are applied to basic dyeable polyester fibers. Pigments can change their appearance as a result of the binder or substrate material in which they are dispersed.

3.8 From sections 3.6 and 3.7 it is evident that the appearance of a dye or pigment is not totally fixed in their respective molecules, but is the result of colorant, colorant concentration, and substrate.

4 Light Mixture versus Colorant Mixture

4.1 To demonstrate the results of light and colorant mixture, the CIE chromaticity diagram will be used. As discussed in Chapter 6, in the CIE colorimetric system individual spectral lights as well as broadband lights such as the equal energy light (*EE,* having a flat spectral power distribution of 1 across the spectrum) are "filtered" with CIE color matching functions, functions containing the same information as the cone sensitivity functions but in a different format. The result describes the light as transmitted through the lenses of the eye and absorbed in the retina in form of three numbers, the tristimulus values X, Y, and Z. The three tristimulus values imply a three-dimensional space, but the chromatic aspects of the results can be expressed in the CIE chromaticity diagram, as shown earlier (for example Fig. 8.3). This diagram does not represent brightness (it would be plotted perpendicularly to the chromaticity diagram).

Figure 8.6 is a rough approximation of the appearance of different lights in this diagram. The location of colorless light (EE) is found near the center of the diagram.

Spectrally different lights that are metameric, that is, lights that have different spectral functions but the same tristimulus values, plot in the same locations in the diagram. Individual spectral lights form the horseshoe-shaped outline, closed off at the bottom with the purple line. The chromatic results of the mixture of any two lights fall in the diagram on a point along the straight line connecting the locations of the two lights being mixed. The location of the point depends on the ratio of the two component lights.

4.2 In the chromaticity diagram (Figs. 8.6 and 8.13), mixtures of the red (R) and green (G) lights lie on the line connecting them. The diagram shows that appropriate mixtures of green and red lights (as defined in the diagram) have hues of yellowish green, yellow, or orange, depending on the mixing ratio.

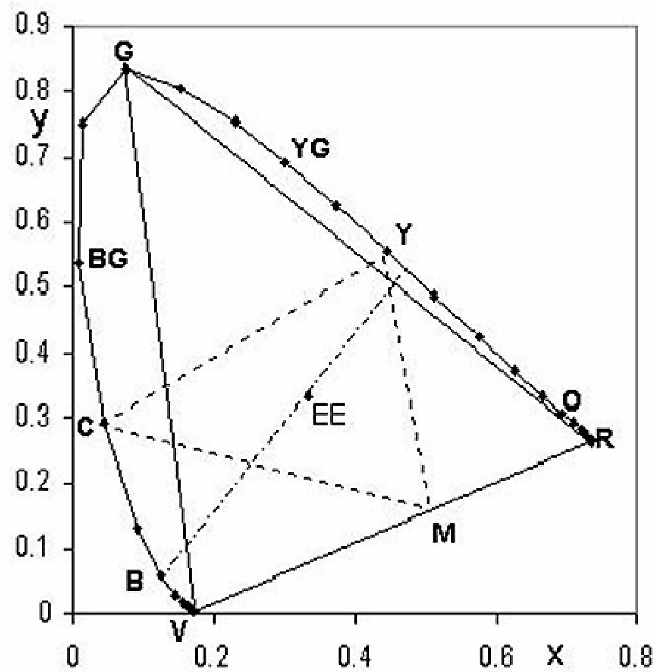


Fig. 8.13. CIE chromaticity diagram with approximate name designations given to several spectral lights, including the equal energy light EE, red R, green G, blue B, yellow Y, magenta M, cyan C, and intermediate hue lights YG, orange O and blue-green BG.

4.3 In Fig. 8.13, several spectral lights are identified as colors, such as violet (V), green (G), and red (R). Such lights include yellow (Y), cyan (C) and magenta (M). Dashed lines form the triangle on and within which the chromaticities of all possible mixtures of these lights are located. It is evident that, as with spectral lights V, G, and R, these lights can be used to create lights that produce all the hues of the hue circle. But saturation levels are in most cases much more limited than in case of primary lights *V*, *G,* and *R*. This leads to the general rule that the hues of the hue circle can be generated with a large number of appropriately selected spectral light triples, but some triples can result in more highly saturated appearances than others. Any such triple of lights can be called primaries for the purpose of indicating that they have been used as a basis for mixtures.

4.4 The appearance of colorless light EE can be matched (among others) with appropriate pairs of spectral and purple line colors (connected with a line passing through EE). The dash-dot line in Fig. 8.13 from B through EE ends up near Y indicating that light B and a light with slightly higher wavelength than Y is required to match the appearance of EE (that is, they desaturate each other completely). Light EE can also be matched with triples, e.g., the two sets already mentioned, or by V, YG, and M, or an endless number of additional combinations. We can use four, five, ten, or more wavelengths for the mixture and it is evident that if we mix all wavelengths appropriately the result is also colorless light EE.

4.5 Not considered up to now is the matter of the brightness or the breadth (in terms of wavelength) of the lights used in the mixture experiments. Both issues are complications the full consideration of which is beyond this level of discussion. In regard to brightness, the following applies: as mentioned, the appropriate mixture of R and G spectral lights forms a near-spectral Y light, a light that is, as is known from experience, brighter than either of the two component lights (see also Fig. 8.7). When Y light is appropriately mixed with B light the result is EE that is even brighter than the Y light. Mixing primary lights G and V results (in appropriate ratio) in a slightly desaturated C light and the appropriate mixture of V and R light results in M light, in all cases brighter than their components.

4.6 To demonstrate the difference in results between mixing lights and mixing colorants, a simplified case of binary mixture is used where the spectral functions of lights and colorants are identical (Fig. 8.14).

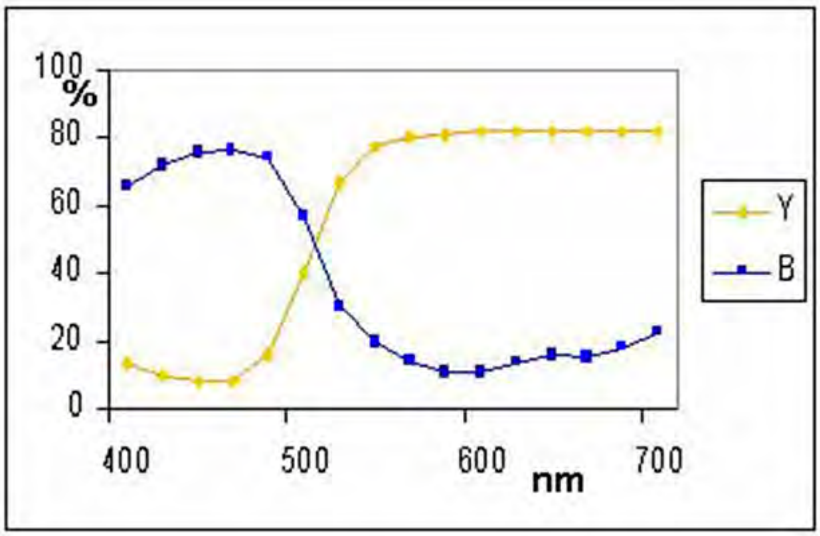


Fig. 8.14. Absolute spectral power curves of two lights Y and B. The curves are at the same time reflectance functions of a yellow and a blue dyeing.

Curve B also represents the reflectance function of a blue dye at a certain concentration on a white textile material and curve Y represents the same for a yellow dye. If an observer views the corresponding colorations in colorless EE light, the two functions can also be considered to represent the amount of light reflected at each wavelength from the dyed samples.

4.7 In the next step, you are asked to imagine a piece of equipment in which the total light reflected from each sample can be collected and mixed together (superimposed). The location of this additive mixture of two lights in the chromaticity diagram is then compared to that of the light reflected from a dyed sample where both dyes have been applied in the same concentrations used for the dyeings in Fig. 8.14. To calculate the reflectance function resulting from this dye mixture, it is necessary to apply the Kubelka-Munk law (see section 3, above).

Fig. 8.15 illustrates the two resulting spectral functions. The curve labeled “Add” represents the result of the addition of the two lights reflected from the individual painted samples; “Subtr” is the reflectance function of the dye mixture and thereby represents the amount of EE light reflected from the sample dyed with both dyes.

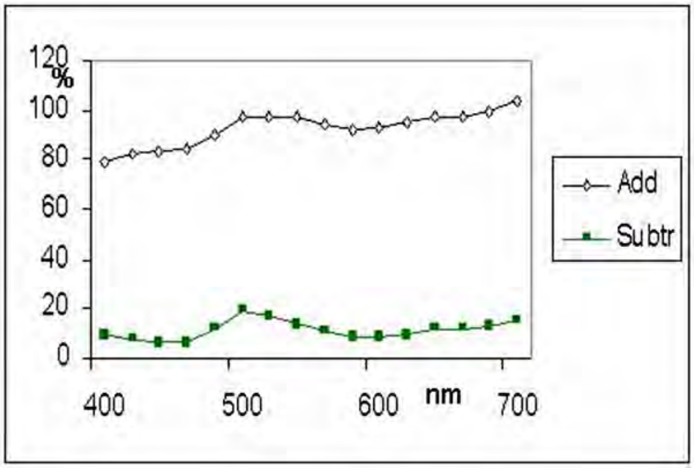


Fig. 8.15 Spectral curves representing the addition of lights Y and B of Fig. 8.14 (Add) and the reflectance of a dyeing of dyes Y and B of Fig. 8.14 (Subtr).

4.8 The corresponding plot in the CIE chromaticity diagram is shown in Fig. 8.16.

Because lights and dyed samples before mixture have the same functions (in one case representing the lights directly, in the other representing the lights reflected from the dyeings) they plot at the same location in the diagram. Mixing the lights is additive and the result must plot on the straight line connecting the two individual lights.

Mixing the two dyes and viewing the result in EE light produces a chromaticity that is nonlinearly related to those of the individual dyes. It is the result of subtractive color mixture. The light mixture is nearly colorless, with a slight greenish tinge compared to EE light. The result of the dye mixture is a more saturated green. The much larger difference, however, is in the perceived brightness of the light mixture vs. the perceived lightness of the dyeing. This is expressed in terms of luminance for the lights and luminous reflectance for the dyed sample (both identical to the CIE tristimulus value *Y*). The *Y* values are given in the Fig. 8.16 chromaticity diagram, next to the locations of lights and dyed samples. The result for the light mixture is the sum of the individual *Y* values. For the dye mixture, the result is less than half that of the darker dye due to broad light absorption across the spectrum by one or the other of the two dyes.

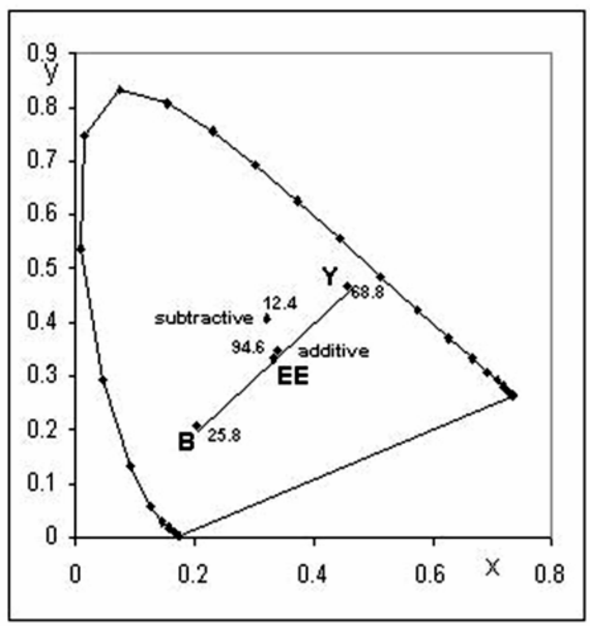


Fig. 8.16. Locations of Y and B in the chromaticity diagram and of the additive and subtractive mixtures. Equal energy light source EE is also shown. The numbers represent luminance *Y* for lights and luminous reflectance *Y* for dyeings. The additive result is nearly hueless and close to EE. The subtractive result is much darker and greenish.

4.9 The appearance is near white in one case (light reflected from a white screen) and a dark olive in the other, approximated in Fig. 8.17.

The saturation of the dye mixture color depends on the saturation of the two component colors and the nature of the overlap of the two reflectance functions.

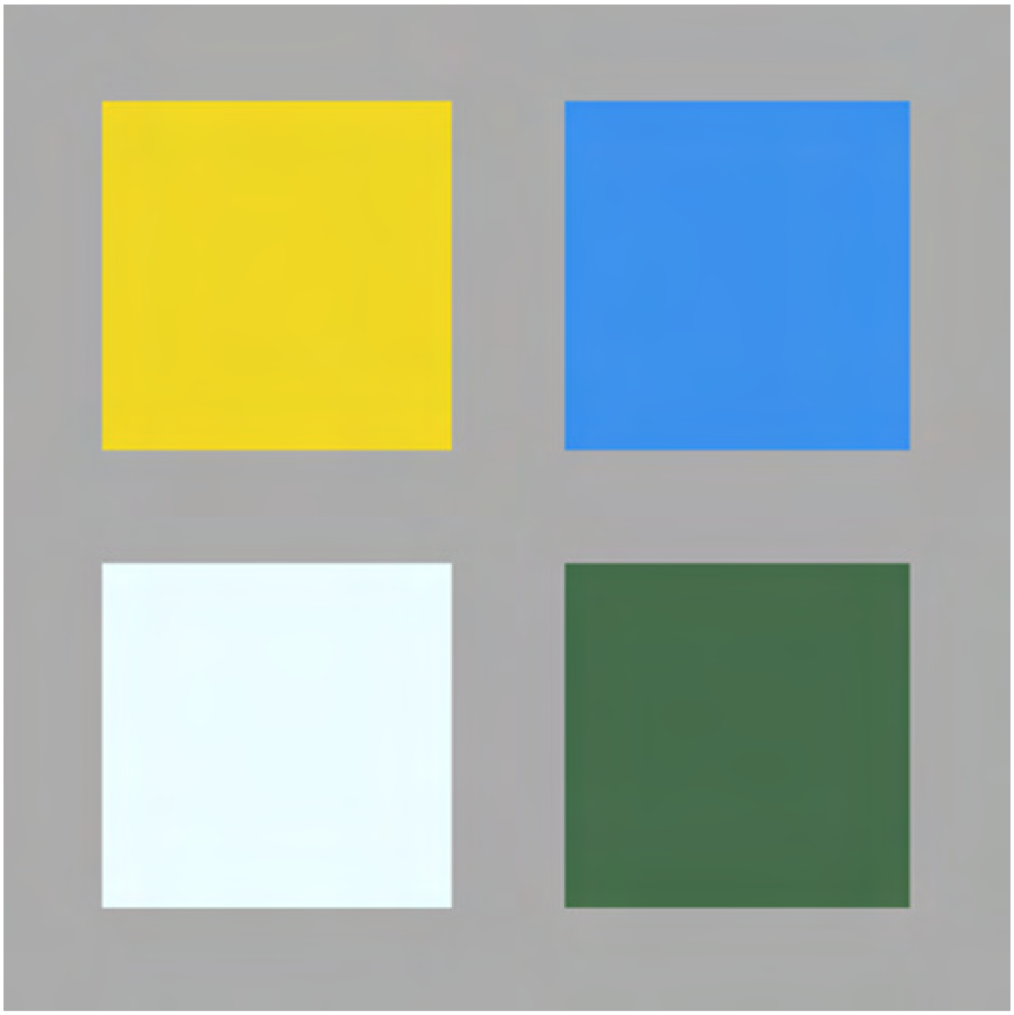


Fig. 8.17. Approximations of the appearance of the lights and dyeings of Y and B on top and of the additive mixture (bottom left) and the subtractive mixture (bottom right).

4.10 A full understanding of the difference between additive and subtractive color mixture required an ability to make spectral measurements of lights and objects and to have a system, such as the CIE colorimetric system, in which to express the results quantitatively. Such understanding was reached only in the middle of the 19th century. Particularly difficult to grasp is the nonlinear nature of colorant mixture.

5 Summary

Additive color mixture involves the direct mixture of lights. The primary spectral lights that allow exact matching of most other lights are from the beginning, middle, and end of the spectrum. The biggest practical application of additive mixture is in video displays.

Subtractive mixture refers to the mixture of colorants applied to a substrate. In the case of transmitting substrates, absorbance values are added up to obtain the result. In case of dyeings on textile materials, the results are more complex because of the scattering effects of the textile materials and require application of a scattering theory, such as the one by Kubelka and Munk. The difference between additive and subtractive color mixture was only understood about 150 years ago.

Chapter 9 COLOR REPRODUCTION

1 Color Reproduction

1.1 *Color reproduction* refers to the duplication of light or object color stimuli with different lights or colorants and/or in a medium different from the original one. The original medium may consist of natural or man-made materials of many different kinds. The duplication may be on video screens, printed on paper, or projected from a slide projector. The color may also be duplicated in a different material substrate, such as a dyed cotton standard reproduced on polyester fiber or a painted color chip reproduced in a plastic substrate.

1.2 The means of color reproduction can be additive color mixture (video screens), but in most cases it is by subtractive mixture involving colorants different from those present in the original (say, reproducing the appearance of a painting in four-ink book printing).

2 Color and Appearance

2.1 The final appearance of an object is not just a matter of reflectance, but also of material structure. It is possible to have two materials with identical measured reflectance but considerably different appearance because of differences in the structure of the substrate. This is often the case with textiles.

2.2 Appearance involves primarily surface structure and glossiness of the material. In the case of textiles, surface structure can differ in many ways as a result of the fibers used and the construction of yarn, fleece, woven, or knitted fabric. An unlimited number of surface structures is possible in the case of other solid materials.

Glossiness depends on the smoothness of the material's surface. Among the smoothest, and therefore glossiest, surfaces are highly-polished metals and glass. In the case of textile materials, man-made fibers can be extruded smoothly, with a perfectly round cross-section, resulting in fabric appearance with a considerable degree of glossiness (100% polyester filament yarn) Silk yarn also has these properties. When plied and woven or knitted, glossiness is reduced due to scattering among fibers. Glossiness also depends on the fineness of the fibers, with scattering increasing with fineness of the yarn.

2.3 Appearance is also affected by transmittance, translucence, or opacity. These are substrate properties that affect scatter and reflectance as discussed in Chapter 4.

2.4 A high level of fidelity of reproduction involves not only reproducing the reflectance of the material (mostly affected by the content of colorants), but also the general appearance. The general appearance affects measured reflectance due to the surface structure of the material and the measuring geometry.

3 Levels of Reproductive Accuracy

3.1 For technical, economic, and aesthetic reasons, different levels of reproductive accuracy may be required or desired.

3.2 At the highest level is perfect reproduction of the reflectance function and appearance of the original (Fig. 9.1). To reproduce color and general appearance accurately requires the use of a material that is identical or very similar in all respects to that used in the original. For color, it requires the accurate reproduction of the reflectance curve of the original. Together, both steps result in the highest fidelity of reproduction. The match appears identical to the standard in different lights and for different observers. It does not mean that the coloration is color constant—that depends on the reflectance curve of the standard (see Chapter 11). This kind of reproduction is known as a *spectral match* on identical material.

Fig. 9.1. Perfect reproduction.

3.3 Spectral reproduction is not achievable in many or most cases of reproduction. Spectral reproduction requires that identical colorants be used in the standard and the match. This is often impossible because the standard and match are made from chemically-different materials that require different classes of colorants. A different application procedure may be necessary, or for competitive reasons, different colorants may be used.

When a spectral match is not possible, a *colorimetric match* may be acceptable, meaning that the tristimulus values of the standard and the match should be the same. Colorimetric matches can be metameric, that is, they can be mismatches of smaller or greater magnitude in lights different from the reference light and for real observers different from the CIE standard observer. In addition, a different material structure may result in the match being considered unacceptable, even though the tristimulus values are the same. For textiles, colorimetric matches are the normal case. For this reason final visual approval is often required.

Fig. 9.2. Fabric, lining, thread, zipper, and other components of this jacket must match.

A special case is a garment with components made from different fibers, structures, and degrees of gloss, all required to match. Colorimetric matches may appear unsatisfactory in such cases. Visual approximations are made until a visually pleasing effect is obtained for all materials involved (Fig. 9.2). Once this is achieved, spectrometric or colorimetric specifications can be established for each of the component materials.

3.4 *General appearance reproduction* refers to technically-best approximations when the color media differ strongly, such as in nature vs. color film, art work vs. reproduction in four-ink halftone printing, or monitor display vs. color printer. Here, fidelity is usually limited (Fig. 9.3). To optimize the results requires complex calculations for smoothly transferring spectral or colorimetric data of the original to the available *color gamut* of the reproduction media.

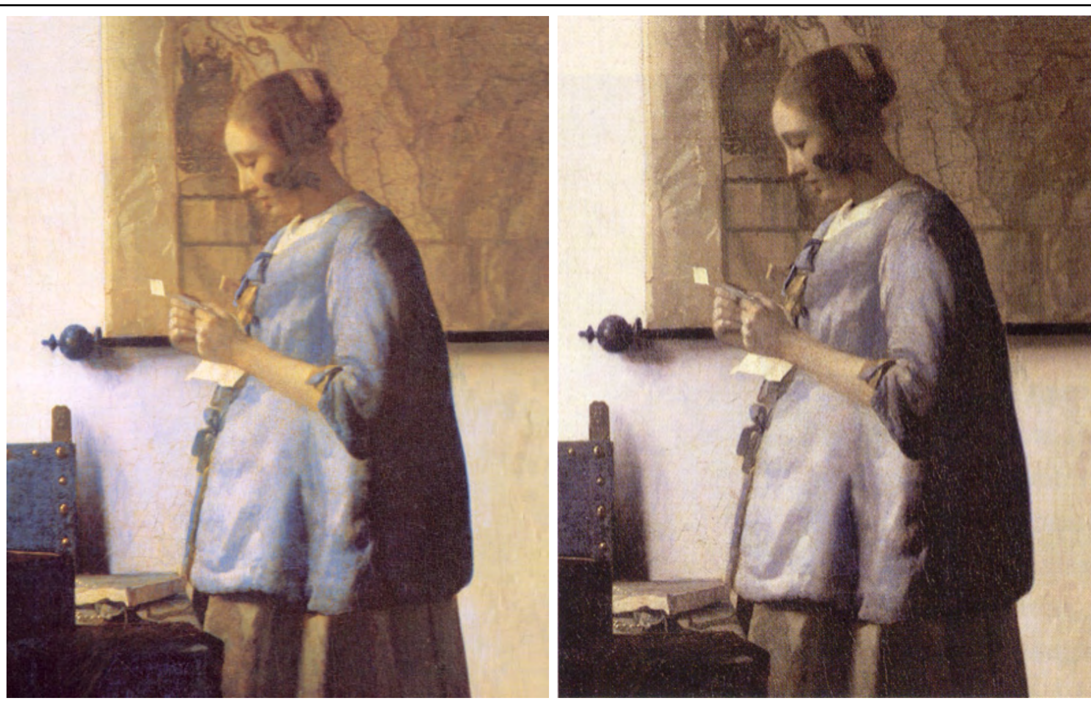


Fig. 9.3. General appearance reproduction: unmodified scans from the same scanner of a detail of Vermeer's *Woman in Blue* from books published in 1996 and 1999. Both versions may differ considerably in appearance from the original.

3.5 Only a general kind of fidelity is desired in case of *preferred reproduction*. This term refers to modifications in the coloration of an image to achieve specific (usually pleasing) results. Artists often use preferred colorations for their subjects, as do photographers and cameramen. Preferred reproduction can be achieved with special lighting or, in case of digital images, with digital manipulation using software. Increases in chroma or saturation, that is, more- rather than less-strongly colored results, are usually preferred (Fig. 9.4). The opposite may also be the case. For this type of reproduction, fidelity is not an issue except in the most general sense.

Fig. 9.4. Preferred reproduction. Left: original digital image; right: more highly-contrasting reproduction

4 Color Reproduction on Textiles

4.1 There are three kinds of reproduction in textiles. The first is matching the standard. Designers select color standards on the basis of ideas about fashion or about harmonic relationships to other color samples. The representative samples in most cases are a different kind of fabric from the one on which they are to be matched. They may also be chips from a color atlas, printed on paper; they may be in the form of watercolors applied to paper; or samples may be in the form of reflectance curve data or specifications in some other measurement-based system. The result of this matching activity is the *master standard*.

The second kind of reproduction is matching of the master standard by a production facility using the dyes to be used in production. Different manufacturing facilities may select different dyes for production. The problem this raises for a retailer is that different production matches for a given master standard may have different levels of color constancy and may result in different kinds of metamerism (see Chapter 11). This may make it impossible to combine pieces from two different manufacturers in the final garment or other consumer product. The result of this activity is *production standards*.

The third type of reproduction in textiles is reproduction of the production standard from batch to batch on repeated production.

Standards

4.2 The master standard is either produced in the textile dyeing laboratory of the retailer, a service laboratory specializing in master standard production, or in the laboratory of a production facility.

In the first and third cases, matching may be done on the actual production fabric. In the second case, matching will most likely be on a standard fabric of the same chemical nature (sometimes not even that), but with different specific properties from the standard fabric and with a different weave or knit.

4.3 Master standards must meet the following requirements:

- match the design standard in a selected light, say artificial daylight, to the degree possible with commercial textile colorants
- be reproducible with commercial colorants
- have a low index of color inconstancy (see Chapter 11)

Depending on the choice of designer standards, master standards sometimes cannot be matched closely even in daylight. It may not be practical or important to match the designer standards under other lights. More important is to have a master standard with good color constancy.

4.4 Production standards have additional requirements:

- economics of the formula
- fastness properties
- reproducibility of the formula in the production process
- matching of the master standard—usually under at least three different lights: daylight, tungsten light, and a fluorescent light

Ideally, the reflectance curve of the approximately color constant formula of the master standard can be matched accurately with the production dyes, guaranteeing good color constancy of the production match. Because of the other mentioned requirements, this may not always be possible. As a result, the production match may be more or less metameric to the master standard and, thereby, usually less color constant.

Visual Matching

4.5 Before the 1960s, color matching was done visually. Visual color matching requires the colorist to know the results of using certain dyes alone or in combinations, on certain materials. Colorists also relied on systematic collections of past matching results and on systematic combination results offered by dye manufacturers (see Fig. 7.9 for an example). From a starting formula, either estimated or from a past result, the color of the standard was approached by trial and error. Here, the experience of the colorist was essential to achieve a useful result in a timely manner. The process was very complex, requiring hitting a target in three dimensions, in three different ways, simultaneously, if a good match in three lights was required. Five to 15 trials per standard were typical in such conditions. Visual matching was also required in production (Fig. 9.5).

Fig. 9.5. Late 19th century painting of French dyers visually checking a match.

Computer Colorant Formulation

4.6 With the development of commercial reflectance measurement and analog and digital computers, tools became available in mid-20th century to assist the colorist in arriving at a solution to a matching problem more quickly. Computer colorant formulation began with large business computers at chemical companies and the analog COMIC (color mixture computer, Fig. 9.6) developed in the early 1960s in the US by Davidson and Hemmendinger. With the availability of small digital computers in the early 1970s, development switched entirely to digital systems. Different approaches to match calculation were pursued. An approach that turned out to be quite successful for textile dyeing was published in 1966 by Eugene Allen. Modern approaches are likely to differ in detail from the Allen procedure. They are trade secrets and confidential. The Allen procedure is briefly presented in the following sections.

Fig. 9.6. Davidson & Hemmendinger analog color matching computer (COMIC) from the mid-1960s.

4.7 Approximating the reflectance curve of the standard is not a satisfactory procedure because of metamerism. Nearly all matches are to a smaller or larger extent metameric to the standard because different colorants are usually involved. It is also possible to create metameric matches with dyes identical to those used in the standard. The degree of metamerism can only be meaningfully assessed from tristimulus values and therefore, it is sensible to calculate formulas matching tristimulus values from the beginning. If color constancy is important, the reflectance curve of the calculated match is determined and its color constancy assessed with further calculation.

4.8 The Allen procedure consists of calculating an initial formula from a given three (or more) dye formula and improving it to the degree possible for the dyes involved with a so-called *iteration* process. Calculating the initial formula uses the Kubelka-Munk relationship between reflectance and absorption/scattering (see Chapter 4). The assumption is that at any wavelength, the *K/S* value of the standard can be matched with a sum of *K/S* values of the dyes and that of the substrate:

$$K/S_{M,\lambda} = [c_1 \times K/S_{1,\lambda}] + [c_2 \times K/S_{2,\lambda}] + [c_3 \times K/S_{3,\lambda}] + K/S_{S,\lambda}$$

where $K/S_{M,\lambda}$ is the *K/S* value of the match at a given wavelength λ (lambda), $c_{1\text{-}3}$ are the concentrations of three dyes, typically a yellow, a red, and a blue, and $K/S_{1\text{-}3,\lambda}$ are the normalized *K/S* values of the three dyes at the given wavelength λ, typically the *K/S* values of a dyeing of 1% on weight of goods.

The formula can be simplified by calculating so-called *pseudo-tristimulus values*, where the *K/S* curve—rather than the reflectance curve—is weighted with color matching functions. The pseudo-tristimulus values of the match are known; they are the same as those of the standard. Also known are the *K/S* values of the three dyes at the standard concentration, and the substrate that has undergone the dyeing process in a blank dyebath. The only unknowns are the three dye concentrations. They can be calculated by setting up three equations, one for each of the three pseudo-tristimulus values, and solving the equations for the three unknown values. The result is an initial formula for up to three dyes (things are a bit more complicated for four or five dyes, a matter beyond this discussion).

If the relationship between dye concentration and *K/S* values was simply proportional (linear), this formula could be expected to produce good results. But from discussion in Chapter 4 it is evident that in most cases the relationship is not linear. For this reason, multiple so-called *calibration dyeings* are produced for each dye involved in matching. The problem is that initially it is not known what the final concentration of a given dye will be. The initial formula is calculated on basis of the *K/S* values at a standard dye concentration, say 1%.

In the iteration process that follows, the initial formula is improved by using *K/S* values (interpolated from the nearest calibration dyeings) at the most recently calculated concentration for each dye. In each iteration step, the computer calculates a reflectance curve of the match by converting the *K/S* values to reflectance. Regular tristimulus values are then calculated for both standard and match and the color difference (usually for daylight) between the two is calculated. The iteration process is repeated until the resulting difference between standard and calculated formula is zero (or less than some accepted value). At this point, color differences for the additional two light sources as well as the dye cost of the formula are determined.

Such formulas are usually calculated for a group of suitable dyes in use at a given finishing plant. This produces several formulas for the standard. They differ in dye selection, in color differences for the second and third light source, in dye cost and, if calculated, in color inconstancy index. It is now up to the colorist and/or the dyer to select the best compromise between competing requirements.

With modern high-speed desktop computers, calculation of a set of formulas from a dozen dyes in all possible three-dye combinations usually takes less than a minute. The computer has to attempt all combinations, even though many of them would never be considered by a colorist, because the computer cannot assess in advance which combinations may produce a useful result, unless specifically programmed.

The selected formula is then dyed. It may or may not be visually acceptable depending a number of issues:

- accuracy of the calibration dyeings
- substrate differing from the calibration dyeings
- absence of errors in preparing or dispensing the dye stock solutions

It may be necessary to make additional calculated or estimated corrections. The use of *dye dispensing units* may be helpful in obtaining repeatable results.

4.9 The so-called calculation *algorithm* of the process is shown in simplified form in Fig. 9.7.

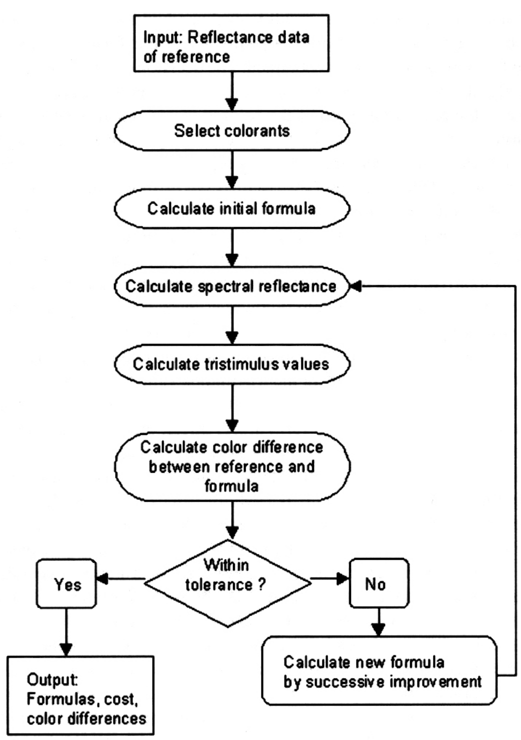


Fig. 9.7. Calculating procedure (algorithm) for the computerized calculation of dye formulas.

4.10 Routines have been built-in to some modern color matching software by which the computer learns from the obtained errors that have been fed back into the computer, and makes the adjustments necessary to obtain ever better formulas.

4.11 While less than perfect, computer colorant formulation has been proven valuable in the textile and other color-related industries by making it possible to produce acceptable formulations more rapidly and by making possible identification of the best compromise formula available from a group of dyes.

Transfer of Lab Formula to Plant

4.12 Dyeing conditions in the laboratory and the plant are never exactly the same, potentially producing different results in terms of color.
Among the possible reasons are:

- ratios between dye liquor and material may be somewhat different
- relative movement between dye liquor and material may be different
- water quality may be different
- dyeings deviating somewhat from the manufacturer's standard may be used in the plant lab

The effects of such differences on the final dyeing may compensate for each other (small overall difference) or add up (large overall difference). As a result, production batches may differ more or less from the master standard compared to the production standard. This may require adjustments during the dyeing process, or rework. Either step is costly, and attempts should be made to minimize or eliminate them.

Repeat Production Batches

4.13 Differences similar to those between lab match and production can occur among repeat production batches:

- the machine used may not be identical or even of the same type
- the water quality may have changed
- different dye batches may be used
- there may be subtle or not-so-subtle differences between the fibers used in repeat batches
- the fabrics may not be prepared identically
- the dyeings may not be finished identically

4.14 Dyeing processes have a large number of variables. A high degree of repeatability requires identification of the more influential variables and controlling them within tight limits. A quality improvement process is the technology used successfully in industry to accomplish this goal.

4.15 Finishing processes after dyeing can have considerable effects on measured reflectance and color appearance. After the dyeing process, textile materials are dried and, in most cases, finished in some manner. This may mean application of softeners or anti-wrinkle finishes, or a number of other modifiers of fabric properties. These, and the heat treatments of the finished fabric that are often involved, can have considerable effects on color appearance. It is essential to consider the effects of finishing in the total color management process, including the setting up of standards.

5 Color Management in Textiles

5.1 Color management is a term used to describe the process instituted in a firm to control all steps in the manufacturing process related to the color of finished goods, such as garments.

5.2 The color management process consists of several steps that depend to a degree on the operations of the company. The most complete process is required for large retailing companies that design and manufacture their own products, or that outsource manufacture. Less extensive color management is required for companies in a supply chain that handle only portions of the manufacture.

Companies operate in large international networks of supply and demand and are largely free to design their own processes. This results in color management processes being components of competition, spurring on innovation. On the other hand, lack of uniformity among color management systems creates problems for dyers and finishers who have to deal with many different color management demands from their customers.

5.3 Color management systems require a number of up-front decisions to be made:

- objective measurement choices, including reflectance measurement instrumentation, measuring geometry details, sample preparation for measurement, calibration details for all instruments involved in the color management process, standard observer and illuminant data for calculation of tristimulus values, color difference equation used for expressing objective color differences, reporting requirements, and others
- visual evaluation choices, including light boxes and their calibration, spectral power distributions of the lights used for visual evaluations, number of observers required to arrive at the final judgment, standard terminology for visual expression of color differences (see Chapter 13), averaging method for individual judgment results, reporting requirements, and others
- communication tools
- decision-making responsibilities and chains

5.4 A complete, hypothetical color management process consists of the following steps:

- Design color standards are expressed in terms of a standard system, such as Pantone color standards, or Munsell chips. Colorimetric specifications are associated with these standards. Exceptions are made for colors not available in such systems. In this case, the samples are measured and standard colorimetric data are calculated for them.
- Colorimetric data are furnished to a specialty firm that produces master standards. Requirements for the standards are that they are color constant in three defined illuminants. The illuminants are selected for good agreement with lighting in major retail stores of the operation.
- Cuttings of the master standard and a yardage of the fabric involved are sent to several finishers for quotes. The requirement is to match the master standard non-metamerically within set tolerances, meeting given fastness and performance properties, and to submit a standard-sized, finished swatch of the match, together with spectrophotometric and color difference data.
- After a match has been approved, a contract is issued for manufacture. The finisher submits color difference data regarding conformance of production to the master standard and uniformity of the batches. When the batches have been approved, the material is forwarded, together with the color control data, to the cutting and sewing plant.
- At the cutting and sewing plant, batches are selected to avoid cutting adjacent pieces of a garment from batches with objectionable differences.

It is evident that the above only outlines the complete process and that there are many possible variations. The goal is to design the process so that it flows with maximum efficiency and minimal cost.

6 Summary

Color reproduction is a technological problem dating back to antiquity. For textiles and other manufactured products, it relied, until the mid-20th century, entirely on the experience of colorists and trial-and-error laboratory work to arrive at acceptable matches. With the introduction of relatively inexpensive measuring and calculation equipment, as well as suitable software, the matching process is more and more supported by technology. Matching has changed from an art to a technologically supported art.

Depending on requirements and technological capabilities, reproductive fidelity can range from high to very modest. The requirements in the case of textiles are usually high, now often involving color constancy of the dye formulation. But quality of match is only one of several important aspects of a formulation. Others are economics, fastness properties, and performance in the manufacturing process. Color matching, therefore, is usually the art of finding the best compromise between different, competing requirements.

Color is a very important aspect of many consumer products. Its control from design to display in stores and advertisements, and ultimately into the hands of the consumer, requires a detailed management process to assure a smooth and efficient flow. Such a process has many components that need to be selected carefully and with the overall functioning of the process in mind.

Chapter 10 STRENGTH OF COLORANTS

1 Coloring Power

1.1 Different dyes and pigments differ in their ability to cause absorption of light when applied to undyed substrates.

1.2 *Coloring power* refers to the ability of colorants to absorb light in relation to the amount of colorant applied to the substrate. Coloring power of both dyes and pigments is a function of their chemical structure. In pigments, the *particle size distribution* also has an effect on scattering. The following discussion is limited to dyes, the most widely used textile colorants.

1.3 Different coloring powers are shown in Figs. 10.1 and 10.2 as sets of reflectance curves of two different dyes at various concentrations on a textile material.

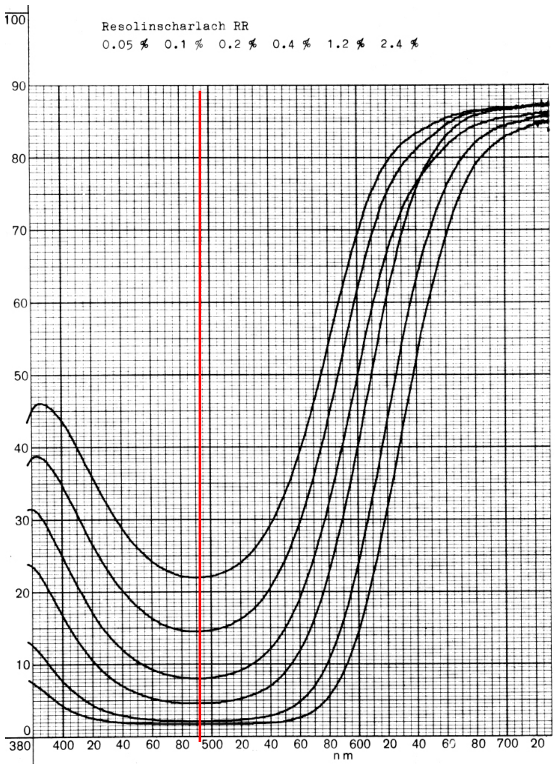


Fig. 10.1. Reflectance curves of a scarlet disperse dye on polyester in five concentrations. The red line in this and the next figure indicates the wavelength of lowest reflectance or highest light absorption.

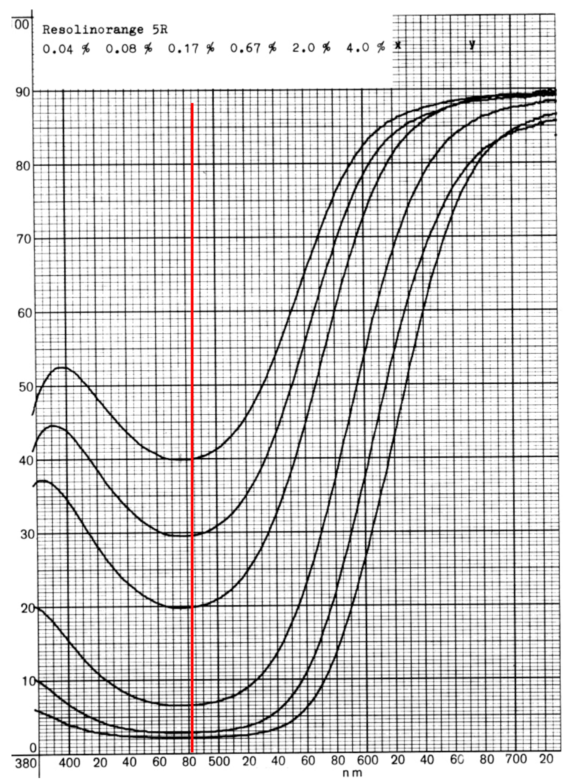


Fig. 10.2. Reflectance curves of a reddish-orange disperse dyes on polyester in five concentrations.

In Fig. 10.3, the *K/S* values (see Chapter 4) calculated from the reflectance values at the lowest point of the reflectance curves (red lines in Figs. 10.1 and 10.2) of the two dyes are plotted against their concentrations. The steepness of the curve is a measure of the coloring power. The more light absorbed by the dye at a given concentration, the lower the reflectance, and the higher the *K/S* value. From this it is evident that Scarlet RR has higher coloring power than Orange 5R. (The figure also demonstrates that, unlike the predictions of the Kubelka-Munk theory, the actual relationship between dye concentration and *K/S* values is often not linear (not a straight line), requiring calibration data for multiple dye concentrations when calculating formulas by computer (see Chapter 9).

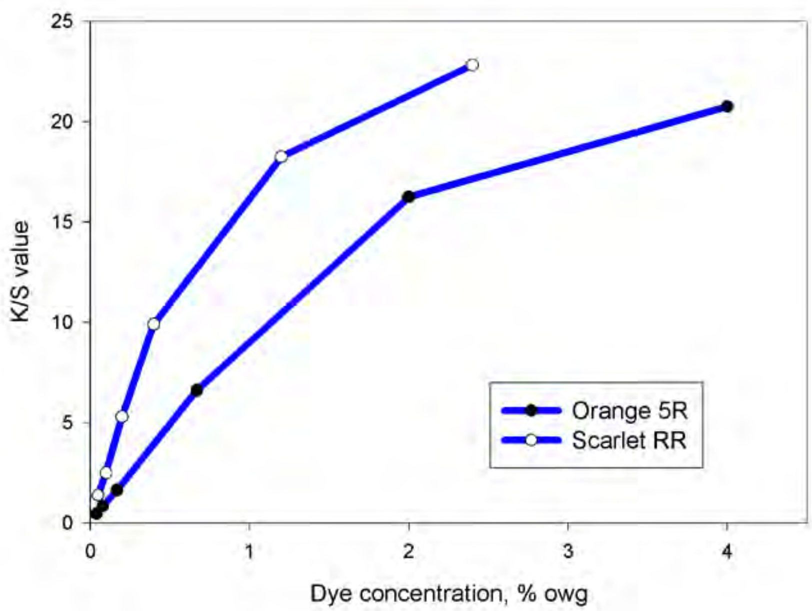


Fig. 10.3. The relationship between *K/S* values and dye concentration for the two dyes of Figs. 10.1 and 10.2, determined at the respective wavelength of lowest reflectance.

1.4 The strength of colorants can be expressed in absolute and in relative terms. *Absolute strength* is expressed in terms of a unit number of dye molecules, depends on the chemical nature of the colorants and other factors, and is of interest to dye chemists. *Relative strength* is the strength of a dye batch compared to a commercial dye standard. Colorant standards are set up by colorant manufacturers to represent the quality of a given product in all respects, including strength and shade.

1.5 Dyes are never sold as pure products, but in diluted or cut form, standardized products. It would be very expensive to separate the dyes from the various possible byproducts generated during the chemical manufacturing steps. Commercial dyes are diluted with salts or dispersing agents, depending on the class.

1.6 Pigments used in textile coloring are usually sold as a diluted aqueous dispersion.

1.7 Standardization of production batches assures that the coloring power of each batch of a given product is, within manufacturing tolerances, identical to that of the standard maintained by a manufacturing company. The standard is a commercial standard and arbitrary in how much pure dye it contains. The commercial standard is always weaker in pure dye content than the manufacturing batches so that batches can be standardized by addition of an inert diluting material.

1.8 Dyes are often sold in multiple concentrations such as 100%, 200%, or 50% products. These percentages relate to the commercial standard at 100%. Products at 200% concentration may be less expensive to produce because some filler material can be saved. Liquid products are often at 50% because it is impossible to produce them at 100% strength. Liquid forms usually have their own standards, tied to the solid product standard in regard to strength and color.

2 Relative Strength and Color (Shade)

2.1 Relative strength, as the name implies, is the coloring power or strength of a dye relative to that of the corresponding 100% standard. The colloquial term “shade” refers to the perceived color (hue, chroma, and lightness) of a dyeing of a batch made under standard conditions compared to that of the standard.

2.2 Accurate determination of relative strength and shade is important to help the manufacturer produce a reliable product and assure the user that producers’ shipments are, within tolerances, equal to the standard.

2.3 Is checking dye shipments for conformance to standard a necessity? If, within a quality management process, a supplier has demonstrated the capability for reliably supplying quality products, user checks are not a necessity. It is desirable to inspect shipments when developing a relationship with a new supplier. It must be understood that checking conformance to a standard requires considerable expertise and a laboratory that can run the required tests.

2.4 Most dye manufacturers routinely supply quality assurance reports (QARs) with their shipments. QARs provide valuable information about the quality of the shipment relative to the standard that can be used to adjust the weight of dyes in textile dyeing production. Some skepticism is justified in regard to suppliers that cannot provide QARs with their shipments.

2.5 For many dye classes, relative strength can be measured more rapidly in solution than by making dyeings. Accurate shade determination still requires dyeings, however, because the color of the dye in solution may be considerably different from the color on a textile substrate. The final quality control assessment of dyes is always done by making dyeings.

3 Relative Strength in Solution

3.1 The strength of a dye in solution is assessed by measuring the transmittance of a solution of the standard and of the batch, and comparing them.

3.2 Many dye classes can be measured as solutions in water; others, such as disperse dyes, require an organic solvent.

3.3 There are many factors that can have a bearing on the accuracy of strength measurements, such as dye concentration, solution pH , and byproduct presence. Solutions can be sensitive to temperature changes or exposure to light. Dye manufacturers have usually worked out reliable procedures for their products that may be consulted for quick, reliable results.

3.4 Solutions are prepared from samples weighed on *analytical balances* in *analytical glassware*. Often, further dilutions with *analytical pipettes* for exact measurement are required (Fig. 10.4).

Fig. 10.4. Careful measurements require analytical glassware and pipettes.

3.5 Transmittance values, usually at the lowest point of transmittance, are converted to absorbance values (see Chapter 8). The absorbance values are directly proportional to relative strength if the solution procedure has been tested in this respect.

3.6 Strength measurements in solution, if performed by competent technicians using proven solution procedures (see 3.3 above), is relatively rapid and accurate for several dye classes. It is more problematical in the cases of vat and sulfur dyes. Measurement in solution is usually not valid in the case of reactive dyes because they contain varying amounts of non-reactive dye that is included in the transmittance measurement but washes out in scouring after dyeing.

3.7 The relative color of a dye (its shade) cannot be accurately assessed by solution measurement, but requires standard and batch dyeings.

4 Parts versus Percentage

4.1 Two kinds of strength reports are used, parts and percentage, and it is important to understand the difference.

4.2 Strength of a dye sample relative to the standard sample can be reported in the form x parts = 100 parts of standard. Samples weaker than the standard have greater numbers than 100; samples stronger than the standard have smaller numbers. A sample designated as 80 parts in strength takes 80 parts of the sample to equal 100 parts of the standard. If the standard is applied in a dyebath at 1% on *weight of goods*, the sample needs to be applied at 0.8% on weight of goods to result in a dyeing (everything else being equal) with identical reflectance properties.

4.3 Strength can also be reported in the form x% = 100% of standard. In this case, samples weaker than the standard have lower values and samples stronger than the standard have higher values. It takes twice the amount of a 50% liquid, or 2.0% to equal the reflectance of a dyeing dyed with 1.0% of the 100% standard (100/50=2).

4.4 Strength in percent and strength in parts are reciprocal to each other. A 150% dye powder is (150/100) = 1.5 times stronger than the 100% standard. It takes (100/150) = 0.667% of that sample to produce a dyeing with the same reflectance as obtained from the standard. Its percentage strength is 66.7%.

4.5 It is important to use one strength expression within a company to avoid confusion and errors.

5 Relative Strength and Shade from Dyeings

5.1 For the highest assurance of dye batch conformity to a standard, it is necessary to prepare dyeings. Dyeings are usually prepared on a standard substrate under standard dyeing conditions. These conditions include the ratio of dye liquor to fabric, dyebath pH, addition of chemicals, temperature and time profile of dye cycle, post-scouring process, drying, finishing (if any), and equilibration for measurement. To avoid errors in preparing dyebaths and to obtain repeatable results, automated *dye stock solution* dispensing and automated laboratory dyeing equipment is often used.

5.2 Repeatability of the dyeing process depends to some degree on the dye class and fiber combination. Past studies have indicated that the repeatability depends on the complexity of the dyeing process; the simpler the process, the higher the repeatability. The highest repeatability was obtained with acid, basic, and disperse dyes on the corresponding fibers. At an intermediate level are direct and reactive dyes on cotton, with sulfur and vat dyes having the lowest repeatability.

5.3 The measured reflectance of dyeings can vary depending on the temperature and relative humidity of the dyed material sample. Dyeings should be equilibrated to a given temperature and relative humidity before measurement to avoid differences due to temperature and humidity alone. Laboratory equipment to achieve this is being marketed today.

5.4 Because of the possibility of errors in single dyeings, assessments of strength and shade by dyeing are often made by making triple dyeings of standard and sample. In this procedure, both standard and sample are dyed, say, at 0.95%, 1.00%, and 1.05% on weight of goods. Such dyeings can be used to assess both strength and shade visually and instrumentally, making possible multiple comparisons from which a statistically more secure average can be calculated.

5.5 In visual assessments, the relative strength is determined by comparing the known strength differences within the three standard and three batch dyeings to the unknown difference between standard and batch and estimating an average relative strength value in parts or percent.

5.6 Instrumental assessment of strength is based on reflectance measurements of the dyeings. To obtain accurate and repeatable results, it is important, as mentioned previously, to have opaque samples and to make repeat measurements of the samples at different angles, averaging the results (see Chapter 3).

5.7 The wavelength at which standard and sample are compared and the reflectance values at that point can have an effect on the results. The wavelength at which the result is calculated is usually the lowest point in the absorption trough of the reflectance curve (see 1.3 above, Figs. 10.1 and 10.2). In the curves of Fig. 10.1, the wavelength that would be selected for strength calculation is 490 nm. Both figures also illustrate why the reflectance values at the wavelength of calculation is important. The reason is what is termed *surface reflectance*, mentioned earlier in Chapter 4. The reflectance at the lowest point of the curve trough does not fall below a minimal value. This value represents the surface reflectance. It is the portion of reflectance due to the surface glossiness of the fiber material, not affected by dye in the fiber. It usually has a value of 1%-2%. In Fig. 10.1, the surface reflectance (1.7%) has been reached at the highest dye concentration. The closer the reflectance value at which the strength relationship is calculated is to the surface reflectance value, the more it is affected by it. For this reason, strength determinations are made at a dye concentration where the minimum reflectance value is well above the surface reflectance value, typically around 10% reflectance. Another method (if the surface reflectance value of the textile material involved is known) is to subtract the surface reflectance value from both measured reflectance values of standard and batch and calculate the strength relationship from the adjusted values.

5.8 The wavelength selected for calculation of relative strength is always identical for the standard and batch.

5.9 Strength assessment is less certain if there is a color difference between the standard and sample. Color differences can affect the reliability of strength calculations at the wavelength of lowest reflectance. Other assessment methods are sometimes used, however, there is no clear agreement on when to use each method. This subject is too complex for a full discussion here; information on this subject has been published in the second edition of AATCC's *Color Technology in the Textile Industry*, and the interested reader is encouraged to consult it. The method used in calculating strength from reflectance data should be reported, together with the result, and when setting up procedures in a supply chain it is important to agree on a method.

5.10 The reflectance values at the wavelength selected for strength determination are converted to *K/S* values (see Chapter 4). *K/S* values are directly proportional to relative strength, at least at lower dye concentrations.

6 Interrelation of Strength and Color Difference

6.1 Differences in strength between two dyeings automatically result in a perceived and calculated color difference because their reflectance curves and their CIE tristimulus values differ.

6.2 To visually distinguish between color differences caused by strength differences and other causes is difficult.

6.3 The question arises how to assess the so-called *residual color difference*, the color difference that remains if the standard and batch dyeings have equal strength.

6.4 For visual assessment of the residual color difference, having three dyeings each of the standard and of the batch (as discussed in section 5.4 above) provides an improved opportunity to make a reasonably accurate assessment.

6.5 Instrumental assessment requires special software that adjusts the reflectance curve of the batch dyeing, using the Kubelka-Munk relationship (see Chapter 4). The *K/S* curves of the batch dyeing are adjusted with a factor so that at the chosen wavelength, the standard and batch have the same value (and implicitly, the same strength). The adjusted *K/S* values of the batch dyeing are converted back to reflectance. The residual color difference between the original standard reflectance curve and the adjusted batch reflectance curve is then calculated as a measure of the perceived residual difference.

6.6 The color difference values between standard and batch reported on quality assurance reports from dye suppliers are usually residual color difference values. It is important to ascertain that this is so.

7 Summary

Absolute strength of colorants is a function of their chemical nature and other factors, such as, in the case of pigments, particle size. Relative strength assesses the concentration of active colorant in the product, relative to that in the designated standard product. Relative strength assessment in the case of certain dye classes can be made by measurement of transmittance of solutions. Assessment of relative strength and color (shade) of colorants for textiles is made by making dyeings under standard conditions. The assessment can be made visually or instrumentally. Assessment of the shade of batches is usually done as residual color difference; for good accuracy it requires reflectance measurements.

Strength and residual color difference assessment is a relatively complex matter and valid procedures have been worked out by colorant manufacturers. Many colorant manufacturers provide reliable information about the quality of their products in regard to strength and shade (and other properties) in the form of quality assurance reports. It is important to understand the information on such reports, how it has been arrived at, and how the procedures used by different suppliers compare.

Chapter 11 COLOR CONSTANCY AND METAMERISM

1 Constancy and Metamerism

1.1 Both terms refer to important perceptual properties of objects and, in the case of metamerism, also lights.

1.2 Color constancy refers to a perceptual property of a single object.

1.3 Metamerism refers to a property of two or more lights or objects. Metamerism has been previously discussed in Chapters 5 and 6 but will be more fully discussed here again.

2 Color Constancy

2.1 Color constancy refers to the fact that some objects approximately maintain their color appearance in a wide range of lights, while others change in appearance depending on the light in which they are viewed, sometimes drastically.

2.2 Usually, the basis for judging color constancy is the appearance in standard daylight, for example CIE daylight D_{65}.

2.3 To see objects in approximately constant color regardless of the light in which they are viewed is a genetic adaptation that proved useful for our early ancestors. Today, it has less survival value than aesthetic value. If a customer buys a bathrobe that looks blue in the fluorescent light of the store, she may not appreciate it looking brownish purple in the tungsten light of her bathroom at home.

2.4 As discussed in Chapter 1, our brain interprets the color of an object from the spectral power distribution of the light reflected from it. This reflected spectral power distribution depends on the spectral power distribution of the light itself. Natural and artificial lights can vary very widely in their spectral power distribution. Colorless lights, lights that, when reflected from a white surface, look "white," are generally of greatest interest for normal lighting purposes.

2.5 Many different spectral power distributions of lights may be reflected from a color-constant object with the brain interpreting them as having approximately the same color. This requires a complex mechanism of interpreting the lights. The nature of this mechanism is not fully known at this time.

2.6 If a *color-inconstant* object is viewed in the same lights, the brain applies different colors to the object.

2.7 A component of the process of color constancy is an activity of the visual system called adaptation. Our visual mechanism has the ability to adapt (within limits) to spectral power distributions of lights. Complete adaptation to a light source takes a certain amount of time, up to half a minute. If we are adapted to the light of an overcast sky and we see tungsten light coming out of the windows of houses, the light appears to us distinctly yellowish to orange in color (see Fig. 11.1). If we happen to be inside the house and we are adapted to tungsten light, it appears to us to be essentially "white" in color. Such adaptation has limits and more strongly-colored theatrical lights are seen as colored regardless of our exposure time. We also do not get fully adapted to the reddish light of a sunset.

Fig. 11.1. A cabin viewed in the subdued light of an overcast sky toward evening. The tungsten lamplight inside appears distinctly yellowish-orange.

2.8 There is also an aspect of object reflectance curves that results in greater or lesser color constancy. This aspect is still somewhat mysterious but, in general, natural products tend to have the property of color constancy (at least in natural lights), while many artificial objects are color-inconstant. The adaptive effect of color constancy probably developed a few million years ago, under natural conditions. We have less than a 200-year history of many artificial colorants and artificial light sources, and there have been no strong reasons for humans to see most artificial objects as color-constant.

2.9 To become aware of color inconstancy requires one or more of the following:

- strongly color-inconstant objects
- lights with spectral power distributions that tend to accentuate color inconstancy
- a special set up in which we can view objects in two or more different lights nearly simultaneously (a light box where we can rapidly switch from one light to another).

However, in the third case we are most likely not fully adapted to the light sources and so do not obtain a true picture of the degree of inconstancy. Our color memory is relatively poor and we recall the color of an object seen in the past in a given light only vaguely. This helps the impression of color constancy, unless the object is quite strongly inconstant.

2.10 Artificial light sources vary in their tendency to result in color inconstancy. This subject will be discussed in more detail in Chapter 12.

2.11 Figs. 11.2 and 11.3 show the reflectance curves of objects with good and poor color constancy in artificial standard daylight (D_{65}) and tungsten lamp light (illuminant A), and Fig. 11.4 shows simulations of the appearance in the two lights.

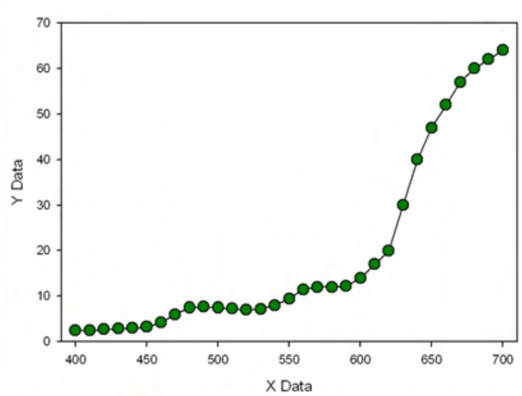


Fig. 11.2. Reflectance curve of an object with good color constancy in daylight and tungsten light.

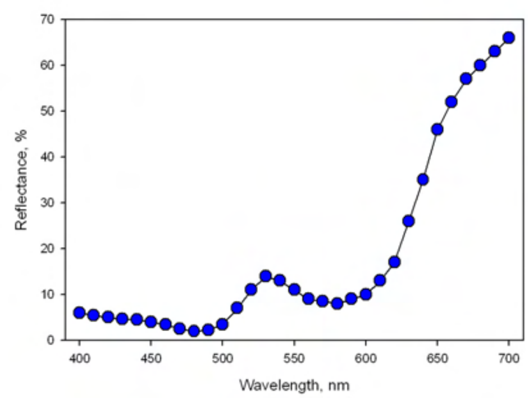


Fig. 11.3. Reflectance curve of on object with poor color constancy in daylight and tungsten light.

Fig. 11.4. Simulations of the appearance of the objects of Figs. 11.1 and 11.2 in artificial D_{65} daylight and in tungsten light (A).

2.12 Color constancy is an issue of consumer satisfaction in the case of textiles and some other products, as indicated in section 2.3 above. A high degree of inconstancy is undesirable to avoid customer dissatisfaction and returns.

2.13 Color constancy as a product quality issue can now be addressed because there are software tools to assess a dye formula for its level of color inconstancy. Several color inconstancy formulas have been proposed in recent years and standards organizations, such as the International Standards Organization (ISO), are in the process of making recommendations. Suppliers of formulation software offer packages that include inconstancy formulas.

2.14 It is important to understand that formulations can rarely be constant for several lights at the same time. Usually, it is necessary to restrict the number of lights for which good results are expected.

The degree of inconstancy depends on the dyes used to match the color and the specific reflectance curve that results from a combination of dyes. Dyes are not color-constant or color-inconstant; it is the final reflectance curve from a combination of dyes that has these properties.

2.15 Color constancy is an additional constraint on formulation, limiting the number of dyes that can be used and sometimes requiring compromises in fastness properties or cost of formulation to achieve it.

2.16 As briefly discussed in Chapter 9, it is important to decide who in a supply chain has responsibility for color-constant dye formulations. Only that formulation, in the form of a dyeing or a reflectance curve, can be used as the primary standard that must be matched non-metamerically.

3 Metamerism

3.1 Metamerism is an important fact of color vision, as discussed in Chapters 1, 6, and 8. Metamerism is the term for the fact that different spectral power distributions (SPDs) can produce the same result when they are sensed by a limited number of sensor types, such as the three human cone types. The different SPDs can represent lights themselves or lights as reflected from objects.

3.2 To demonstrate this fact, we use as an example a single sensor with a symmetrical sensitivity that peaks at 550 nm; somewhat like the M cone sensor (see Fig. 11.5). In Fig. 11.6, there are seven very different hypothetical reflectance curves of objects. Table 11.1, demonstrates that these different objects all produce an identical stimulus value (only one because there is only one sensor) when "seen" by this sensor in equal energy light. Therefore, the sensor cannot distinguish between these different objects. There are an endless number of other reflectance curves that produce the same result in this sensor. This is the central fact of metamerism.

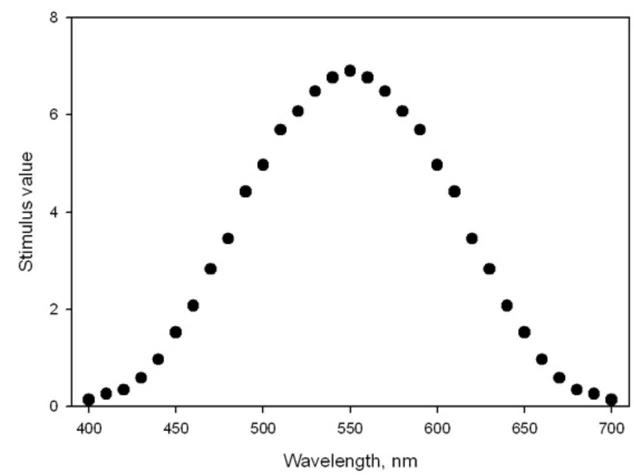


Fig.11.5. Spectral curve of a single sensor with symmetrical sensitivity.

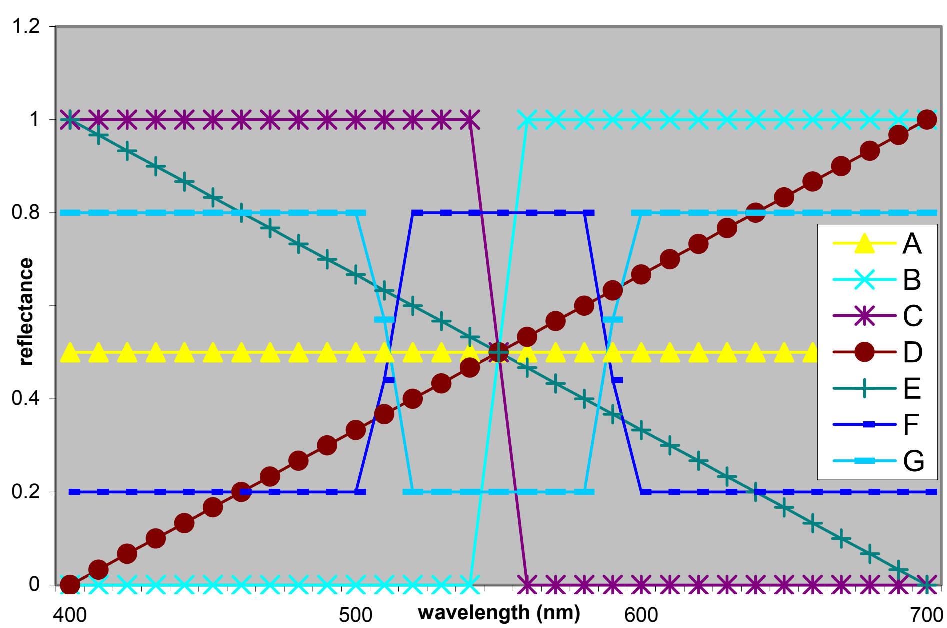


Fig. 11.6. Reflectance curves of seven hypothetical objects that when "viewed" in equal energy light by the sensor of Fig. 11.5 produce the same stimulus value (see Table 11.1).

TABLE 11.1

Sensor and Reflectance Data Producing Identical Stimulus Values

Wavelength (nm)	Sensor[a]	A[b]	B[b]	C[b]	D[b]	E[b]	F[b]	G[b]
400	0.14	0.5	0	1	0.000	1.000	0.2	0.8
410	0.26	0.5	0	1	0.033	0.967	0.2	0.8
420	0.34	0.5	0	1	0.067	0.933	0.2	0.8
430	0.59	0.5	0	1	0.100	0.900	0.2	0.8
440	0.97	0.5	0	1	0.133	0.867	0.2	0.8
450	1.52	0.5	0	1	0.167	0.833	0.2	0.8
460	2.07	0.5	0	1	0.200	0.800	0.2	0.8
470	2.83	0.5	0	1	0.233	0.767	0.2	0.8
480	3.45	0.5	0	1	0.267	0.733	0.2	0.8
490	4.42	0.5	0	1	0.300	0.700	0.2	0.8
500	4.97	0.5	0	1	0.333	0.667	0.2	0.8
510	5.69	0.5	0	1	0.367	0.633	0.44	0.57
520	6.07	0.5	0	1	0.400	0.600	0.8	0.2
530	6.49	0.5	0	1	0.433	0.567	0.8	0.2
540	6.76	0.5	0	1	0.467	0.533	0.8	0.2
550	6.90	0.5	0.5	0.5	0.500	0.500	0.8	0.2
560	6.76	0.5	1	0	0.533	0.467	0.8	0.2
570	6.49	0.5	1	0	0.567	0.433	0.8	0.2
580	6.07	0.5	1	0	0.600	0.400	0.8	0.2
590	5.69	0.5	1	0	0.633	0.367	0.44	0.57
600	4.97	0.5	1	0	0.667	0.333	0.2	0.8
610	4.42	0.5	1	0	0.700	0.300	0.2	0.8
620	3.45	0.5	1	0	0.733	0.267	0.2	0.8
630	2.83	0.5	1	0	0.767	0.233	0.2	0.8
640	2.07	0.5	1	0	0.800	0.200	0.2	0.8
650	1.52	0.5	1	0	0.833	0.167	0.2	0.8
660	0.97	0.5	1	0	0.867	0.133	0.2	0.8
670	0.59	0.5	1	0	0.900	0.100	0.2	0.8
680	0.34	0.5	1	0	0.933	0.067	0.2	0.8
690	0.26	0.5	1	0	0.967	0.033	0.2	0.8
700	0.14	0.5	1	0	1.000	0.000	0.2	0.8
Stimulus Value		*50.0*	*50.0*	*50.0*	*50.0*	*50.0*	*50.0*	*50.0*

[a]See Fig. 11.5
[b]See Fig. 11.6

3.3 The situation is somewhat more complex if there are three sensors—a tristimulus system—as we have in our vision system. The basic fact is the same: There are an endless number of reflectance curves and resulting spectral power distributions that produce identical results in three sensors.

3.4 In the case of object colors, there are three factors responsible for this result:

a) the sensor functions (the observer),
b) the spectral power distribution of the light source (the illuminant), and
c) the reflectance curve of the object.

In order to have control of the situation, all three aspects need to be controlled.

3.5 The sensor functions of an individual observer can be measured, for example, in the form of color matching functions (CMFs). It is known that these vary quite markedly among observers, all having normal color vision. As a result, what is a match for one observer is not a match for a different observer with different CMFs. The CIE has defined two standard observers (see Chapter 6), the 2º standard observer and the 10º standard observer, to represent average human observers for two different sample sizes in the field of view. Two different SPDs that produce identical tristimulus values for the 2º standard observer do not do so for the 10º standard observer, and vice versa. The same applies to two different individuals that have different CMFs. For this reason it is not surprising that people differ in their judgment about how good a match is. There is no objective basis for declaring that one observer is right and the other wrong.

3.6 The SPDs of lights can be measured accurately with a spectroradiometer. Practically, SPDs of specific lamp types can differ considerably from the “normal” SPD of this type, primarily as a function of manufacturer, age, and use. For this reason, lamps in light boxes should be replaced according to a schedule recommended by the manufacturer, or periodically checked with a spectroradiometer to determine if replacement is necessary.

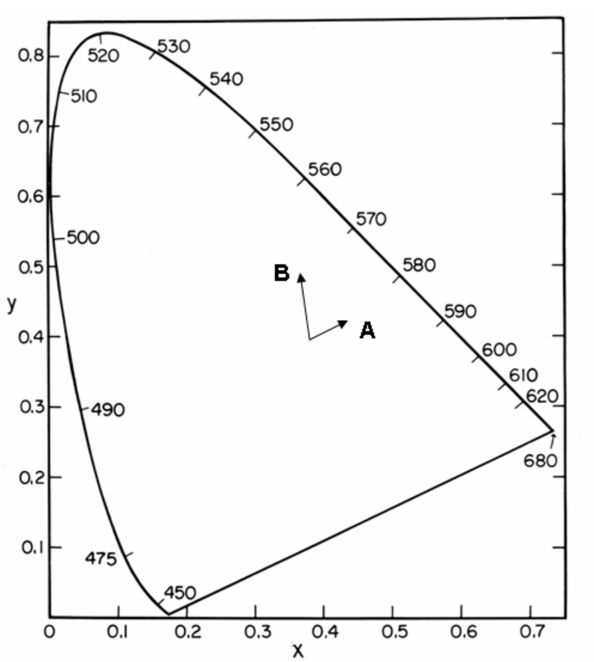


Fig. 11.7. The location of a metameric pair in the CIE chromaticity diagram is identical in the reference light (say, daylight D_{65}), but is distinctly different when calculated for tungsten light.

3.7 In the case of object colors, the SPD arriving at the eye is the product of the SPD of the light and the reflectance curve of the object. The spectral reflectance of the samples can also be measured with good accuracy with a spectrophotometer (the issues behind good measurements of textile samples, discussed Chapter 4, should be kept in mind).

3.8 Two samples with different reflectance curves that produce, for a standard observer, identical tristimulus values for illuminant D_{65}, for example, and thereby are a perfect match for the standard observer, may be a distinct mismatch under a different light (say, illuminant A). This is easily shown by plotting the chromaticity of the samples in the CIE chromaticity diagram, as shown in Fig. 11.7.

3.9 Samples that match, but have different reflectance curves are most commonly the result of different dyes having been used in their production. This also occurs if samples dyed on, say, polyester, are matched on cotton or wool.

3.10 In terms of color constancy of the samples (discussed in section 2, above), the situation discussed in 3.8 means that the two samples have different degrees of color constancy.

One sample may be color-constant and the other inconstant, or both samples may be inconstant, but in different ways. The reflectance functions of Figs. 11.2 and 11.3 are actually a metameric pair and are an example of this situation.

3.11 It is possible for samples with different reflectance curves to match in two lights, but not match in a third. The greater the number of lights in which the samples match, the closer the reflectance curves of the samples are. To match in all lights, the reflectance curves have to be identical. If dyes different from those used in the reference sample need to be used, a good match in three or more lights may be impossible. In practice, this often requires compromises.

3.12 Conventionally, metamerism due to a change in illuminant is, for two reflectance curves, assessed by calculating the color differences (see Chapter 13) between them for the different light sources involved, a procedure known as the CIE Special Index of Metamerism, Change in Illuminant. It applies where the color difference under the reference illuminant (say, D_{65}) is zero, as it should be. In practice, it is often not exactly zero. As a result, it is not known how much of the calculated difference for the other illuminants is due to metamerism. Some authors have used the term *parameric* (paramers, paramerism) to denote sample pairs that are not perfect matches in the reference light. To obtain measures for metamerism in this case, a correction is made for the difference between the samples in the reference illuminant, converting the pair from paramers to metamers (somewhat similar to the issue of residual color difference discussed in Chapter 10).

3.13 For the case of different observers, the CIE developed the CIE Special Index of Metamerism, Change in Observer. It is only rarely used. The results for the 2º observer and the 10º observer are compared, or data for the so-called *standard deviate observer* can be used. The standard deviate observer has been calculated statistically from the data of individual observers from which the standard observer data have been calculated and represents an average observer deviating from the standard observer.

3.14 Conventional matching software prints out color differences between a standard and the calculated match under the reference illuminant, as well as under the additional illuminants of interest. However, this approach does not consider the issue of adaptation. As a result of adaptation to a particular light (see Chapter 5), the perceived difference between reference and sample may be smaller or larger than indicated by the conventional color difference. A more correct and complex adaptation correction calculation for each illuminant can be made before the calculation of the color differences, in addition to parameric correction.

3.15 It is evident from the preceding discussion that metamerism is a considerable problem for industrial colorists. Calculations, as discussed in 3.12 through 3.14, provide help for selecting the optimal dye combination to minimize metamerism from a basket of dyes.

3.16 As mentioned in Chapter 9, the problems of metamerism discussed above, are in a general sense compensated for by the advantages it provides for color reproduction. It is the fact of metamerism that is the basis for many reproduction technologies, such as three- or four-color halftone printing, color photography, television, and others.

4 Summary

Color constancy is the human ability to experience certain objects as having the same or similar color appearance in lights of different spectral power distributions. It is the result of complex ”calculations” in the brain of the observer. In today’s industrial society, with a multitude of artificial colorants and artificial light sources with substantially different spectral power distributions, manufactured products are often color-inconstant, that is, they change appearance (sometimes drastically) when viewed in different lights. Interest in color-constant materials developed in recent years for aesthetic reasons and reasons of customer satisfaction. There is now software available to calculate the degree of color inconstancy of a reflectance curve.

Metamerism is a natural result of the reduction of the complexity of information in spectral power distributions to three values, the three tristimulus values, representative of the three types of cones in our color vision system. Practically, it means that given colors of objects can be matched (more or less closely) in a reference light with many different dye combinations. However, the matches may not hold in different lights or for different observers. Matches valid in multiple lights and acceptable to different observers are of interest, again, for aesthetic reasons and reasons of customer satisfaction.

The natural fact of metamerism has made several color reproduction technologies involving three primary colors possible.

Chapter 12 ARTIFICIAL LIGHTS AND COLOR RENDERING

1 Color Rendering

1.1 The appearance of colored objects depends to some degree on the quality and quantity of the light in which they are viewed. Color constancy (Chapter 11) looked at this problem from the point of view of the materials; *color rendering* looks at it from the point of view of the light source.

1.2 Unfortunately, the two viewpoints of this issue have diverged, the former being mainly in the hands of color scientists, the latter in those of lighting engineers. This has resulted in different test procedures and different methods of assessment.

1.3 The CIE defined color rendering as follows: “Effect of an illuminant on the color appearance of objects by conscious or subconscious comparison with their color appearance under a reference illuminant.”

1.4 As discussed in Chapter 11, color appearance is dependent upon the light because of an imperfect ability of the visual system to register objects as having the same color regardless of the light in which they are viewed.

1.5 As mentioned there, reasonable color constancy can only be expected if the light sources involved are “white” or “near-white” in appearance. Because of metamerism and the general adaptation effect, lights with many different kinds of spectral power distributions (SPD) are experienced as “white.” Several of these were introduced in Chapter 1 and are briefly reviewed here.

2 Natural and Artificial Light Sources

2.1 The most important natural light source is the sun. By the time sunlight arrives on the surface of the earth, it can have many different SPDs. They differ as a result of scattering and absorption due to weather conditions.

2.2 Daylight is the result of a process called incandescence, defined as the release of electromagnetic radiation from a hot body. The SPD of incandescent light (and its appearance) depends on the temperature of the body giving it off. The quality of incandescent light is defined by the temperature in degrees Kelvin of the body releasing it, the *color temperature*. The relationship between temperature and SPD, as well as apparent color, is based on a theoretical material called blackbody (mentioned in Chapter 1). Real solids differ somewhat from the blackbody and the apparent color of light they release is expressed as their correlated color temperature.

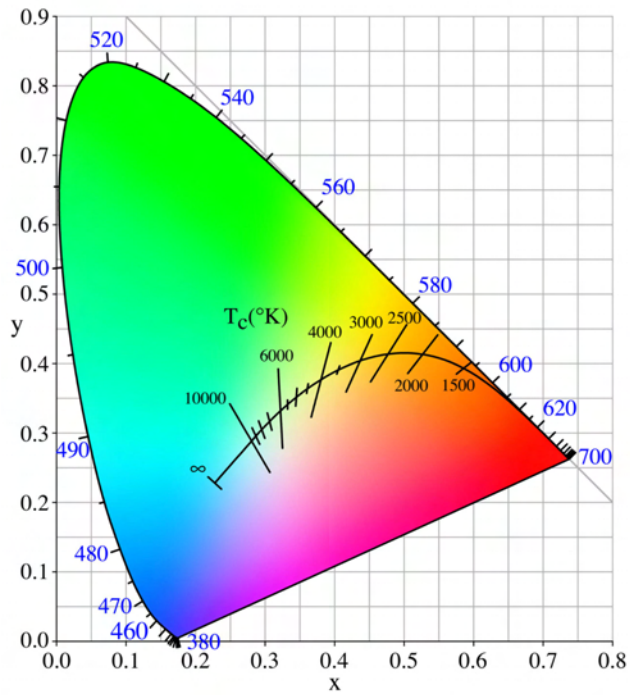


Fig. 12.1. The CIE chromaticity diagram with the arc of blackbody radiation chromaticities at different temperatures, beginning in the red at low temperatures and ending in desaturated blue at infinite temperature. Tungsten light at approximately 2,800K is in the yellow-orange region. Daylight D6500 falls near the white point of the diagram. The slanted lines indicate the range of chromaticities for lamps with a correlated color temperature equal to blackbody light where they intersect the curve.

2.3 The points of blackbodies at different temperatures in the CIE chromaticity diagram form an arc (Fig. 12.1).

At the lower temperatures, the bodies appear red in color. As the temperature increases, the color turns orange, yellow, then white, and at the highest temperatures bluish-white. Keep in mind that that these appearances apply for an observer adapted to average daylight. With changes in temperature go changes in the SPD of the light energy. A few examples are shown in Fig. 12.2. This figure shows that commonly-used incandescent light of low color temperature is not energy-efficient in terms of its visible portion (400–700 nm) because much of the energy given off by the blackbody is in the infrared wavelength range, outside the visible range.

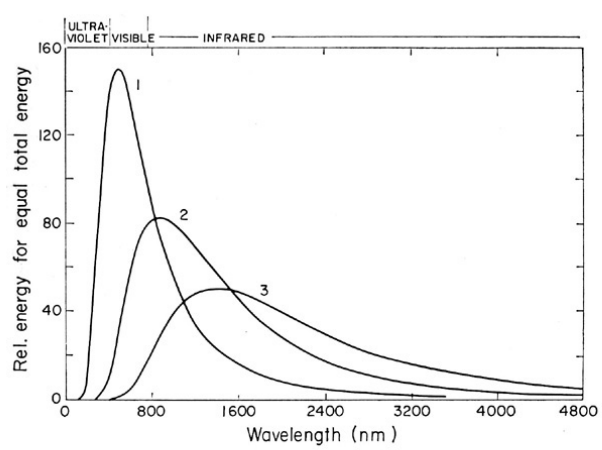


Fig. 12.2a. SPD curves of blackbody lights at three different correlated color temperatures (1 = 6,000K, 2 = 3,220K, 3 = 2920K) from 0 to 4,800 nm. It is evident that most of the energy of distributions 2 and 3 is outside the visible range (400–700 nm). *Courtesy of John Wiley & Sons Inc. (Grum, F. R., Physical Methods of Chemistry, Vol. I, Part 3B, 1972). Used with permission.*

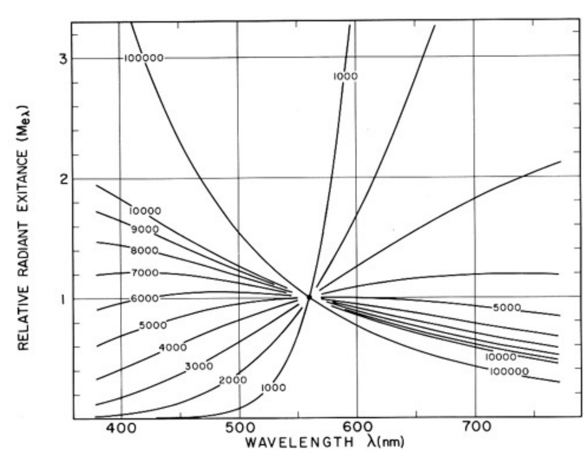


Fig. 12.2b. SPD curves in the visible range for a blackbody at different temperatures. *Courtesy of John Wiley & Sons Inc. (Wyszecki, G. and W. S. Stiles, Color Science, 1982). Used with permission.*

2.4 In the last half century, the search has intensified for light sources with SPDs with all or most of their energy output in the visible range, however, some of the most efficient of these light sources result in poor color-rendering. The continuing goal is to find energy-efficient light sources with good color-rendering properties.

2.5 It may be helpful to review the list of light sources and important examples in Table 12.1 before pursuing this matter further.

TABLE 12.1.

Light Sources

Type	**Examples**
Combustion	candle, oil lamp
Incandescent	tungsten light bulb
Tuned energy conversion	fluorescent lamps
Electroluminescence	LEDs (light emitting diodes)
High intensity discharge	metal halide, sodium or mercury vapor, xenon arc

2.6 Quality indicators of artificial light sources are:

- Energy efficiency (lumens per watt)
- Lamp life
- Color rendering index (CRI)

2.7 Energy efficiency is the amount of light, measured in lumens produced per watt consumed. The definition of lumen is complex and its details exceed the scope of this text (see also section 2 in Chapter 4). A watt is a measure of energy (usually electric). It is important to understand that a higher lumens-per-watt value indicates a more energy-efficient lamp. Typical lamps range from about 10 to about 180 lumens per watt.

2.8 The life of a lamp is measured in operating hours. A higher number represents a longer life.

3 The CIE Color Rendering Index

3.1 The color rendering index (CRI) is based on a colorimetric comparison of the perceived color of selected objects in a test light compared to that in a reference light. The definition of the reference light takes the correlated color temperature (CCT) of the test light into consideration. The reference light for test lights with a CCT of below 5000 Kelvin is a blackbody at the corresponding color temperature. (e.g., The reference light for a tungsten lamp is the blackbody at the same color temperature.) If the CCT is above 5000K, the reference light is a daylight phase with the same color temperature as that of the test light, for example, daylight D_{55} or D_{65}.

3.2 This definition means that daylight D_{65} and tungsten light A (at 2856K) have the same perfect CRI of 100. In Chapter 11, we saw that there are objects that dramatically change in appearance when switching the light source from daylight to tungsten light. As a result, CRI is not a predictor of color inconstancy.

3.3 The CRI continues to be an important quality indicator for lamp manufacturers and for consumers selecting lamps. It is important to keep the discrepancy between color constancy (from the point of view of the object) and color rendering (from the point of view of lamps) in mind when making decisions about lamps. Using lamps with a high CRI does not ensure color constancy. It only indicates that the appearance of objects will be similar in daylight or light of an incandescent lamp of the same CCT.

3.4 The calculation of the CRI is complex and only a brief overview is provided here.

The general CRI is the average of a special kind of calculated color differences, calculated for eight samples defined by the CIE. First, the tristimulus values of the samples are calculated for the reference illuminant and for the test illuminant.

These values are converted to values on the CIE *u, v* chromaticity diagram, a modified version of the *x, y* chromaticity diagram, to make geometric distances in better agreement with perceived differences. To correct for the change in adaptation from the reference light to the test light, these values are converted to *u*', *v*' coordinates. The luminous reflectance values *Y* for the two illuminants must be normalized.

The total color difference is then calculated for each sample between the respective *u*', *v*' coordinates and normalized luminous reflectance values in the reference and test illuminants.

For a given sample *I*, the Special Color Rendering Index is R_i = 100 - 4.6 DE_i (4.6 times the color difference value for the sample between the data for the two illuminants is subtracted from 100 to result in the CRI for the test illuminant and sample involved). The General CRI is the average of the CRIs for the eight samples defined by the CIE. The higher the value, the better the color rendering of the test lamp relative to that of the reference lamp. CRIs range typically between 0 and 100, but negative numbers are possible.

3.4 Table 12.2 lists energy efficiency and CRI data for a series of lamps.
It is important to understand that with the latest technologies it is often possible (at a cost) to fine-tune lamps of a certain kind to produce CRIs in a considerable range. This applies in particular to fluorescent lamps where the choice and amounts of phosphor compounds can be adjusted to change not only the CCT, but also the CRI.

TABLE 12.2.

Energy Efficiency and Color Rendering Indices (CRI) of Different Lamp Types

Lamp Type	Lumens per Watt	CRI
Incandescent	7–25	99
Mercury vapor	30–63	20–50
Fluorescent tubes	30–100	
Cool white	30	62
Triband	100	≥ 90
Metal halide	75–125	65
High pressure sodium	65–140	22
Low pressure sodium	100–183	≤ 10
Light emitting diodes (LED)	30–50	70

The most energy-efficient lamp is the low-pressure sodium lamp. The light is emitted from vaporized sodium metal in a narrow wavelength range, giving the light a yellowish appearance. Its color-rendering properties are poor. Such lights are often used on large parking lots (Fig. 12.3).

Fig. 12.3. A sodium lamp in a parking lot at night, showing the strong yellow color of the light.

Fluorescent light is produced from vaporized mercury. The mercury activates fluorescence in phosphor compounds coating the interior surface of the light tube. These compounds give off light over broad spectral bands (see also chapter 4). An advance in energy efficiency with high CRI was made with the invention of triband lamps. They give off light limited essentially to the visual range (little ultraviolet or infrared). By fine-tuning the light emission with up to six different phosphor compounds, CRI values approaching 95 can be obtained. Research in these areas will undoubtedly continue, resulting in further improvements.

An interesting demonstration of the effects of lighting on garments and other materials can be found at www.gelighting.com/na/business_lighting/education_resources/learn_about_light/color_lamp.htm. At the site, click on “Interactive Color Booth.” It is important to keep in mind that when you view the effect of a particular lamp you have not been adapted to that light: The display in incandescent light, for example, appears much more yellowish-orange than it would to an observer fully-adapted to the light.

3.6 For marketers of textile garments, it is important to consider the kind of light in which the customer is making selections. Stores are often lit with a combination of fluorescent and tungsten lights (the latter for highlights, Fig. 12.4). Changing rooms, on the other hand, are usually lit with fluorescent lamps only. It is possible for the color appearance of garments to change substantially between daylight, store light, and changing room light.

Fig. 12.4. In the store, garments are often displayed in fluorescent light with tungsten highlights.

3.7 For energy efficiency reasons, many of the modern fluorescent lamps have little or no output of near-ultraviolet energy (340 to 400 nm). This means that optically-brightened fabrics or fabrics dyed with fluorescent yellow or orange dyes look much less white or intense than they would in daylight.

4 Summary

The interaction between object and light is complex, and the resulting appearance of the object can remain relatively stable or change dramatically. Such effects can be numerically defined for materials with a color inconstancy index (see Chapter 11). Historically, the standard index for the effect of the light source on the appearance of objects has been the CRI. It rates lamps in comparison to reference lamps with blackbody radiation or defined daylight phases at the same correlated color temperature. A daylight simulator lamp and a tungsten lamp have the same, near-perfect CRI, but the appearance of a given object in the two lamps may differ greatly.

Choice of lamps for the display of textile products is usually a compromise between lighting cost and color rendering, and can have noticeable effects on customer satisfaction.

Chapter 13 QUALITY CONTROL: COLOR DIFFERENCE PERCEPTION AND CALCULATION

1 Color Difference: Top Down and Bottom Up

1.1 A color difference is the perceived difference between two color experiences. Color experiences, as mentioned in earlier chapters, are the result of color stimuli—direct lights or lights reflected from objects—processed by the visual system.

1.2 Two color experiences can be compared directly, for example in the form of side-by-side placed samples, or at different locations in the visual field; or indirectly, by comparing a color experienced earlier in time and stored in memory with one directly experienced. Both kinds are mental comparisons, but the second case involves the stored memory of one experience.

1.3 Side-by-side comparison can involve fields of color, for example textile fabric samples, directly abutting. They can also involve samples separated by strips of a differently-colored background, for example the light gray of the interior of a light box (Figs. 13.1 and 13.2).

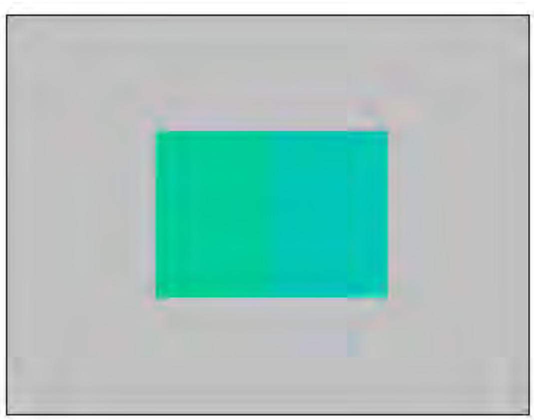


Fig. 13.1. Reference and sample adjacent in presentation.

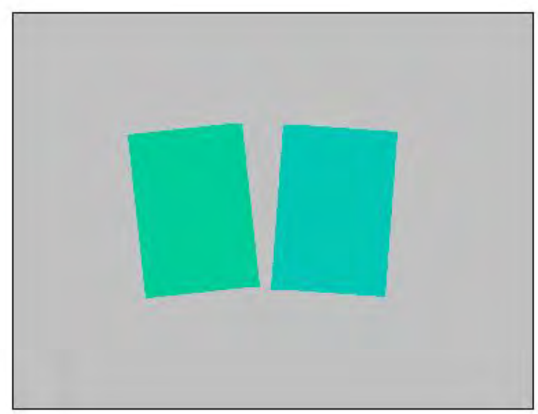


Fig. 13.2. Reference and sample separated in presentation.

1.4 Color differences are classified into three groups, based on the magnitude of the difference:

- Threshold differences (just noticable differences)
- Supra-threshold, small differences
- Large differences

Threshold difference refers, as the name indicates, to a difference caused by the minimal change in stimulus required for an individual to perceive a difference between two similar stimuli (or samples). If the stimulus difference is smaller than the threshold difference, no difference is perceived. Threshold differences are also known as just noticeable differences (JND). From this it is clear that a stimulus difference has to be of a certain magnitude before a perceptual difference is noticed.

Supra-threshold, small differences are perceived differences where the stimulus difference exceeds the threshold difference but not by large amounts. These are the kinds of differences typically encountered in color quality control.

Large differences are differences where the stimulus difference between the two samples is larger than, say, 20 JNDs. There is no official definition of large difference. Large differences can be very large, for example between black and white, or between high-chroma red and blue. Such differences are rarely of technical interest. Large differences can occur in fastness testing, and so there is a degree of interest in them in the textile industry.

1.5 As shown in Chapter 7, all color experiences can be placed systematically into a color solid, with the shape of the solid depending on the perceptual meaning of the geometrical distances between selected points in the space.

As a result, it is conceptually possible to divide the solid top-down by dividing large differences into ever-smaller ones, or build it bottom-up from JNDs. One might wonder if the two results are identical, and the answer is: no.

1.6 The reason for the difference is not clear in detail but has to do with the fact that, in our species, the brain developed several specific tools to exaggerate small stimulus differences.

The most significant of these effects, already discussed in Chapters 5 and 7, is the hue superimportance effect. It describes the fact that changes in stimuli that we perceive as a hue difference have to be only half as large as the changes in stimuli for a chroma difference. Our visual system operates according to the rule that hue differences have a higher survival value than chroma or lightness differences. This not only applies at the JND level, but for any size of difference. Any useful color difference formula needs to incorporate this fact.

2 Different Kinds of Judgments

2.1 Differences in color between a standard and a test sample can be in many different directions in color space. As already discussed in Chapter 7, differences between a standard and samples can be in terms of the attributes hue, chroma, or lightness, or combinations of two or all three. In a perceptually-uniform space, samples that all have the same difference from a standard are, by definition, located on the surface of a sphere around the central standard color.

2.2 Perceptual comparison of differences in different directions from the standard is difficult. This may be a reason that individuals differ significantly in their judgments of color differences.

2.3 In technical color difference evaluation, three techniques have typically been used as a basis for making judgments:

- Absolute judgments: no comparison tool is used and the observer judges the difference based on his or her experience. In the textile industry, such judgments are known as acceptability or pass-fail judgments. The observer makes a yes-no judgment as to whether a match is acceptable for the intended purpose of the material. In the case of matches for a particular customer, the evaluator certainly uses past experience with this customer to support the judgment, but in general, the results of pass-fail judgment experiments are reasonably similar to results from other techniques.
- Pair comparison against a reference pair: here, the differences between two pairs are compared. The reference pair is usually a pair of achromatic gray samples with a certain difference between them. If a value of 1.0 is assigned to the visual difference between the two gray samples, the observer is asked to judge the magnitude of the difference between the test pair as a fraction or a multiple of 1.
- Pair comparison with multiple reference pairs: here the judgment is aided by having a range of reference pairs, typically a gray scale such as the AATCC Gray Scale/Change of Shade. The observer, presumably, is helped in making judgments by having multiple reference pairs, but the method is not without its built-in issues.

2.4 In perceptual experiments of this kind usually there is, for a given color, a standard dyeing and several sample dyeings with colors that differ from that of the standard dyeing in various directions around it. The difficulties in making very accurate dyeings make it nearly impossible to produce test dyeings that differ from the standard in a specific, defined direction (for example, only in lightness). As a result, the test dyeings usually differ to a smaller or larger extent in all three attributes. There are two questions of interest at this point. For both situations, there are only limited detailed data available.

- When the experiment is repeated several times, how much does an observer differ from test to test for a given sample? This is *intra-observer variability* (within an observer)
- How much do different observers vary in their results? This is *inter-observer variability* (between different observers).

2.5 Intra-observer variability. In recent experiments, people without training in color difference evaluation, as well as some experts assessed the perceived difference between standard and samples two to four times on different days, in otherwise identical conditions. The results indicate wide variability in the consistency of judgments, from high to low consistency.

If there are repeated judgments by a given observer, the usual procedure is to average these.

2.6 Inter-observer variability results differ from experiment to experiment for reasons that are not known. Some of the variability may have to do with the way the test samples are distributed around a given standard. Another important reason may be that in each experiment, the group of observers usually consists of entirely different individuals. But fundamentally, for reasons not yet known, individuals differ in how they compare a chromatic difference in terms of one or more achromatic reference pairs. This is the case regardless of the consistency of judgment within an observer. Keep in mind that there is no objective way to say which observer is right in these results.

A method used to express inter-observer variability is to fit ellipsoids to the data in a colorimetric space and compare the ellipsoids in the space. The results are difficult to visualize and instead, elliptical cross-sections are often shown. As has been discussed above, if the space in which the data are presented were uniform, the contour of all samples having one perceptual unit of difference from the standard would be a sphere. In a colorimetric space, because of hue superimportance, the contour is an ellipsoid.

2.7 The method of fitting ellipsoid averages assumes that an ellipsoid is the optimal geometrical representation of unit differences around a standard.

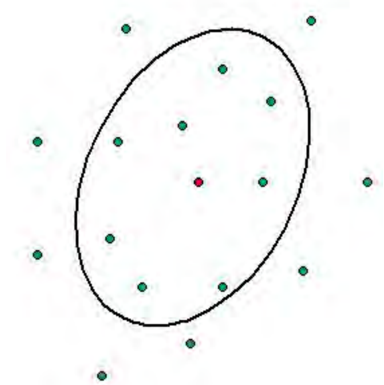


Fig. 13.3. Reference sample (red dot) and several test samples (green dots) in a chromatic diagram that were found to have, by average judgment, visual color differences from 0.75 to 1.5. The ellipse is the mathematically-derived contour that takes all the differences into account and represents, on average, 1.0 units of visual difference from the standard.

Fig.13.3 shows hypothetical results of judgments around a standard, for simplicity's sake in two dimensions. Also shown is the ellipse that averages these results. The ellipse represents the best compromise between the results for individual samples.

2.8 Inter-observer Variability Data

Fig. 13.4 shows the results for 3 of 22 observers in a well-known experiment of visual color difference assessment, the RIT-DuPont data, involving painted chips rather than textiles.

The results are shown for two kinds of ellipsoid cross-sections fitted in three-dimensional space, in this case, the space of the CIELAB color difference formula (discussed in detail below). The first is in a small portion of the *a**, *b** chromatic diagram, the second in a diagram that shows implied individual differences in assessing lightness (in the vertical direction). It is obvious that the ellipsoids of the three observers vary distinctly. Why this is so is not known, but may have to do with variations in the observers' color vision systems and/or with past visual experiences. In certain directions, there are differences in assessment up to a factor of 2 (when one observer gives the difference a value of 1, another gives it a value of 2 or 0.5). Inter-observer variability of textile sample data is no better than what is shown here for painted samples.

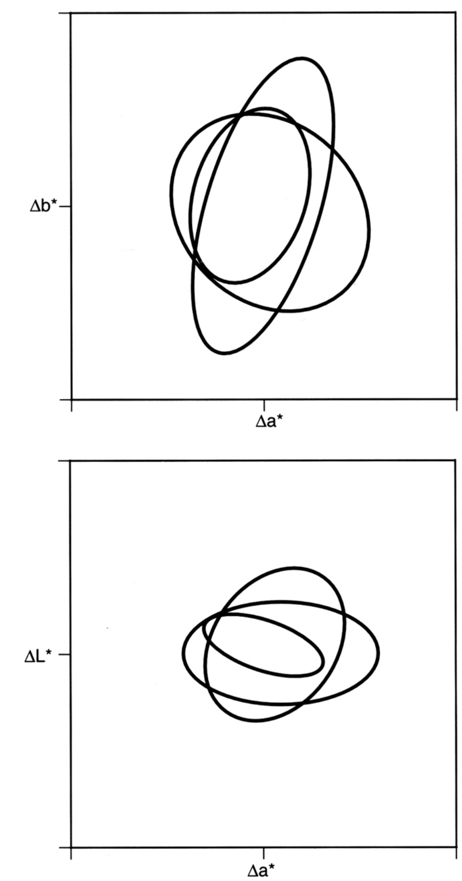


Fig. 13.4. Elliptical cross-sections of the color difference judgments of three observers in a Δ*a**, Δ*b** (chromatic difference) and a Δ*L**, Δ*a** (lightness versus *a** difference) diagram. Together, they represent the unit ellipsoid in three dimensions. No central standard was used in this experiment. *Courtesy of John Wiley & Sons Inc. (Berns, R. S., Color Research and Application, Vol. 21, 1996). Used with permission.*

2.9 The “Average” Observer

For a given set of data, results for the average observer are calculated as the average of all of the individual observers. As is evident from Fig. 13.4, such an average may be a good fit for some observers; for others it is a poor fit, depending on how close their individual results are to the average.

2.10 Are humans equipped to make reliable judgments of perceptual differences?

There are many other kinds of sensory data in which the reliability of human judgments has been evaluated: judging differences in lengths of lines, weights, sounds, temperature, and so on. At least one psychophysicist who has spent a lifetime investigating these matters has concluded that humans can only make *ordinal judgments* of color along an attribute with good accuracy. With normal color vision they can place the samples of a gray scale in proper order or the samples of a hue scale (such as in the Farnsworth-Munsell 100 hue test. When it comes to judging differences (*interval judgments*) in color, there are no objective standards, only the mean results of many observers. When comparing many different colors, these mean results represent the individual results of only a minority of a typical group of observers with reasonably good accuracy (±20%), perhaps one third.

3 Describing Perceived Color Differences

3.1 Communication of perceived color differences in a supply chain requires a standard terminology. In everyday communication, description of perceived color differences tends to be vague, with the possibility of misunderstandings resulting from it.

3.2 There is no officially-sanctioned method of verbal communication of color differences. A proposal for such a method is given in section 3.3.

3.3 A Proposal for Color Difference Terminology.

Magnitude of difference scale
The following 5-grade scale is proposed for consistent description of the magnitude of differences:

- Trace
- Slight
- Distinct
- Considerable
- Much

Hue differences
In agreement with Hering's psychological approach, hue differences should be described using only four terms, in combination with the appropriate magnitude term:

- Yellower
- Redder
- Bluer
- Greener

Lightness differences
The two terms lighter and darker are sufficient in combination with a magnitude term.

Chroma differences
This is the most problematic subject. Dyers and colorists are used to describing the non-hue aspect of chromatic color in terms of colorant strength: stronger and weaker. But the locations of dyeings that differ in strength only of a given colorant in a color solid change along paths that can be much different (Fig. 13.5). Usually, as the dye concentration increases, lightness decreases and chroma increases, but only up to a certain point. Hue also may change as concentration changes. By saying that the dyeing must be weaker or stronger, not much specific is said about how, in terms of the three standard attributes, the color must change. In addition, dyers often use the terms brighter and duller. The general meaning of these terms is: brighter means lighter and higher chroma, duller means darker and less chroma.

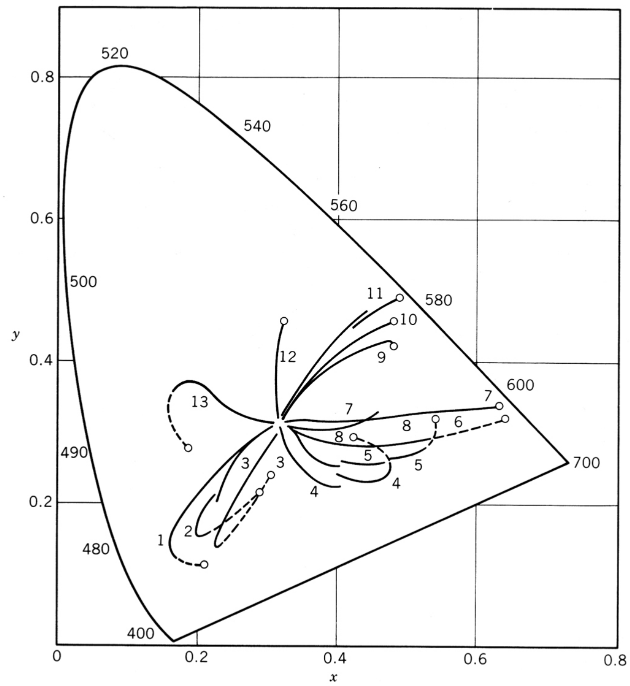


Fig. 13.5. CIE chromaticity diagram with chromatic traces of 13 different colorants. These are lines formed from calculated points for colorations at different colorant concentrations. It is obvious that different colorants behave differently in regard to hue constancy and change in saturation. *Courtesy of John Wiley & Sons Inc. (Johnston, R. M., Pigments Handbook, Vol. III, 1973). Used with permission.*

For accurate verbal communication of a required change it would be best to express the change in terms of all three standard attributes. For the chroma attribute this would mean: lower chroma, or higher chroma, together with one of the magnitude terms.

The value of consistent verbal terminology in regard to required changes in color should not be underestimated.

4 Objective Color Difference Assessment

4.1 Visual assessment of the color difference between two textile samples is subjective and can vary for a given observer between observations, and between observers.

For this reason, an objective method for assessing differences based on some kind of physical measurement is very desirable. As has been discussed in Chapter 3, measurements with (comparatively) high reliability of the spectral power distribution of lights and the reflectance functions of materials are possible today with the appropriate instruments. But SPD or reflectance data by themselves cannot tell us anything about how humans judge the differences between samples. Since the early 20th century, ways of using reliable physical measurements to predict average human difference judgments have been investigated.

4.2 Dozens of increasingly complex color difference formulas that predict average perceived color difference from reflectance measurements have been developed over the last 50 years.

Over this time period, the CIE has proposed five different formulas, the most recent one being CIEDE2000. The formulas have become more and more complex in an effort to reduce the error of prediction of the average visually judged difference from reflectance data of the samples.

4.3 The CIEDE2000 formula predicts the average judged color differences of textile sample pairs with about 65% accuracy based on several field tests of the formula.

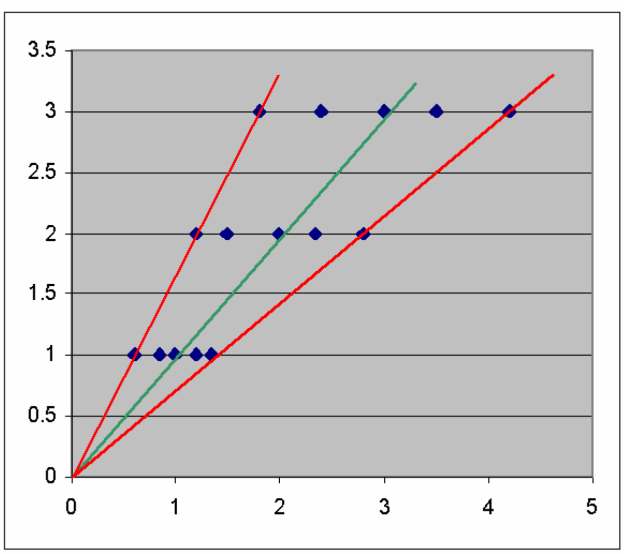


Fig. 13.6. Hypothetical representation of a relationship between calculated (horizontal scale) and visual (vertical scale) color differences that results mathematically in an accuracy of 65% for the total set.

It is important to keep in mind that this value applies to the mean observer for the various sets of visual data that have been used to fit the formula. Fig. 13.6 is a schematic example of the meaning of this value for five different samples, each with average visually judged differences of values 1, 2, or 3. The red bars in the figure show the limits (in this example) of calculated color differences for the 15 samples that result in a total accuracy of prediction of 65%. In this example, for a visually judged difference of 2 units, the calculated differences range from 1.2 to 2.8 units.

4.4 For the CMC(2:1) formula, recommended by the AATCC and other organizations, the accuracy of prediction for textile samples, as determined in field trials, is also about 65%, but the results of the two formulas differ in specific detail.

4.5 The comparable accuracy of prediction for the CIELAB formula is approximately 50%. Using the CMC(2:1) formula is a definite improvement over CIELAB but the accuracy of the results remains modest and is only valid for the average observer. The main reasons behind the limited accuracy of the formulas are the large inter-observer variability in the visual data and the fact that there are usually different experimental conditions behind various data sets used to optimally fit a formula.

5 CIELAB Color Space and Color Difference Formulas

5.1 The CIELAB formula was introduced by the CIE in 1976 (together with the CIELUV formula) because a formula on which it is based had been shown in previous years to be among the best available for predicting average perceived color differences of material samples such as painted chips or textile materials.

5.2 CIELAB uses a *cube root compression* of the CIE tristimulus space (see Chapter 6). When a mathematical formula was fitted in the 1940s to the relationship between the Munsell Renotation lightness scale values and the luminous reflectance value Y of the samples, it was found that the relationship is expressed with good accuracy by a cube root formula. It is important here to point out, as mentioned in Chapter 7, that the Munsell Renotation lightness scale itself is the average of three sets of average data obtained for three conditions of surround (white, black, and mid-gray). It has been assumed, without experimental confirmation, that the same cube root compression also applies to the X and Z tristimulus values.

5.3 CIELAB *metric lightness* L^* is defined as:
$L^* = 116 \times (Y/Y_n)1/3 - 16$.

The luminous reflectance value of the sample, for example the value $Y = 50$, is divided by the luminance value of the light in which the sample has been viewed, say daylight D_{65}, shown as Y_n in the formula. In practice, the luminance value of illuminants most always has a value of 100, thus the result in our example is 50/100 = 0.5. The cube root value of 0.5 is 0.7937. The L^* value for $Y = 50$ is then (116 × 0.7937) – 16 = 76.03. The term “metric” is used here and below to distinguish calculated data from perceived data.

Fig. 13.7 shows the relationship between *Y* and *L** over the range of *Y*.

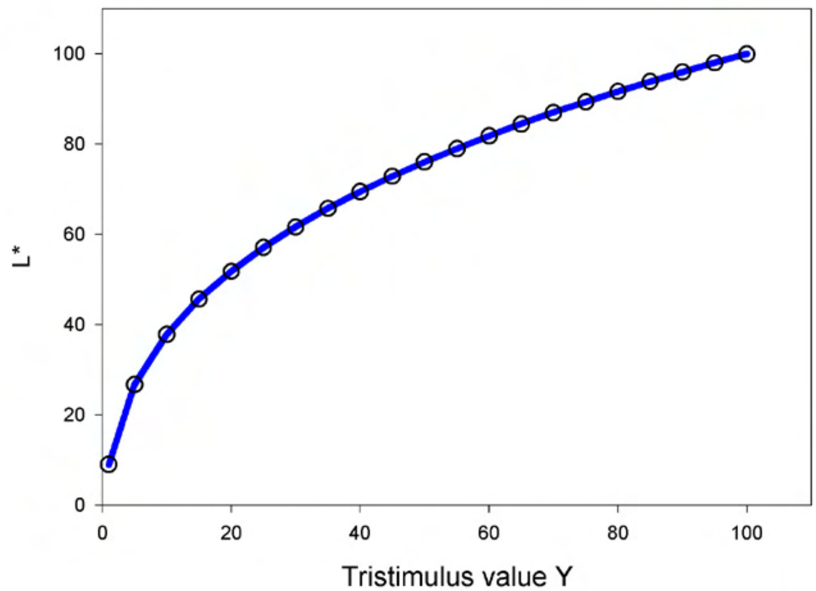


Fig. 13.7. Relationship between CIE tristimulus value *Y* and calculated metric lightness value *L**.

In CIELAB, the chromatic information is expressed with the values *a** and *b**. They are calculated as follows:

$a^* = 500 \times [(X/X_n)\ 1/3 - (Y/Y_n)\ 1/3\ ]$

$b^* = 200 \times [(Y/Y_n)\ 1/3 - (Z/Z_n)\ 1/3\ ]$

The value of Y_n, as mentioned, is almost always 100, but the corresponding values X_n and Z_n differ for each illuminant. For example, for the 10° standard observer and daylight D_{65} the values are $X_n = 94.8$ and $Z_n = 107.4$. These values assure that the neutral or achromatic point always falls at the center of the diagram, regardless of the illuminant data used. The CIELAB *a**, *b** chromatic diagram differs from the CIE *x, y* chromaticity diagram in this respect. It is a simple method to account, to a degree, for the adaptation effect.

The *a** scale results from subtraction of the adjusted cube root value of *Y* from that of *X* and forms what can loosely be described as a redness (positive *a** values) – greenness (negative *a** values) scale. The *b** scale results from comparable subtraction of *Z* from *Y* and can be described as yellowness (positive *b** values) – blueness (negative *b** values) scale. The two scales have different weights to normalize them: 500 for *a** and 200 for *b**. Note that for very small values of *X*, *Y*, or *Z* the definitions of *L**, *a**, and *b** differ from those given above, a matter that does not concern us here.

5.4 The three dimensions of CIELAB are *L**, *a**, and *b** and each color stimulus falls on a point in the resulting space (Fig. 13.8).

The *L**, *a**, *b** space is a Euclidean space and as a consequence, differences between two samples are expressed as the square root of the sum of the squares of the differences in the applicable dimensions. It does not consider the hue-superimportance effect.

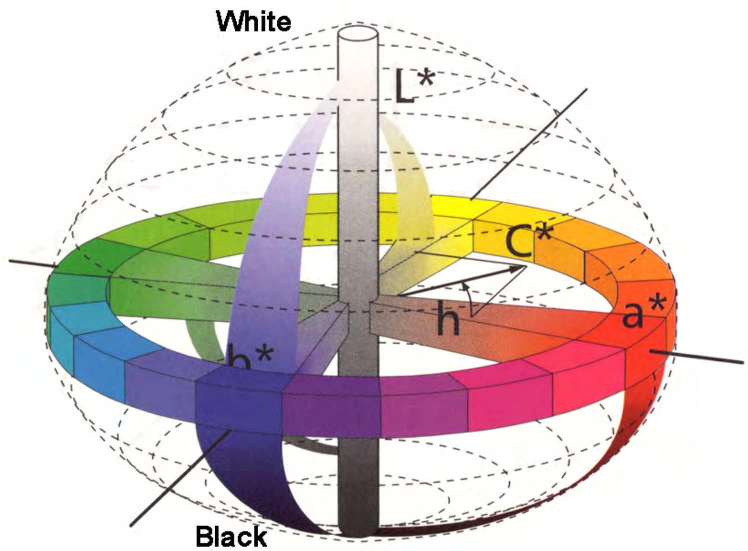


Fig. 13.8. Representation of the structure of CIELAB color space with the vertical *L** axis representing a gray scale, and the chromatic axes *a** and *b**. Colors are approximations.

5.5 In the *a**, *b** diagram, colors of constant *metric hue* fall on straight radial lines and colors of constant *metric chroma* on circles (Fig. 13.9).

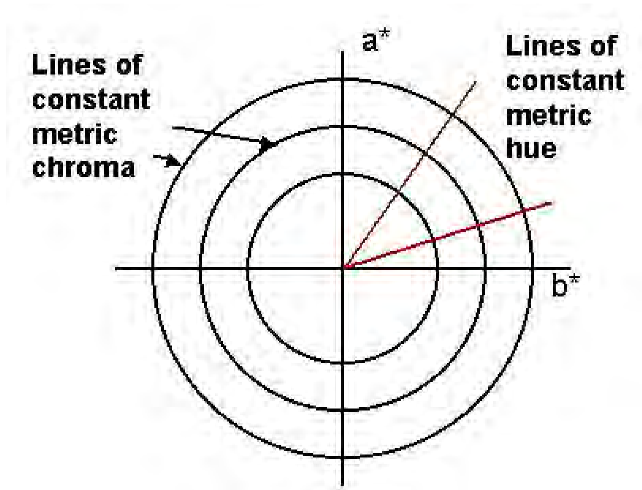


Fig. 13.9. CIELAB *a**, *b** diagram with circles of constant metric chroma and radial lines of constant metric hue (red).

5.6 Metric chroma C^* is calculated as the length of the line from the origin of the diagram to the point of the sample as the square root of the sum of the squares of the distances in a^* and b^* (see Fig. 13.10):

$$C^* = [(a^*)^2 + (b^*)^2]^{1/2}$$

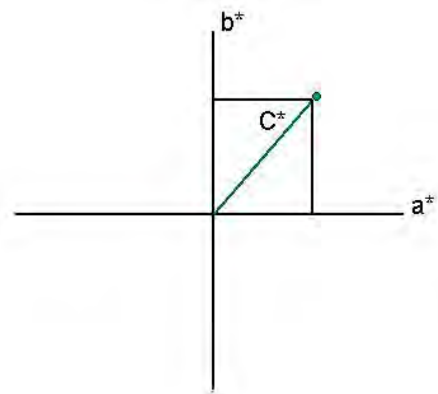


Fig. 13.10. CIELAB *a**, *b** diagram with a color indicated by the green dot. The metric chroma *C** of the color is calculated from the distances along the *a** and the *b** axes.

5.7 The total *metric color difference* between two samples, ΔE_{CIELAB}, is calculated according to Euclidean geometry as the square root of the sum of the squares of the three component differences:

$$\Delta E_{CIELAB} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

The Greek letter Δ (delta) is used to express a difference; for example, ΔL^* means the difference in L^* values of two different samples.

5.8 Differences in metric lightness and metric chroma are calculated in a comparable manner.

5.9 Using Euclidean geometry, it is also possible to calculate a metric hue difference ΔH^* by subtracting from the total metric difference between two samples the metric lightness and the metric chroma difference. The result, by definition, must be the metric hue difference:

$$\Delta H^* = [(\Delta E^*)^2 - (\Delta L^*)^2 - (\Delta C^*)^2]^{1/2}$$

5.10 The total color difference between two samples can be expressed in two different manners:

a) as the result of differences in L^*, a^*, and b^*, as shown in section 4.6 above
b) as the result of differences in L^*, C^* and H^*:

$$\Delta E_{CIELAB} = [(\Delta L^*)^2 + (\Delta C^*)^2 + (\Delta H^*)^2]^{1/2}$$

In the former case, the a*, b* diagram has a square organization; in the latter it has a radial organization in agreement with the visual attributes chroma and hue (Fig. 13.11).

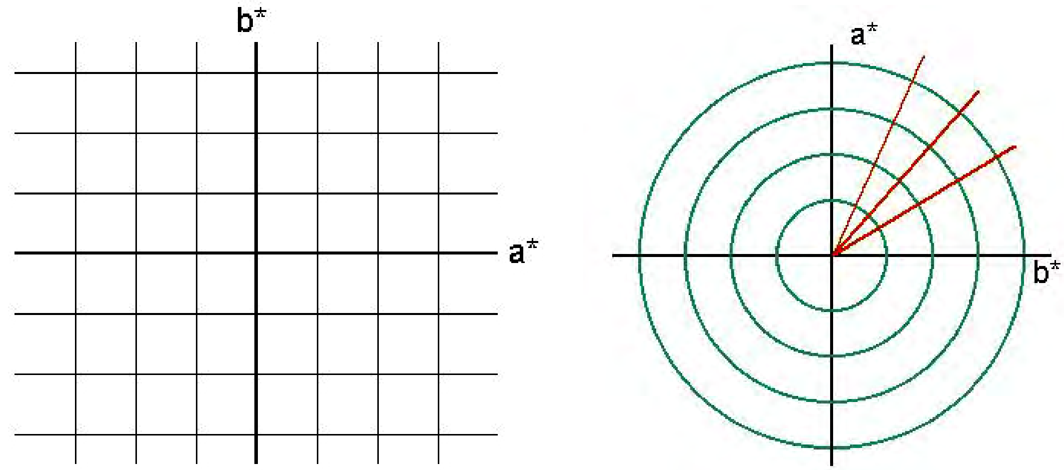


Fig. 13.11. Square internal organization of the *a**, *b** diagram (left) and metric hue/chroma organization of the diagram with green circles of constant metric chroma and red radial lines of constant metric hue (right).

5.11 A Δ*E* value does not provide any indication of how the two samples involved differ. For this purpose, it is useful to have the three components of the total color difference, the metric lightness, chroma, and hue difference. There are conventions that make it easier to understand the meaning of difference values. In the calculations, usually the data of the sample are subtracted from those of the standard. As a result, a negative Δ*L** value means that the sample is darker than the standard, and vice versa for a positive value. The same applies to chroma differences Δ*C**. The matter is more complicated in case of hue. The hue difference Δ*H** does not indicate where in the *a**, *b** diagram the colors of reference and sample are located. To know the meaning of the hue difference requires the calculation of the hue angles in this diagram (Fig. 13.12). Once the hue angles of reference and sample are known, the meaning of the hue difference can be determined. In the example of Fig. 13.12, the general hue of reference and sample is orange, with the sample, having a larger hue angle value, being yellower (closer in direction to the positive *b** semi-axis). To avoid problems, the hue direction of the sample compared to the reference should be determined by the software and printed out. In a supply chain, it is important to assure that the same conventions are used by everybody in regard to the meaning of the difference components.

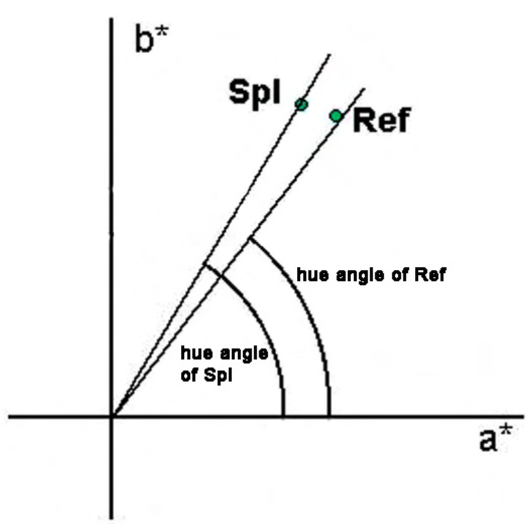


Fig. 13.12. First quadrant of the *a**, *b** diagram with a reference and a sample color (green dots) that differ in hue angle, and thereby in metric hue. The sample has a larger hue angle, indicating that the hue is yellower.

5.12 How well is the CIELAB formula in agreement, for example, with the Munsell Renotation system and how well does it predict average perceived small supra-threshold differences?

The formula has not been fitted to any particular kind of experimental data. Fig. 13.13 shows that it does not represent the Munsell Renotations accurately. Some of the samples of that system considered to have identical hues do not fall on straight lines and samples of constant chroma in the Renotations do not have constant metric chroma in the *a**, *b** diagram. The constant chroma contours are irregular ellipses instead of circles. The biggest difference is along the *b** axis where the yellow colors have nearly twice the metric chroma of the blue colors of the same Munsell chroma.

As mentioned, the accuracy of the formula for representing average perceived small supra-threshold color differences is about 50%.

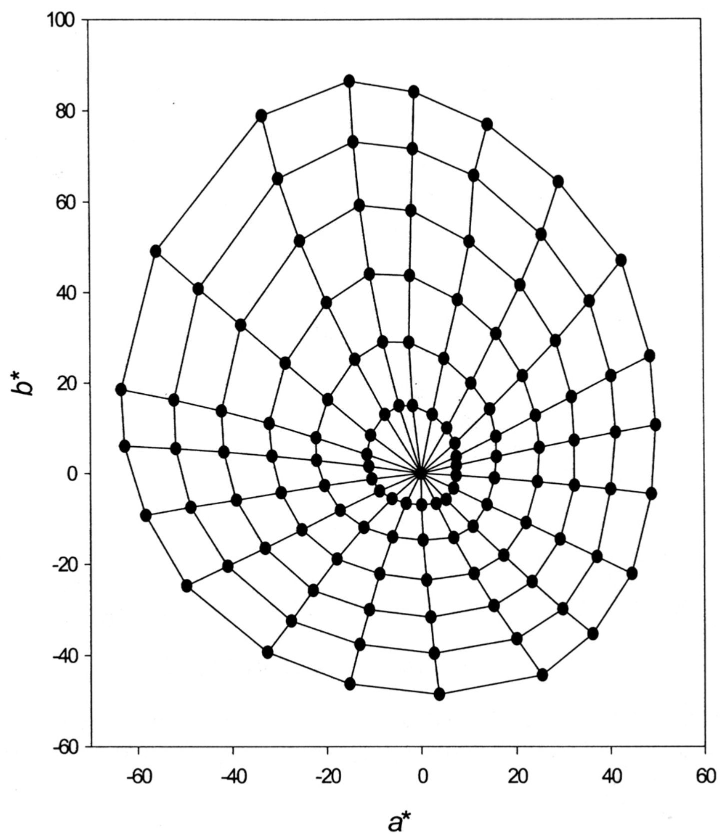


Fig. 13.13. A selection of Munsell Renotation colors in the *a**, *b** diagram.

6 The CMC(2:1) Formula

6.1 With only moderate accuracy in predicting average perceived color differences from CIELAB , the question arose how the unit difference contours in the *a**, *b** diagram differed from circles and how they differ in the *L**, *a**, *b** space from spheres.

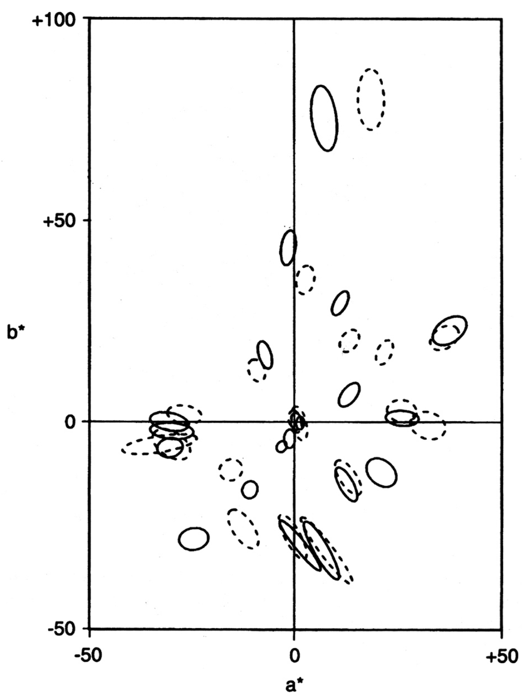


Fig. 13.14. Unit difference ellipses optimized to a selection of average visual data from two different experiments (full lines and dashed lines) in the *a**, *b** diagram. *Courtesy of John Wiley & Sons Inc. (Melgosa, M., et al, Color Research and Application, Vol. 22, 1997). Used with permission.*

The meaning of a unit contour is that all differences between the standard, the central point, and any color located on the contour is the same, 1.0. As mentioned in sections 2.7 and 2.8 above, this was investigated by plotting unit contours that were fitted to the visual data in the *a**, *b** diagram. Fig. 13.14 shows typical results for selected data from two larger sets.

Several facts can be seen:

a) Nearly all contours are ellipses.
b) Most ellipses have their longer axis pointing toward the neutral point in the center of the diagram.
c) Ellipses near the center point tend to be small and become larger farther away from the center (i.e., with higher chroma).
d) Ellipses along the negative *b** axis are tilted away from the center.
e) Contours near the center in most cases are still ellipses and not circles.

What are the likely reasons for these facts?

a and b) Ellipses with their longer axis pointing toward the neutral point can be expected as a result of the *hue-superimportance* effect according to which the color vision system is more sensitive to hue differences (shorter axis) than to chroma differences (longer axis).

c) According to the *crispening effect*, the visual system is most sensitive to differences between colors near the surround than farther away. As a result, one can expect unit ellipses determined in a gray surround to be smaller for near-gray colors than for saturated colors.

d) There is no obvious perceptual reason for the tilt of ellipses along the negative *b** axis. We can assume that it is an artifact of the CIE colorimetric system.

e) Near the center, the ellipses are very small and aligned more or less with the *b** axis. This may indicate an imbalance in the CIELAB system in the way it describes discrimination in the red-green and the yellow-blue directions.

A factor not yet discussed is lightness crispening, the fact that the visual system is most sensitive to small lightness differences if the colors are similar in lightness to the background color. From this, one would expect that the relationship between L^* and perceived lightness difference is not a simple any gray surround. Neither of the three formulas discussed is making explicit adjustments for the lightness crispening effect.

6.2 The CMC (l:c) color difference formula is a modification of CIELAB that adjusts this formula to be in better agreement with average perceptual data in three respects.

The lightness/chroma/hue version (LCH) of CIELAB (see section 4.9 above) makes it possible to adjust unit contours that are ellipses aligned toward the neutral point, because the longer axes are aligned approximately with the constant hue lines of the a^*, b^* diagram.

The increase in size of the ellipses, as the chroma of the color increases, can be adjusted in a relatively simple manner based on the metric chroma value of the standard.

Non-linearity between the L^* scale and the visual lightness differences can be adjusted for by a correction factor for the metric lightness difference.

6.3 The CMC (l:c) formula was developed in 1984 by the Colour Measurement Committee of the Society of Dyers and Colourists in England. In this formula separate adjustments are made to the metric lightness, chroma, and hue differences that have been calculated according to the CIELAB formula:

$$\Delta E_{\mathrm{CMC}} = \left[\left(\frac{\Delta L^*}{l S_L} \right)^2 + \left(\frac{\Delta C^*}{c S_C} \right)^2 + \left(\frac{\Delta H^*}{S_H} \right)^2 \right]^{0.5}$$

As is evident, the metric lightness difference (ΔL^*), the chroma difference (ΔC^*), and the hue difference (ΔH^*) are adjusted with factors S_L, S_C, and S_H. In addition, the first two can be adjusted with two factors, l and c, respectively. The total color difference is then calculated in the normal manner as the square root of the sum of the squares of the adjusted metric lightness, chroma, and hue difference components. The formulas for the S adjustment factors are relatively complicated and beyond the needs of readers of this text.

6.4 The *l* and *c* adjustment factors.

When testing the formula without these factors, the developers of the formula noted that in order to achieve the highest predictive accuracy for various sets of textile data, they needed to reduce the weight of the calculated lightness difference component in the total difference by a factor of 2. This adjustment appears to compensate for a loss in lightness difference perception due the lack of sharp dividing lines between the two samples that are being compared. Sharp dividing lines are possible in the case of painted paper or plastic samples, but not in the case of textile samples. The resulting formula for textiles became known as the CMC(2:1) formula where 2 is the value for *l* and 1 for *c*.

6.5 The CMC(2:1) formula is recommended for use with textile materials by the International Standards Organization (ISO) and by AATCC.

6.6 How well does the CMC(2:1) formula predict average perceived supra-threshold small color differences?

As mentioned earlier in this chapter, this formula reduced the error of predicting average perceived small differences from 50% of CIELAB to about 35%. This is (relatively speaking) a 30% improvement, clearly worth the implementation of the formula in a color management process in place of CIELAB. On the other hand, a 35% error is still less than satisfactory.

6.7 The mentioned accuracy of formulas applies only to judgments of small supra-threshold differences in the range of approximately 0.5 to 8 CMC(2:1) units of difference. For larger differences, the accuracy of the formula declines further.

7 Predictive Ability Improvements

7.1 In 2001 the CIE recommended a new color difference formula (CIEDE2000) that, in addition to the improvements of CMC (l:c) over CIELAB, made several further improvements.

Additional adjustment factors improve the uniformity of hue differences around the hue circle, adjust for the tilt of ellipses along the *b** (minus) axis, and treat the contour forms near the center point of the *a**, *b** diagram as ellipses. This was necessary because the formulation of $_{SC}$ in CMC automatically results in circular unit contours near the neutral point.

7.2 However, in four independent international field trials of this formula for textiles, no statistically significant improvement of CIEDE2000 over CMC(2:1) was found.
For this reason, the ISO and AATCC have so far refrained from recommending it. A new formula should show clear improvements in performance before there is scientific and commercial value in implementing it.

7.3 The main factor in the remaining lack of agreement between average visual data and formula is quite certainly due, first of all, to different groups of observers participating in the experimental studies and the resulting differences in average judgments, and secondly, to the differences in experimental conditions (both discussed earlier in this chapter).

It appears that the number of observers required to obtain a valid statistical average for differences in color matching functions may not be sufficient for a similarly statistically valid standard color difference observer.

It may be possible to develop formulas/systems that predict the results of a world-average observer with high accuracy (95% or more), valid only for a specific set of conditions of obtaining perceptual data. It remains to be seen if there is enough interest in the field to pursue such an approach.

8 Color Difference Calculation in Color Quality Control

8.1 Color difference calculation has several places in color quality control:

- formulation by computer
- comparing different kinds of standards
- comparing batches to standards and to other batches
- testing colorants
- complaint analysis
- competitor analysis

8.2 When applying color difference calculations, the limitations of such calculations need to be kept in mind.

Color difference formulas are fits to perceptual data determined in different ways by different observer panels. The best formulas currently available represent averages for these panels and represent the resulting mean data, at best, at an accuracy of 65%. In any given situation, judgments by individuals may vary significantly from the calculated results.

8.3 Color difference calculation programs are built into formulation software. Separate programs for other applications are usually found in software packages supporting spectrophotometers.

8.4 In a supply chain, care should be taken that different software packages produce identical results from the same reflectance data.

8.5 When reporting results, it should be clear what standard observer data and what formula were used to calculate them.

8.6 Despite the indicated limitations, calculation of color differences for the purposes of setting standards and communicating semi-objective data is clearly very useful.

9 Objective Assessment of Fastness Testing Results

9.1 Fastness testing usually requires assessment of a changed sample compared to an original sample.

Such assessments are usually done subjectively by persons making judgments about the degree of change (either in staining undyed material or change of shade).

9.2 In many test methods, gray scales, such as those from ISO or AATCC, are used to aid in comparison and rate the changes.

There are two gray scales, the scale to assess change of shade and the scale to assess staining. The former runs from dark gray toward white, the latter in the opposite direction, from white toward gray. In the former case, for each grade there is a pair of samples; one of them does not change while the other one changes in steps of increasing magnitude toward white, thereby making the difference between it and the reference gray larger and larger. In the latter case it is the opposite.

9.3 Gray scales allow for grading from 5 to 1, in half steps.

In AATCC Evaluation Procedure 1: Gray Scale for Color Change, a grade of 5 means there is no change, with both samples identical grays (Fig. 13.15). A grade of 1 means there is a large change. In AATCC Evaluation Procedure 2: Gray Scale for Staining, a grade of 5 means there is no staining, with both samples white (Fig. 13.16). A grade of 1 means there is a large change with the lightness difference between the two samples being large.

9.4 Gray scales are prepared according to a geometric scale.

The differences between the two samples of a pair on the scale have a certain metric color difference with the difference growing from the lowest to the highest, not according to a simple linear scale, but according to a geometric one (the size of the difference doubles from one pair to the next).

Fig. 13.15. The AATCC Gray Scale for Color Change.

Fig. 13.16. The AATCC Gray Scale for Staining.

9.5 To help in the assessment of staining of chromatic samples AATCC also offers a Chromatic Transference Scale (Fig. 13.17).

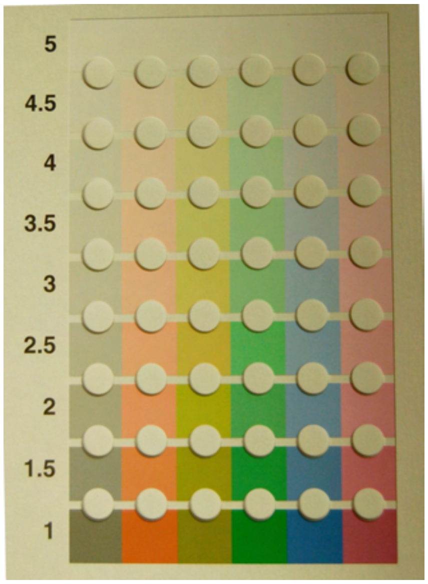


Fig. 13.17. The AATCC Chromatic Transference Scale.

It consists of a gray and five chromatic scales. The gray scale corresponds to the samples of the AATCC Gray Scale for Staining. The chromatic samples were selected to represent a comparable degree of staining to those from the gray scale. The corresponding test method is AATCC Evaluation Procedure 8. It contains the clause: "For very critical evaluations and in cases of arbitration, ratings must be based on the geometric Gray Scale for Evaluating Staining."

9.6 Gray scale judgments are pair comparison color difference judgments (see also section 2.3 above). The magnitude of the difference between the original and the changed sample is compared to the magnitude of the difference between samples on a gray scale.

9.7 Given the intra- and inter-observer variability in gray scale-based assessment, it is of interest to have an objective method available that can predict the average visual gray scale judgment.

One might expect the metric color differences that define the gray scale to be sufficient for this purpose, however the average visual assessment for samples of different chromatic color generally deviate from the gray scale data. For this reason, experimental formulas have been developed that make it possible to calculate gray scale ratings from the reflectance data of samples before and after the fastness test procedure.

At the time of writing this text, the final formula to be used had not yet been decided on. Interested readers should consult the latest *AATCC Technical Manual*.

10 Summary

Color difference calculation is an important component of the color quality control process in the manufacture of textile products. Calculated color differences are psychophysical, that is, they combine objective measurements, reflectance and spectral power distribution, with subjective judgments, the average interval judgments of differences between pairs of samples for a group of observers. The considerable variability in judgments of individual observers and the relative inflexibility of mathematical formulas appear to be the main reasons for the limited accuracy of formulas in predicting the average judgment results.

The variability in individual judgments makes an at least semi-objective method desirable and useful. However, it is important that the meaning and limitations of the calculated results are understood by all parties using them.

Chapter 14 KEY CONCLUSIONS

Light is a carrier of information.

All visual information we obtain about objects in the visual field in front of us is based on interpretation, by the brain, of light arriving at the surface of the eyes. During its evolution, the mind has learned how to interpret this information to the benefit of the owner. We are aware of the information indirectly from the images provided to our conscious self.

Are eyes and brain a color-measuring system?

The eyes and brain cannot "measure" the spectral power distribution of lights, or the reflectance or transmittance of materials. They can only determine ratios of cone response values in the retina at different locations in the visual field and make best estimates of the nature of lights and objects based on previous visual experiences accumulated over a lifetime.

Are visual experiences always "truthful?"

Differences in the spectral nature of light are interpreted by the visual system as differences in lightness and, simultaneously, as differences in color. The relationship between the physical properties of the light arriving at the eyes and the color experiences we have is a very complex one. Because of the interpretive nature (not objective measurements) of the human visual system, the results are at times not truthful—as illusions of form and color show.

What is more important to our visual system, determining "exact color" or determining small differences?

The fact that individuals do not experience given stimuli identically and several perceptual effects, such as adaptation, crispening effects, and hue superimportance indicate that detecting small differences in reflectance of neighboring objects was more important to our early ancestors than having identical color experiences for individuals.

Does the human brain have a tool to "measure" color differences?

The considerable variability in judgment of color differences indicates that we probably do not have such a tool but that we are merely guessing at the size of differences. Just as in every other field, we can train the brain to improve the guesses according to some learned plan.

Are there persons that have truthful color and color difference vision while others do not?

There is no objective basis to declare a person to have truthful vision while others have not. However, some people have clearly impaired color vision, as determined with some test methods. Among color-normal people, the “truth” is determined on the basis of statistical averages. Some individuals differ more or less from such averages, but there is no basis for declaring the vision of those differing from the average as less truthful, they only differ more or less from the average observer.

Physical measurements of stimuli are highly reliable.

We can measure spectral power of lights and reflectance of objects with high, if not perfect, reliability. However, the results depend to some degree on the exact conditions of measurement, especially for complex materials such as textiles.

Visual judgments are dependent on conditions.

When making visual judgments, the lighting and surround conditions influence the results, sometimes strongly. To minimize this effect, it is important to maintain standard conditions of some kind when making visual judgments and to use the same conditions throughout the company or supply chain.

Average visual color difference judgments depend on the observer panel from which they have been derived.

Because color difference experiments have as yet not been replicated, that is, repeated exactly except for the observer panel, there are no data to indicate how many observers are required to assure that the statistical average is valid for all color-normal observers.

Can we expect a color difference formula/system with an accuracy of 95% or better for the average observer?

This is unlikely anytime soon. It requires extensive new perceptual data that show which test method results in lowest intra- and inter-observer variability, followed by data representing most of the object color solid under those conditions. Such a formula/system would be accurate only for the given test conditions and the average observer. Other test conditions would likely require modifications of the formula.

Reflectance measurements of textiles are useful for several purposes.

Reflectance is a useful tool to help provide answers to many problems, such as color matching, dye strength determination, dye identification, calculation of color constancy, etc. Care must be taken to assure accurate and repeatable results.

Calculated data, such as color differences, index of metamerism, color inconstancy index, objective gray scale ratings, etc., may not agree well with individual judgments, primarily because they are based on the standard observer and individual real observers may differ in their judgments for various reasons.

Calculated data offer a neutral yardstick, easy to communicate in the form of numbers. Because textiles can be structurally complex and aesthetic judgments are occasionally called for, there can be situations were objective data should be overruled.

Not every individual will be happy with decisions based on calculated data.

As mentioned above, there is no objective basis for calling one trichromat's color experiences true and another's false. For this reason there may be disagreements about color that cannot be resolved except by compromise.

In color formulation, choices need to be made about illuminants, taking into consideration store lighting and lighting in which the customer is making use of the product.

Color constancy calculations and computer color matching help to rapidly find the best compromise between economics of formulation and customer satisfaction in terms of color appearance, given a basket of dyes to choose from.

A color management program within a company or supply chain requires careful consideration of what to test, how to test it, and when to test.

A successful color management program can contribute noticeably to competitiveness and customer satisfaction. To work out a flexible, but effective program is an important task.

If you need to know more...

Unfortunately, the selection of reasonably up-to-date books (less than eight years old) that offer more in-depth information on color science than offered in this book is very limited. The following books are suggested for readers that are interested in obtaining additional information:

Berns, R. S., *Billmeyer and Saltzman's Principles of Color Technology*, 3rd edition, John Wiley & Sons Inc., Hoboken, N.J., USA, 2000.

Kuehni, R. G., *Color: An Introduction to Practice and Principles*, 2nd edition, John Wiley & Sons Inc., Hoboken, N.J., USA, 2005.

Specific questions can be addressed to the author at rkuehni@carolina.rr.com.

GLOSSARY

Absorption (color): a measure of the light retained by a material such as a dye in solution; nonlinear reciprocal of transmittance. p31.

Absorption (electromagnetic radiation): the process of transferring energy from a photon to matter, resulting in transformation of the photon. p28.

Accuracy: the degree to which a measured or calculated quantity is in agreement with the true value; two related terms are reproducibility and repeatability. p70.

Achromatic: neutral in color, possessing no hue and chroma. p24.

Adaptation (to a light source): there is light adaptation and chromatic adaptation: the former refers to changes in the sensitivity of the visual system as a result of the amount of light impinging on the eye; the latter refers to changes in spectral sensitivity of the eye to light of different color temperature in a way that makes many slightly colored lights appear white after half a minute or so of exposure, if they are the only source of illumination. p74.

Affinity (chemical): electronic properties of atoms or molecules that makes it possible for them to form larger chemical compounds. p37.

Algorithm: a mathematical procedure with specific instructions that accomplish a given task from an initial state to an end state. p172.

Analytical balance: a scale or balance that allows accurate weighing of milligram or smaller quantities. p180.

Analytical glassware: laboratory glassware calibrated to contain an accurate volume of liquid (analytical flask) or to dispense an accurate volume of liquid (pipette). p180.

Analytical pipette: a laboratory tool that makes it possible to dispense an accurate volume of a liquid. p180.

Attribute: an inherent characteristic; for color of an object a typical example is hue. p82.

Auxochrome: a group of atoms in a molecule that intensifies the light absorption of the molecule and thereby its apparent color. p39.

Blackbody: an idealized nonreal material that absorbs and emits electromagnetic energy at all wavelengths without restriction. p11.

Bolometer: a device for measuring electromagnetic radiation impinging on it. p59.

Broadband absorber: a material with light absorption properties over a relatively broad range of wavelengths, such as a colorant. p31.

Calibration dyeings: a set of dyeings of a dye at different concentrations on a standard material used to characterize the relationship between dye concentration and reflectance properties for the purpose of computer color matching. p157.

Candela, unit of luminous intensity of a light; power emitted by a lightsource in a given direction, weighted by the photopic luminous efficiency function. p60.

Chroma: attribute of a visual sensation permitting the judgment of the degree to which a chromatic field of color differs from an achromatic field of the same lightness; compare to saturation. p80.

Chromatic crispening: perceptual effect according to which the change in stimulus intensity required to perceive a chroma difference of unit magnitude against a gray surround increases with the distance of the stimuli from the achromatic gray of the same lightness. p93.

Chromatic intensity: a general term describing the magnitude of saturation of a light or chroma of an object. p131.

Chromophore: the region of a molecule responsible for its light absorption properties and thereby for its perceived color. p38.

Chromaticity coordinates: coordinates of a rectangular diagram in which color stimuli can be plotted, resulting in different locations for stimuli of different perceived hue and chromatic intensity. p114.

Color assimilation: effect according to which the color of small fields is directly influenced by that of adjacent other small fields: a red field appears bluer when surrounded by blue fields and yellower when surrounded by yellow fields. The assimilation effect is opposite to the simultaneous contrast effect. p93.

Color constancy: lack of change in the appearance of an object when illuminated by “white” lights of different spectral power distribution. p88.

Color gamut: range of colors (form and size of the color solid) that can be achieved from mixture of three or more primary lights or colorants. p166.

Color inconstant: term to describe objects that change in appearance when illuminated by “white” lights of different spectral power distribution. p185.

Color matching functions: three sets of numbers describing the spectral functions of three real or (in case of the CIE color matching functions) hypothetical lights used to match the appearance of all spectral lights. p114.

Color mixture: colloquial term for the mixture of lights or colorants to produce as many different color perceptions as can be obtained from the primary lights or colorants. p150.

Color mixture, additive: colloquial term to describe certain results of mixing lights. The results are limited to describing lights that match in appearance and do not express anything about color appearance of the lights itself. p150.

Color mixture, subtractive: colloquial term to describe certain results of mixing colorants. The results are limited to describing objects that match in appearance and do not express anything about color appearance of the objects itself. p155.

Color rendering: the fidelity with which artificial light sources render the color appearance of objects compared to viewed in daylight of a given color temperature or incandescent light, calculated psychophysically. p194.

Color solid: a portion of a color space in which all color stimuli or perceptions obtainable under certain conditions fall on points on the surface or within the interior according to a certain order defined by the color space. p85.

Color space: three-dimensional coordinate system within which color stimuli or experiences can be represented as points with unique positions. Typical coordinates of such spaces are CIE tristimulus values, or Munsell attributes hue, chroma, and lightness. p85.

Color stimuli: under normal conditions the term refers to lights that result in color experiences. p24.

Color temperature: the temperature on the Kelvin temperature scale of a blackbody that gives off electromagnetic radiation of a particular spectral power distribution. The color temperature is used to describe the spectral power distribution of daylight phases or incandescent lights. p194.

Color temperature, correlated: result of a method of assigning a color temperature to artificial light sources with a chromaticity near but different from that of a blackbody light source. p11.

Colorant: a material that changes the absorption characteristics of other materials, typically dyes or pigments or certain metal salts. p28.

Colorimetric match: a match in which the tristimulus values of the standard are duplicated based on reflectance information about the dyes and textile substrate to be used, and light source data. p165.

Coloring power: the inherent power of a colorant to reduce the reflectance of a substrate material and thereby producing the appearance of color. p177.

Cone: a type of light sensitive cell in the retina of the eye; there are three kinds of cones that together are responsible for color vision. They have different sensitivity along the spectrum. p74.

Contrast, simultaneous: change in the apparent color of a field of color under the influence of a neighboring colored field. There can be either achromatic (gray) simultaneous contrast or chromatic simultaneous contrast. In the former a field can have a different apparent lightness depending on the surround lightness; in the latter case the apparent chromatic color of an filed usually changes in direction opposite to that of the adjacent or surrounding field: for example, a yellow field appears greener when surrounded by a red field and redder when surrounded by a green field. p89.

Contrast, successive: when staring for 10-20 seconds at a given image and then shifting the gaze there is often a fleeting impression of the image but in lightness or colors that are opposite (in case of chromatic colors compensatory) to the original color. It is believed to be due to a fatigue effect in the retina after extended exposure to the same stimulus. p90.

Cube root compression: a term for the modification of the signal between the retina and the resulting perceived color. The scales of light stimulus and perceived color, for example a lightness scale, are not in simple, linear relationship. An increment of luminous reflectance of 5 units produces a smaller change in apparent lightness when the luminous reflectance is high than when it is low (say, from 80 to 85 compared to 10-15). The signal compression, originally believed to be logarithmic, has later been shown to be roughly in cube-root relationship. This relationship is used in some mathematical models of color vision, such as in the CIELAB color space and difference formula. p209.

Cubo-octahedron: a geometric solid found in nature in crystals. It has the property of having 12 edge points equally distant from its center point and being stackable so that multiple cubo-octahedra completely fill a cube space. p145.

Cuvette: a piece of laboratory glassware usually of square tubular form, closed at one end. It is used to measure the transmittance of dye or other solutions in a spectrophotometer equipped to accommodate it. p50.

Denier: a measurement system to express the fineness of man-made filament fibers and silk. The denier number indicates the weight in grams of 9000 meters of the filament yarn. The lower the number the finer the yarn. p33.

Dichromat: an individual with only two types of cones in the retina instead of the normal three. p96.

Difference, just noticeable: a difference between two fields of color where the stimulus of one is constant and that of the other can be varied continuously. A just noticeable difference is the first difference between the unchanged and the changing stimulus that can be perceived as the distance in a given direction between the two increases. p99.

Difference, large: refers to a color difference of a size of multiple, say 10 and more, just noticeable difference steps. p201.

Difference, suprathreshold: refers to a stimulus difference that is larger than the threshold difference. The latter causes a just noticeable difference. Therefore the difference is larger than a just noticeable or threshold difference. p99.

Difference, threshold: a stimulus difference that results in a just noticeable difference. p201.

Diffraction grating: a reflecting or transparent piece of material with a surface engraved with very fine parallel grooves. Light falling on it is separated according to wavelength by the diffraction and the interference effect, producing a spectrum of colors. p28.

Diffuser: a device that diffuses a beam of light, spreading its photons in many directions. p20.

Diffusion: in dyeing technology the process that distributes dye from the surface of the fiber throughout its interior so that, in the end state, the dye is distributed evenly throughout the fiber and fabric. p37.

Diffusion, speed of: the speed at which a given dye diffuses a given distance through a given textile fiber material; it is used to classify different dyes in this respect. Ideally, dyes in a combination have the same or similar speed of diffusion. p47.

Dispersion (or refraction): terms that denote an optical phenomenon according to which photons are separated according to their wavelength. The best-known dispersion device is a glass prism. A beam of “white” light entering the prism on one side emerges as a band of light with the photons sorted according to wavelength and forming a rainbow or spectrum display. p27.

Dullness: (colloquially, in regard to object color) low chroma and darker, as compared to “brightness,” meaning high chroma and lighter. p29.

Dye: a type of colorant that at one stage during its application is dissolved in a solvent. The solvent is typically water. In the case of vat dyes a special chemical process requiring alkali and a reducing agent are used to make the dye soluble. p28.

Dye dispensing unit: a piece of laboratory equipment that can dispense pre-prepared dye solutions or dispersions to result in specific dye concentrations on weight of goods when dyeing a small piece of textile material in a laboratory dyeing machine. p172.

Dye stock solutions: solutions or dispersions of individual dyes in a given concentration used to prepare laboratory dyebaths either by manually dispensing given amounts or dispensing them in a dye dispensing unit. p181.

Dye, fluorescent: a special type of dyes that absorb near-ultraviolet or short-wavelengths visible light and emit photons at higher, visible wavelengths. The resulting color appearances are brighter, more intense than those from conventional dyes. They appear to give off light. p39.

Dyeing: the industrial process of applying dyes to textile or other materials (leather, paper, plastics, etc.) p37.

Electrochemical signals: packets of information that travel along nerve cells through the body; in case of vision they travel from the retina in the eyes to various places in the brain where the information is analyzed and further processed, sometimes resulting in our consciously experiencing certain phenomena, like forms, colors, or motions. p16.

Electromagnetic energy: a form of energy that travels through space and has electric and magnetic aspects. p7.

Emission: in regard to light, the discharge of photons from an object. p70.

Extrusion: the formation of metal or polymeric materials by forcing it through a die; the result can be an endless string, such as a wire or a filament fiber. p33.

Farnsworth-Munsell 100-hue test: a device for testing the ability to distinguish fine hue differences, consisting of 85 color chips differing in hue that need to be placed in the correct hue order. It can detect abnomalies in color vision and measure the ability to make fine hue distinctions. It is not an interval color difference test. p100.

Fastness properties, related to colorants, describes the ability of dyes to withstand exposure to various media, such as light, perspiration, washing, dry cleaning, and others. p32.

Filament: a very fine continuous thread or thread-like structure. p33.

Fluorescence: the ability of certain kinds of molecules to absorb ultraviolet or short-wavelength visible light and re-emit it as visible light. p13.

Fluorescent whitening agent, a type of dye with the ability to absorb ultraviolet light and re-emit it as short-wavelength visible light; used to improve the appearance of whiteness of yellowish materials such as textile fibers or paper. p40.

Frequency: the number of cycles or completed alternations per unit time; a measure of electromagnetic radiation, including light. p7.

Full color: translation of a term by Ewald Hering (Vollfarbe) meaning the most saturated object color of a given hue possible. p132.

Glass prism: a triangular bar of glass used to break a beam of light of multiple wavelengths into its spectral components by the process of dispersion. p28.

Gloss: surface luster or shine of materials, due to direct reflection of a portion of the light striking the object. p29.

Gloss trap: device on a diffuse reflectance spectrophotometer that eliminates the gloss portion of reflected light from the total light. p68.

Glossiness: the property of reflecting a portion of light falling on the object according to the law of reflection. p20.

Goniospectrometer: a type of instrument that can measure the light reflected from an object at different angles and as a function of varying angles of the light beam falling on the object. p67.

Halftone process, a color magazine and book printing process where a large range of colors is obtained by printing with four inks: yellow, magenta, cyan, and black. The original continuous tone image is broken into small dots by photographing it through color filters and halftone screens (defined by lines per inch, the higher the lines per inch the smaller the dots). Today, the process is operated entirely digitally. p135.

Helmholtz-Kohlrausch effect: an optical effect named after two German physicists showing that chromatic colors have an apparent lightness independent of the lightness expressed by their luminous reflectance (the CIE tristimulus value Y). The effect differs by hue. High chroma colors of the same luminous reflectance as a gray appear more or less lighter than the gray. p141.

Hue: a basic attribute of color perception; it is the attribute of color perception denoted by names such as yellow, red, blue, green, and others. p80.

Hue superimportance: term given by D. B. Judd to indicate that it takes less change in activation of the cone types to perceive a hue difference than a chroma or lightness difference of equal perceived magnitude. It is an example of an evolutionary adaptation. p86.

Hue, complementary: complementary hues are hues that cancel each other when the corresponding stimuli are mixed, in the extreme forming stimuli that are seen as achromatic. Which hues are complementary depends on the visual apparatus of an individual. p91.

Illuminant: term used to describe a set of numbers that describe the spectral power distribution of a light source. Examples are illuminant D_{65} (standard daylight) or illuminant A (tungsten lamp light). p21.

Illumination, diffuse: a light can come from a point source, forming a relatively narrow beam or it can be diffused, such as daylight on a cloudy day. In that case light is falling on an object from many different angles. p20.

Incandescence: term for the release of electromagnetic radiation from a hot body, such as a blackbody, or a real solid, such as a hot iron rod. Depending on the temperature of the body, the spectral power distribution of incandescence varies. p11.

Indicatrix: a spherical image of a curve; specifically the distribution of light scattering from a solid material, as measured with a goniospectrometer. p67.

Infrared (below red): term describing a range of electromagnetic radiation with higher wavelengths than the “red” end of the spectrum; experienced by humans as warmth. p8.

Inorganic: a term for molecules that do not contain carbon and hydrogen atoms. p37.

Integrating sphere: component of a color measuring instrument used for measuring reflectance of widely scattering surfaces; it consists of a hollow sphere filled with light from the light source. The sample is attached to an opening in the sphere and the light diffusely reflected from the sample is collected and measured through an additional opening. p65.

Intermolecular force: electrical force between molecules that causes the molecules to influence one another, in particular, to attract each other and bind one to the other. p37.

Interval: specifically, a class of judgments that assesses the magnitude of difference between color perceptions. p85.

Irradiance: power of electromagnetic radiation on a surface, per unit area of the surface, for example watts per square meter. p60.

Isotropic: of equal properties along any axis; specifically, equal geometrical distances in any direction from a point represent equal perceived color differences. p60.

Isotropic system: specifically, a color order system that is isotropic or nearly so. p133.

Iteration: in computing means the repetition of a set of steps in a computer program. p171.

Judgment: the forming of an opinion, estimate, or conclusion from information presented to the mind. p99.

Judgment, interval: forming a judgment at the interval level, that is, about the magnitude of a difference between two percepts such as two color fields. p205.

Judgment, ordinal: forming a judgment at the ordinal level, that is, about the sequence of several stimuli without concern about the size of the intervals in the sequence. p205.

Kelvin temperature scale: temperature scale with an absolute zero (0K), with no lower temperatures possible. The temperature 0K is equal to -273.15C. p11.

Knitting: making a textile fabric by joining loops of yarn either manually or with a mechanical knitting machine. p35.

Lambertian: refers to a surface that scatters light widely so that its lightness appears the same regarding of the angle at which an observer views it; derived from the name of the 18^{th} century physicist J. H. Lambert. p61.

Lightness crispening: crispening effect that involves lightness only. The least amount of change in reflectance to perceive a lightness difference of a given size between two samples is required if the lightness of the surround is between the lightnesses of the two samples. p146.

Light source: A real light-emitting object, such as the sun or a lamp. Illuminants are mathematical models of physical light sources. p21.

Linear transformation: there is no simple definition of the term linear transformation. It is a mathematical operation that changes the reference space in which information is presented without changing the basic information. Conversion from the *L*, *M*, *S* cone space to the *X*, *Y*, *Z* tristimulus space involves a linear transformation with a set of three equations that defines the change. Another example is the transformation from the *XYZ* tristimulus space to the *x*, *y*, *z* chromaticity coordinate space. p111.

Lumen: the unit of luminous flow of light; 1 lumen means a light of 1 candela projected into 1 unit of solid angle of space (1 steradian). p60.

Luminance: light flow of a light beam emanating from a surface in a given direction, per unit solid angle. p60.

Luminous efficiency function: a spectral function that describes the relative sensitivity of the CIE standard observer to light at different wavelengths. Luminous efficiency is the ratio (in lumens per watt) of the power of a light as perceived by the standard photopic observer to its total power. p61.

Luminous reflectance: luminance of the surface of an object compared to the luminance of the surface of a perfectly reflecting diffuser, illuminated with the same light source and at the same angle; identical to the CIE tristimulus value *Y*. p126.

Lux: used in photometry as a measure of light intensity; 1 lux means 1 lumen per square meter. p60.

Man-made fiber: artificially produced, as compared to naturally produced fiber. Examples are rayon, nylon, polyester, or glass fibers. p33.

Measurement, diffuse: refers to reflectance measurement with diffuse illumination of the sample or diffuse viewing. p64.

Mercerization: a treatment applied to cotton fabrics to enhance luster or glossiness. It involves immersion under tension in a sodium hydroxide solution which swells the cotton fiber to a more circular diameter. The result is less scatter and more direct reflectance, making the fabric appear more lustrous. p34.

Mercerized cotton: cotton fabric that has undergone a treatment of mercerization. p29.

Metameric color matching: matching not the reflectance curve of a standard but its CIE tristimulus values. The result is a match under reference conditions (standard light source and standard observer) but may be more or less metameric. p107.

Metamerism: the phenomenon by which two lights with different spectral power distributions can appear identical to a given observer, or two samples with different reflectance curves when viewed in a given light by a given observer can look identical. In case of samples, when changing the light source (illuminant metamerism) or the observer (observer metamerism) the samples may not match any longer. p86.

Metric chroma: a value for the chroma of a sample that has not been visually determined but calculated from reflectance data with a formula, such as the value C^* in the CIELAB formula. p211.

Metric color difference, a calculated rather than a visually determined difference between two samples; for example, ΔE^* as calculated with the CIELAB formula. p212.

Metric hue: a value for the hue of a sample that has not been visually determined but calculated with a formula, such as the value h^* in the CIELAB formula. p211.

Metric lightness: a value for the lightness of a sample that has not been visually determined but calculated with a formula, such as the value L^* in the CIELAB formula. p209.

Microfiber: man-made fibers with a denier of usually less than 1; very fine fibers that result in high light scattering. p33.

Molecule: the smallest unit of two or more different atoms in a compound; the smallest unit of any material, such as a water molecule consisting of 2 hydrogen and one oxygen atom. p33.

Monochromat: an individual with only one type of cone in the retina instead of the normal three. p96.

Monochromatic: refers colloquially to a light consisting of a single wavelength or a light with a very narrow band of wavelengths. p9.

Nanometer: a metric distance unit, one billionth of a meter. p7.

Nit: specifically, a unit of luminance; 1 candela per square meter. p60.

Normalization: specifically, assuring that all components can be properly compared; for example; in case of color matching functions, their values need to be adjusted so that the area under the curves of all three is identical, usually with a value of 100. p120.

Observer, standard: short for usually one of the two CIE photopic standard observers, the 2° and the 10° observers. Sets of three color matching functions that define a color stimulus in terms of its interaction with the three (normalized) cone types. Two different standard observers have been defined by the International Commission on Illumination (CIE), the 2° and the 10° observer, referring to the size of the field of view. p105.

Observer, standard deviate: the statistical definition of an observer whose color matching functions differ in a way from the CIE standard observer that depends on the inter-observer variability in the data used to establish the standard observer. Used for calculation of an observer-dependent index of metamerism. p192.

Observer, standard photopic: short for the CIE photopic standard observer. The standard photopic observer refers to daylight vision, there is also a standard scotopic observer referring to night vision, and a standard mesopic observer referring to vision in the transition from night to daylight vision. p61.

One-beam instrument: a spectrophotometer with only one light beam, rather than two, and thereby mechanically less complex. The single beam is used (at different times) to calibrate the equipment against a white reference standard and to measure the reflectance of a test object. p62.

Opaque: not transparent or translucent, not letting light pass through. Many materials, such as many fibers and plastic materials, are more or less translucent but can be made opaque by thickening the layer until light no longer passes through. p28.

Optimal object color: a group of theoretical objects that at a given level of lightness can result in the maximum chroma possible. They are defined by theoretical reflectance functions. Real objects can approach those chroma levels but never exceed them. p132.

Ordinal: specifically, a class of judgments that assesses the sequential order of a series of objects according to an attribute, such as length, or lightness, without concern with the absolute values of the attributes or the differences in attribute value between the samples. p85.

Organic: a term for molecules containing carbon and hydrogen atoms. p37.

Oxidation: the loss by an atom or molecule of an electron; more practically, the treatment in some fashion of atoms or molecules with oxygen, such as when carbon (C) is oxidized it results in carbon dioxide (CO_2). Vat dyes are reduced during their application process on cotton and are subsequently oxidized, usually with hydrogen peroxide. p44.

Paramer: a term used to describe a near-metamer, such as they often occur in textile color matching: the match is metameric in nature but not a perfect match of the tristimulus values of the standard in the reference light and for the standard observer. p192.

Particle size distribution: describes for a sample consisting of small particles, such as pigments, the relative number of particles of a given size in a sample. p177.

Phase (of daylight): the spectral power distribution of daylight with a defined color temperature, such D_{55} or D_{65}, describing daylight at 5,500K and 6,500K, respectively. p10.

Phosphorescence: a process similar to fluorescence; a phosphorescent material, unlike a fluorescent one, does not immediately release the higher wavelength quanta after absorbing lower wavelength photons but only after some delay, resulting in the material glowing for some time after the irradiation with light stops. p13.

Photodetector: a sensor of light or other electromagnetic radiation; there are several technically different kinds of photodetectors. p69.

Photoelectric cell: an electronic device that generates electrical output that varies as a result of the amount of absorbed light, used to measure light intensity. p59.

Photometry: the science of measuring visible light with an instrument so that the results are in agreement with average perceived brightness of light. p60.

Photon: an elementary particle of light. p7.

Pigment: a type of colorant with low solubility in most solvents that is applied in solid but dispersed form as fine particles, either included in the material (plastic), or applied with a binder to the surface (paint or textiles). p28.

Point source: light source that gives off light in (theoretically) all directions and is of small size. p20.

Polychromatic: refers colloquially to a light consisting of a broad band of wavelengths. p9.

Polymer: a material consisting of very large molecules that are compounds of small molecular units (monomers); typical examples are fibers and plastic materials. p33.

Power, radiant: the rate of flow of electromagnetic energy, for example of light; expressed in watts per second. p9.

Primary light: applied to any light that in combination with two spectrally different lights is used to reproduce the appearance of some or all possible lights. p107.

Printing: to cause a text, design, or picture to be reproduced on a surface by mechanical transfer of inks or colorants. p37.

Pseudo-tristimulus value: a tristimulus value not based on reflectance data of a sample but on light absorption data, typically K/S data, and color matching functions; used in computer color matching calculations. p171.

Psychophysics: a crossover branch of science located between psychology and physics. It deals with the relationship between physical stimuli and perceptions; in case of color with the relationship between lights and color experiences. Because stimuli can be characterized much more accurately than perceptions, the emphasis is often on the physics part. p60.

Purity: specifically, a psychophysical measure of chromatic intensity. p117.

Quantum: the smallest quantity of radiant energy, such as light. p7.

Radiant intensity: or luminous intensity, the power per unit solid angle, watts per steradian. p60.

Radiometer: a device that measures the power of electromagnetic radiation, such as light. p9.

Radiometry: the science and technology of measuring the power of electromagnetic energy. p60.

Reactivity: refers to the rate at which a chemical compound undergoes a chemical reaction with another compound. It is defined as the number of molecules that undergo a particular reaction per second. p43.

Reduction: the gain by an atom or molecule of an electron; more practically, vat dyes are reduced in the presence of sodium hydroxide (caustic) with sodium dithionite to make them water soluble before their application process on cotton. See also, oxidation. p44.

Reflectance curve: the spectral curve illustrating, say from 400 nm to 700 nm, the change in reflectance values of a material against wavelength. p31.

Reflectance scale: expressed either as a factor, from 0 to 1.0, or as a percentage, from 0% to 100%. In graphs, the reflectance scale runs vertical and the wavelength scale horizontal. p71.

Reflection: general term to denote the return of light by a reflecting surface. p20.

Refractive index: a measure for how much the speed of light is reduced inside a medium, compared to a vacuum. p27.

Repeatability: is the variability in measurements or judgments by a single instrument or person under identical conditions. In regard to observers see also intra-observer variability. p47.

Reproducibility: is the variability in measurements or judgments among different instruments or persons. In regard to observers see also inter-observer variability. p47.

Reproduction, color: the technology of reproducing the color appearance of objects or lights using different reproductive media, such as color television, halftone printing, or matching with different colorants. p164.

Reproduction, general appearance: reproduction that is not accurate in terms of reflectance or tristimulus values of components of the image but limited to general resemblance of appearance. p166.

Reproduction, preferred: reproduction of an image in modified, preferred colors, usually of higher chroma. p167.

Residual color difference: refers to the portion of a color difference in dyeings of a standard dye and a test dye that would be found if the standard and test dyes would have exactly identical dye strength. It can be obtained as metric color difference from calculation based on reflectance measurements of the dyeings. p183.

Rod: a type of highly light sensitive cells in the retina of the eye responsible for night vision and not believed to be involved in color vision. p74.

Salt bond: another term for ionic bond, the bond between atoms that exists in salts, such as common salt or sodium chloride ($NaCl$). Similar bonds can exist between organic acids and organic bases, or mixed bonds between inorganic and organic acids and bases. p42.

Saturation: technically, an attribute of a visual perception which permits a judgment of the degree to which a chromatic stimulus differs from that of an achromatic stimulus, regardless of their brightness (lights) or lightness (objects). Colloquially, it is often used as a general term for the degree of chromatic intensity. p82.

Scatter: the change in direction of photons after interaction with a surface of irregular structure. The photons of a beam of light all traveling in the same direction may be changed to travel in many different directions after interaction with a surface of irregular structure (lambertian). Most textile materials are highly scattering. p19.

Screen density: specifically, in halftone printing the number of lines per inch into which an image is divided into. In relatively low quality printing, such as of newspapers, the screen density is less than 100 lines per inch, in high quality art book printing it can approach 200 lines per inch. p135.

Silicon photodiode: device for detecting and measuring the amount of light, based on silicon technology. p69.

Solid angle: the space angle occupied by a section of a sphere that has the form of a cone. p60.

Spectral match: a perfect match of a standard in terms of reflectance, a match that matches the reflectance curve of the standard exactly. p165.

Spectral power distribution: the definition, in a curve or a numerical table, of the absolute or relative spectral power as a function of wavelength. In case of absolute spectral power distribution the units are typically watts per nanometer; in case of relative spectral power distribution the units are fractions or percents, with the spectral power at 555 nm usually set to 1 or 100%. p9.

Spectral scale: the wavelength scale of a graph or table, usually in horizontal direction, ranging for light typically from about 380 nm to about 750 nm, often from 400 to 700 nm. p71.

Spectrophotometer: an instrument that measures intensity of light as a function of the wavelength of the light. Such measurements are used to calculate (by the instrument) the spectral reflectance values of reflecting material, by comparing the amount of light from the instrument's light source as reflected from a calibrated standard plaque with that reflected from the reflecting sample. p61.

Spectroradiometer: instrument that measures intensity of light as a function of the wavelength of the light and expresses the results as absolute or relative spectral power. It is used to measure light sources. p61.

Spectrum: short for electromagnetic spectrum and often limited to the portion known as light. Colloquially, it is a term for the appearance of the light spectrum from about 400 to 700 nm, as obtained from a glass prism or a diffraction grating. p25.

Spectrum, visible: refers to the portion of the electromagnetic spectrum visible to humans. p7.

Specular included/excluded: refers to the settings of a diffuse reflectance spectrophotometer which makes possible inclusion or exclusion of light directly reflected (specular or gloss portion) from the material being measured. p67.

Specular port: device on a spectrophotometer that controls the inclusion or exclusion of the specular or gloss portion of light reflected from the sample. p68.

Spinning: forming yarns from natural or man-made fibers about 1-2 inches in length, for example cotton or wool. Yarn spinning is a very ancient technology. p35.

Standard, master: a physical standard for a textile material, defining minimally the desired color and perhaps also appearance and finish; portions of the master standard may be given to dyeing and finishing plants to match for quotations. p167.

Standard, production: a physical standard representing the color, physical properties, and appearance of a textile material, used to guide the quality of production in a plant. p167.

Standard, reference: a standard material for color that represents the designer's intention in regard to color appearance. It may consist of a material different than textiles, such as a color chip from an atlas. p71.

Standard, working: a standard material used in a finishing plant to guide production and determine the color and finishing quality. p71.

Standardization: the process of establishing technical standards for use by competing organizations in a market, now usually the world market. p41.

Stimulus intensity: the intensity of a light that is the stimulus for vision in general or color vision in particular. p146.

Strength, absolute: refers to the ability by unit concentration of a colorant to reduce the reflectance of a white or near-white object. p178.

Strength, relative: refers to the ability of a colorant (test sample) to reduce the reflectance of a white or near-white object as compared to that of another colorant (standard). p178.

Surface reflectance: portion of light reflected from a textile material that has not penetrated into the textile fibers but is reflected directly as gloss from the fiber surfaces. p182.

Toxicity: a measure of the degree to which a substance is poisonous, that is, harmful to living organisms. p32.

Translucent: describes materials that are neither fully transparent nor fully opaque; applies to most textile fibers. p28.

Transmittance: measure of the amount of light that passes through a transparent material, such as a dye solution or colored glass, expressed as a fraction from 0 to 1.0, or a percentage. p50.

Transparent: having the property of passing light through its substance; some of the light may be absorbed by absorbing materials included in the transmitting material, such as dyes in transparent plastic or a solvent. p28.

Triband lamp: a colloquial term referring to a kind of fluorescent light bulb where the emitted light is produced by phosphor compounds emitting it primarily in three relatively narrow regions of the spectrum. p14.

Trichromat: refers to people (or animals) with three kinds of light sensitive cells in the retina of the eye, operating at daylight level and responsible for normal color vision. p96.

Tristimulus value: a number, one of a set of three, expressing the relative amount of light of a color stimulus captured by one type of cone or one color matching function; used to define color stimuli in psychophysics. p119.

Tungsten light: incandescent light source in which incandescence is produced by electrically heating a tungsten metal wire to a temperature where it gives off light of the corresponding color temperature. p70.

Tungsten light, filtered: a light source in which light from a tungsten light bulb is filtered to resemble in spectral power distribution and appearance daylight of a given correlated color temperature; it is a daylight simulator. p22.

Twisting: a technique in textile technology where multiple filaments or spun yarns are combined to form a thicker, stronger yarn. p53.

Two-beam instrument: refers to a spectrophotometer with two parallel beams of light where one beam is the standard beam, reflected from the white working standard plaque, and the other is simultaneously reflected from the sample. A comparison of the strength of the two beams results in the spectral reflectance curve. p62.

Ultraviolet, (above violet): electromagnetic radiation with a wavelength range shorter than that of visible light. p8.

Units, absolute: units of a scale that represent absolute values; in color technology for example the amount of light at the surface of a light box. p131.

Units, relative: units of a scale that represent relative values; in color technology for example transmittance or reflectance. p131.

Vacuum: a space devoid of matter (in the universe) or a limited space from which all matter has been removed (glass flask pumped free of air and other matter). p27.

Value (lightness): a basic attribute of color perception describing lightness. p80.

Variability, inter-observer: variability in results of observations or judgments under identical conditions of individuals in a group of observers. p101.

Variability, intra-observer: variability in results of repeated observations or judgments under identical conditions by an individual. p101.

Vision-for-action: colloquial term for a component of the visual system that is concerned with the control of movements of the body from information received via the eyes. p17.

Vision-for-perception: colloquial term for a component of the visual system that is concerned with the identification of objects in the visual field. p17.

Wavelength: an indirect measure of the energy content of electromagnetic radiation. Wavelength is expressed in the metric system, for visible light in nanometers. p7.

Wavelength, complementary: definition of a series of color stimuli that in the CIE chromaticity diagram fall on a line beginning at the purple line, passing through the achromatic point of the diagram and ending on the spectral line. Used to indirectly define lights that in the chromaticity diagram are located so that a line from the achromatic point passing through the point of the light in the diagram ends up on the purple line and thereby cannot be defined by a wavelength. p116.

Wavelength, dominant: definition of a series of color stimuli that in the CIE chromaticity diagram fall on a line beginning on the spectral curve and ending on the achromatic point. Used to define lights that in the chromaticity diagram are located on this line. p116.

Weaving: the creation of cloth or fabric from yarns by intermingling them at a right angle on machines called looms. There are many different weaving structures possible. Weaving is an ancient technology. p35.

Weight of goods: the basis of a type of definition of dye concentration on a textile material, for example as percent dye on weight of goods (for example, 2 grams of dye per 100 g of textile material means 2% owg). This is a simple and convenient but not accurate definition because it assumes that the same percentage of dye is exhausted onto the fiber regardless of the initial concentration. In practice, this is often not the case. p181.

Xenon lamp: a type of lamp based on the electrical excitation of xenon gas to give off bursts of light with a spectral power distribution similar to that of daylight. Xenon lamps generally do not operate continuously but can be made to operate with apparent continuity (rapid bursts that are not separately distinguished). p11.

Yarn: thread made of natural or man-made fibers, used for weaving or knitting. p35.