NATURAL AESTHETICS
WITH COMPOSITE RESIN

Douglas A. Terry

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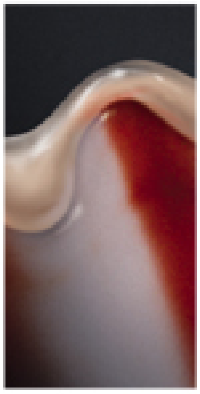

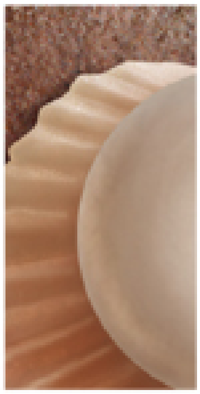

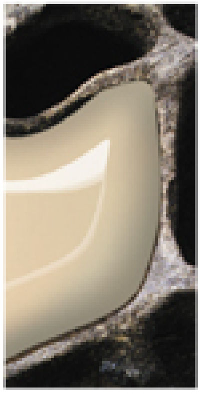

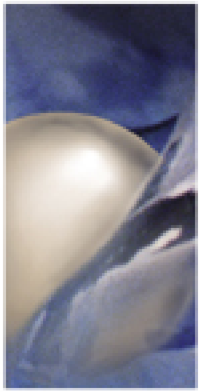

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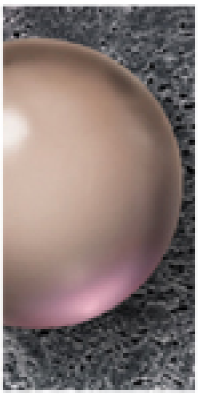

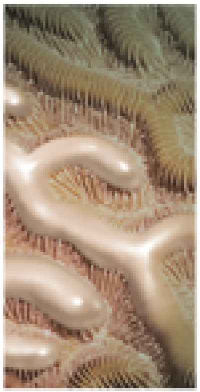

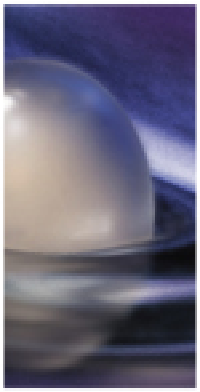

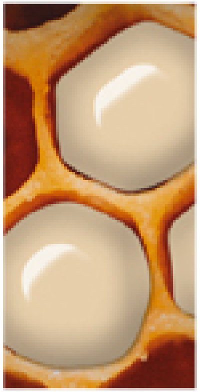

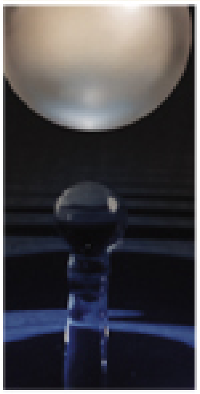

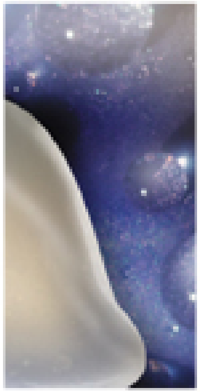

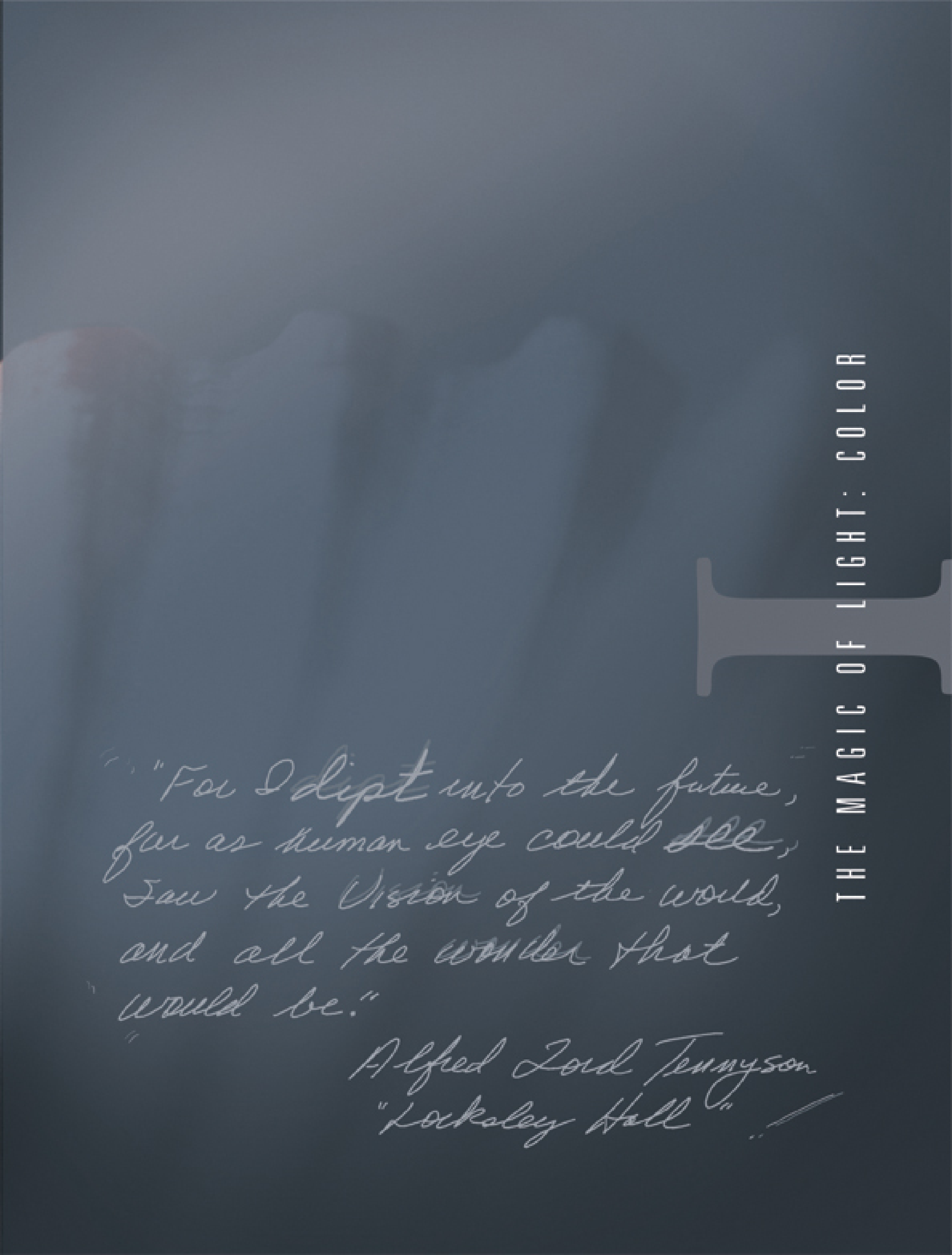

I

THE MAGIC OF LIGHT: COLOR

"For I dipt into the future,
far as human eye could see,
Saw the Vision of the world,
and all the wonder that
would be."

Alfred Lord Tennyson
"Locksley Hall"

THE MAGIC OF LIGHT: COLOR

A longstanding debate exists in the comparison of aesthetic dentistry and art, clinicians and artists. While a consensus may never be reached as to whether an aesthetic restoration may be classified as art, the influence of artists throughout time remains thoroughly etched in the development of aesthetic dentistry. As early as 1611, Forsius presented the concept that color was three dimensional,[1,2] and de Dominis proposed the first approximately correct explanation of the rainbow. In 1669, Newton experimented in atmospheric optics, describing the decomposition of a ray of white light into rays of different colors by means of a prism (Figure 1-1). Expanding de Dominis' ideas, Newton further explained the theory of the rainbow in nature.[3] The basic principles for understanding natural aesthetics in art and the use of color in artistic expression were further established by Runge's development of a color sphere that arranged and identified primary and secondary colors. Concepts of color culminated in the publication of Goethe's Theory of Color and provided guidance to the development and understanding of the principles of light and color.[4] The Swiss painter Itten expanded these ideas by stating, "Whoever would become a master of color must see, feel, and experience each individual color and the endless number of their combinations with all other colors. Colors are capable of spiritual-emotional expression."[5] Successful determination and transfer of color to an aesthetic reproduction of nature depends on these concepts.

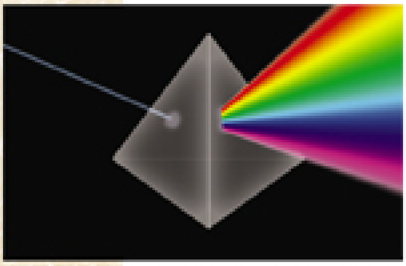

Figure 1-1. Newton's experiment in atmospheric optics demonstrates the decomposition of a ray of white light into rays of different colors by means of a glass prism.

A clear understanding of color allows the clinician to reproduce the natural dentition. The definition of color—as related to physics—does not possess the same significance as when applied to an artist's paints, since the compositional and emotional effects of color cannot be effectively quantified.[6] Therefore, a knowledge of color and the optical properties of teeth and restorative materials must also be developed to achieve consistent shade selection of all restorative materials.

Conventional Definition of Color

Most methods of describing color use a three-dimensional coordinate system that includes hue, chroma, and value.[7] Color spaces and coordinates are arranged in regular intervals and are represented by a sphere in the original Munsell Color System as well as the CIELAB Color System (Figure 1-2). These two systems are recognized as the standards for quantifying, reproducing, and conveying measurements of color.

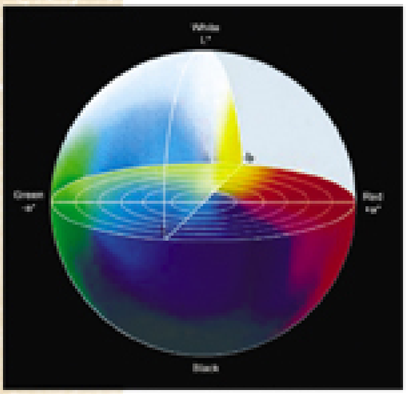

Figure 1-2. CIELAB color system modified.

The Munsell color order system specifies precise colors and identifies the relationship between each shade (Figure 1-3). Scales were also established to provide uniform steps for hue, chroma, and value using a collection of numerically identified colored chips. The Munsell notation, H V/C (Hue Value/Color), identifies the color of any surface by comparison to the chips under proper viewing conditions. While the Munsell color system has international acceptance, its design is focused on opaque surfaces. Accordingly, reliance on this system in dentistry is problematic due to the inherent translucency found in dentin and enamel.[8,9]

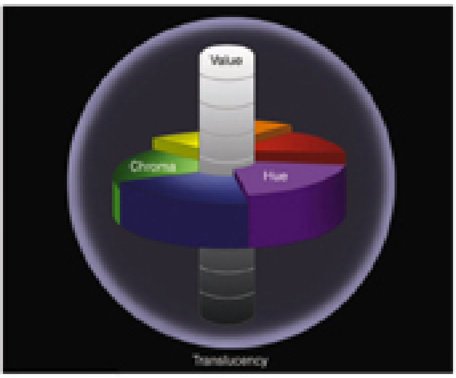

Figure 1-3. Munsell's color analysis modified, identifying the four parameters of hue, chroma, value, and translucency.

The current standard for evaluating and measuring color in dental research can be found in the CIELAB Color System (Figure 1-4). The independent variables are in the form of L*, a*, and b* coordinates and have been derived from mathematical calculations.[10] This system arranges all the color on one plane, on which the lightness value can be vertically altered. This plane is formed by the "a*" and "b*" coordinates, and contains a colorless neutral point. In the "a*" direction, +a* corresponds to red, while –a* is its complementary color, green. In the "b*" direction, +b* corresponds to yellow, while –b* represents its complementary color, blue. The chroma of each color is depicted by a radial axis that extends from the center to the periphery of the space. The vertical axis represents the light value coordinate (L*), which ranges from 100% brightness (white) at the top to 0% brightness (black) at the bottom of the sphere. The center of the sphere has low chroma colors, while the periphery demonstrates high chroma. Since the basic shade of natural teeth ranges between red, red-orange, and yellow wavelengths of the visible spectrum, the color space in this system would be defined between +a* and +b*.[5,11,12]

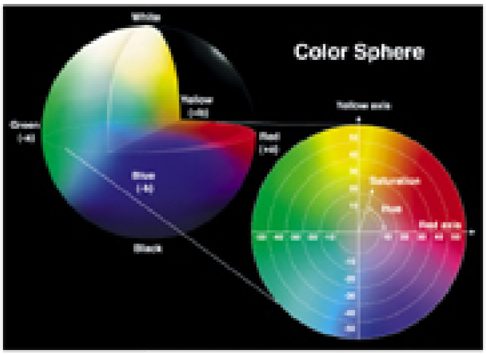

Figure 1-4. The L* a* b* color spaces and coordinates are derived from mathematical calculations and are arranged in regular intervals and presented by a color sphere.

Hue

Coordinates from spectral reflectance curves define how materials modify light by absorption, reflection, refraction, transmission, dispersion, diffraction, and interference.[13-15] In natural dentition, hue is referred to as the "name" of a color.[3] Hue corresponds to the wavelength of reflected light (Figure 1-5). As light passes through the natural tooth, it is reflected, refracted, absorbed, or transmitted by a multi-layered complex tooth structure that varies according to the optical densities of the hydroxyapatite crystals, enamel rods, and dentinal tubules.[16] Its stimulus to the eye is determined by these reflected or refracted wavelengths, which are transformed in the cerebral cortex into perceptions of color or hue.[1] In direct resin bonding, the hue is primarily determined by the selection of the "artificial dentin" or the underlying substrate. The hue of a tooth should always be identified under appropriate illumination with color-corrected light (~5000K).[3]

Chroma

The second characteristic, chroma, can be defined as the intensity of a color or the degree of hue saturation (Figure 1-6). The chromatic component only compares colors of equal hue.[17] The same hues are frequently found at the middle and cervical thirds, but distinct hues can be identified at the incisal third due to the way light is refracted, reflected, absorbed, and transmitted. In direct resin bonding, chroma can be varied in the utilization of internal characterization through the use of modifiers and tints.

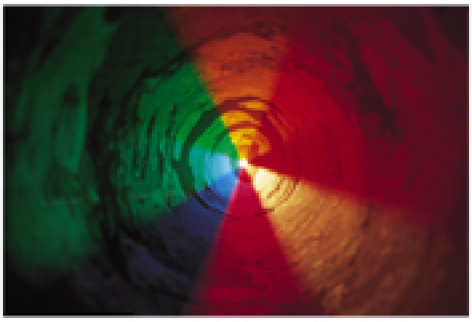

Figure 1-5. Hue and chroma can be determined by comparison of color photographs.

Value

The most easily discernible of the three primary optical characteristics—and the greatest influence on the other two characteristics—is value.[9] Value can be defined as the "brightness" of color (in the "Vita" scale, from the greater to lower value as with B1, A1, B2, D1, A2...C4) and it distinguishes light from dark colors (Figures 1-7 and 1-8).[9,17] In resin bonding, the selection and variation of the composite resin that reproduces the artificial enamel layer is a principal determinant of the value of a restored tooth.

Figure 1-6. Although the chromatic component of the wine in the glass [a] decreases in intensity as water is added [b], its hue remains the same.

Sterile definitions of hue, chroma, and value are useless, however, unless one grasps the relationships between and among these characteristics and develops the ability to quantify, reproduce, and convey these measurements of color.

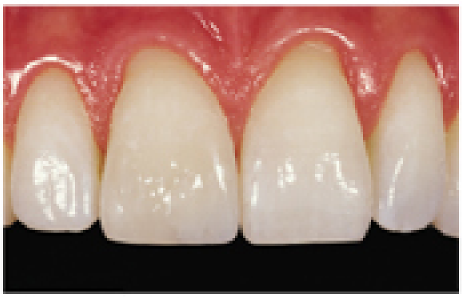

Figure 1-7. To determine the value of a restoration or tooth, a combination of color and black and white photographs is useful.

Anatomical Morphology and Color

In natural dentition, a tooth is rendered polychromatic as differing colors are distributed and various optical characteristics are observed through the enamel and dentin.[4] The polychromatic effect is manifested in various optical characteristics: hue, chroma, value, translucency, opalescence, iridescence, fluorescence, and surface gloss. The relationships between these different optical characteristics and their role in the natural dentition must be properly interpreted in order to fabricate aesthetic restorations.[18] Thus, a broader definition of color is necessary based on anatomy, optical properties, and polychromaticity to appropriately describe the color and aesthetics of teeth, and based on the natural dentition and the relative contribution of dentin and enamel to color.

Figure 1-8. The value of this restoration can be interpreted from a color photograph that is converted to black and white using Adobe Photoshop.

Dentin and enamel have drastically different optical properties, and the relative contribution of each should be considered separately in determining color. Most clinicians determine tooth color at the cervical third of the tooth. This portion of the tooth consists primarily of pulp and dentin, which contribute most of the hue and chroma of the tooth. The incisal third, which consists mostly of enamel, may or may not be considered. Tooth enamel, however, contributes significantly to the total aesthetics of the tooth, and the clinician must consider this in the fabrication of aesthetic restorations.

Translucency/Opacity

The translucency/opacity of a tooth has been viewed as the most important secondary property due to its influence on the quality and quantity of light reflected back to the eyes and its role in the aesthetic vitality of the tooth.[16] The structure and thickness of enamel and dentin, and the amount of light that penetrates the tooth or the restoration before being reflected, absorbed, and transmitted, determines the degree of translucency or opacity. Translucency plays a crucial role in light transmission. While dentin and enamel are translucent in natural teeth, enamel is almost transparent and colorless.[19] Enamel and dentin have different optical densities and, when light passes through enamel and strikes the underlying color of the dentin, it is reflected in all directions. The enamel is composed of rods that are surrounded by prismatic substances that are perpendicular to the dentin and act as conduits or transmitters of the underlying color reflected from the dentin. Therefore, translucency in teeth is affected by the way light is reflected and refracted by the enamel rods and the condition of the dentin (Figure 1-9).[16,19]

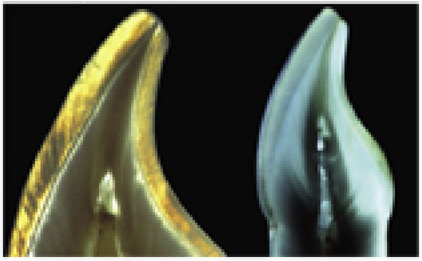

Figure 1-9. The secondary optical properties of the natural tooth are defined in terms of tooth anatomy.

Opalescence

Opalescence, another optical characteristic, is defined as the milky, white-blue iridescent appearance of a dense, transparent medium or colloidal system when illuminated by visible light (Figure 1-10). Opalescence is the light effect that occurs in the tooth when visible light is dispersed and refracted by microcrystals or colloidal inclusions that result in a reflection of the shorter, 0.4 to 0.5 wavelengths of light (bluish tones), the transmission of longer, 0.58 to 0.73 wavelengths (yellow-orange), and the absorption of medium, 0.5 to 0.57 wavelengths (greenish tones).[9] Therefore, opalescent characteristics impart a yellow/orange appearance under transmitted light from the inside of the mouth and a bluish appearance under reflected light from the facial aspect of the tooth or restoration. This effect can be seen in the incisal third of teeth and is predominant in adolescents.[16]

Figure 1-10. Aesthetic translucency is evident at the incisal edge and at the mesial and distal incisal angles of the maxillary central incisors.

Opalescence is primarily observed in the essentially colorless and transparent enamel. Since the color of dentin is dominated by light absorption and reflection creating a yellow-orange appearance and masking opalescent effects, opalescence is not readily discernible in dentin structures. Opalescence in teeth appears as a light scattering effect that is associated with the diameter of enamel rods.[20] In posterior teeth, these characteristics are exemplified on cusp tips and marginal ridges. In anterior teeth, this effect is observed in the incisal edges and proximal incisal surfaces (Figure 1-11).

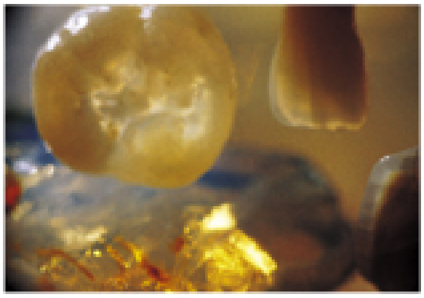

Figure 1-11. The opalescent characteristics of the tooth impart a yellow-orange appearance under transmitted light and a bluish appearance under reflected light.

Iridescence

The Merriam Webster Dictionary defines iridescence as "A lustrous rainbow-like play of color caused by differential refraction of light waves (as from an oil slick, soap bubble, or fish scales) that tends to change as the angle of view changes" (Figure 1-12). The color fluctuates with very small differences in viewing direction, location, and illumination. Differing degrees of iridescence are visible based on wavelengths of dispersion, interference, and diffraction of light.[21]

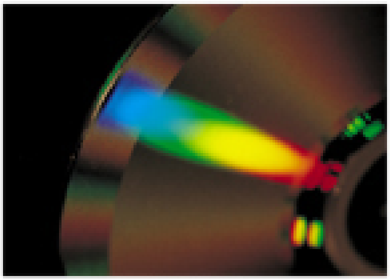

Figure 1-12. Varying degrees of iridescence can be observed based on the direction, location, and illumination of an object.

Fluorescence

Fluorescence is an optical characteristic in which absorption of ultraviolet (UV) rays of light and the subsequent emission of blue or white visible light occur. Fluorescence is primarily found in the dentin because of its organic composition. After penetrating the enamel and reaching the dentin, the UV light rays excite the photosensitive dentin. For the fluorescence to occur, the emission must take place within 10^{-8} seconds of activation.[8,22] The emitted light enhances the brilliance and vitality of teeth, causing both dentin and enamel to fluoresce, further increasing the whiteness or value of the dentition. In nature, this effect is created by the UV rays of sunlight (ie, short wavelengths), which are invisible to the human eye. Natural teeth exposed to UV light rays exhibit fluorescence with an emission spectrum that varies from intense white to light blue, and is observed in the yellow-orange spectrum and detected in the middle third of anterior teeth (Figure 1-13).[22-24]

Figure 1-13. Natural teeth exposed to ultraviolet (UV) light rays possess fluorescence with an emission spectrum that varies from intense white to light blue.

Surface Gloss

The surface morphology of natural teeth influences their surface gloss as well (Figures 1-14 and 1-15). A coarse tooth allows diffused reflection, whereas a smooth surface facilitates specular reflection.

Perception of Color

The primary prerequisites for color perception include three variable elements: the object, a light source for illumination, and an observer (ocular or instrumental).[3,25,26] Additional factors that can influence the perception of color include: the angle of observation, light and dark adaptation, the size of the field of view, and surrounding colors.[26] The relationship between the primary prerequisites of this color triad (object, light source, and observer) is one form of the color experience known as "conscious color perception,"[9] and a change of any one of the triad can result in a change in the perception of color.[26]

Figure 1-14. Surface morphology of natural teeth influences the surface gloss and color perception. Note the diffuse reflection produced by the micromorphologically roughened or coarse surface.

Light Source

Color perception depends on the quality of light illuminating the object. This light source can consist of daylight or artificial light and may be direct or reflected.[27] The quality of light can be described according to the color temperature in Kelvin (K) and spectral energy distribution in relative energy at each wavelength.[8,28] The incandescent bulb (tungsten filament) is considered "warm" and emits white light that contains red, yellow, or orange wavelengths, while the blue portions of the visible light spectrum (400 nm to 450 nm) are mainly missing.[10,25] Therefore, if a red, yellow, or blue material is illuminated, the red and yellow shades will be strong and highly saturated, while the blue appearance will be weak and low in saturation. "Cool" light sources, which include clear mercury lamps and white fluorescent tubes, produce white light that contains blue and green wavelengths of the spectrum and are deficient in red. When illuminating red, yellow, and blue shades under these conditions, the red will appear desaturated, the yellow will be less saturated, and the blue will be strong and highly saturated.

Figure 1-15. The flat or smooth surface allows specular reflection.

With fluorescent sources, the peaks in energy emitted across the spectrum from the mercury gases used to stimulate the phosphors may result in color distortion.[25,28] In dentistry, viewing a restoration in each of these lighting conditions will alter the perceived shade so that a Vita B-shaded restoration (orange-yellow) appears natural (orange-yellow) in color-corrected light, blue-white in fluorescent light, and orange in incandescent light (Figure 1-16). This phenomenon is illustrated by the illumination of a red tomato with a white light. The fruit will appear red, because the tomato has selectively absorbed sufficient amounts of all other wavelengths other than the red, which allows red energy to be reflected to stimulate the observer's eye (Figure 1-17). In illuminating the same red tomato with a green light, however, the observer will see a darker and brownish-gray color, because of the lack of sufficient red wavelengths in the green light to be reflected. This phenomenon is termed "color rendition."[8,29] The eye will only perceive colors that are contained in the illuminating source.[25] Therefore, the optimum light quality to distinguish subtle color differences is Cloud-Diffused North Noon Daylight because it provides a uniform spectral power distribution and a color temperature of 5,000 K.[9,28] The quantity of light source should be approximately 1500 lux, which is equivalent to four 220-watt color-corrected fluorescent tubes at a

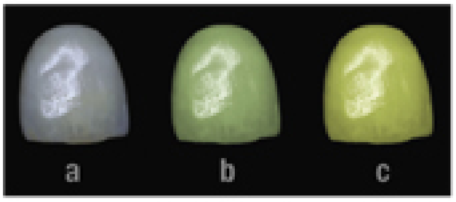

Figure 1-16. Observing the same restoration in different lighting conditions (eg, color-corrected light [a], fluorescent light [b], and incandescent light [c]) alters the perceived shade.

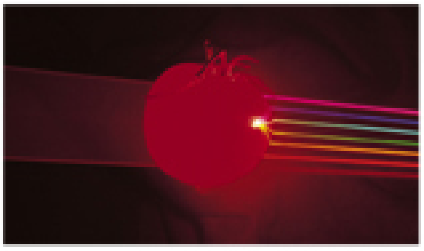

Figure 1-17. Tomato appears red since it selectively absorbs sufficient amounts of other wavelengths of the visible spectrum (right side) except for the red wavelength, which is reflected to the observer.

distance of 2 meters.[23] There are several color-corrected light sources available to provide the proper quality and quantity for a more ideal spectrum balance to prevent inaccurate aesthetic shade matching in the laboratory and dental environments.

The Object

Objects have the ability to modify light waves as well.[25] Color is a physical property of the light that is modified by the object, and the total appearance of the material depends on the object's capacity to modify the color of the incident light.[25,30] Color appears because the material absorbs the radiating visible light, with the exception of the wavelength reflected to the viewer's eyes. As previously discussed, the reflective surface of the object can influence the perception of color.[27,31] A transparent medium will allow visible light to pass through almost unaltered. Translucent objects scatter, transmit, and absorb portions of wavelengths of visible light, while opaque materials do not transmit, but reflect and absorb various wavelengths of visible light (Figure 1-18). Highly reflective surfaces make colors appear lighter and closer to the viewer.[27] The degree of diffusion of the wavelengths of visible light striking the object can also be affected by surface gloss, texture, and curvature.[25,32]

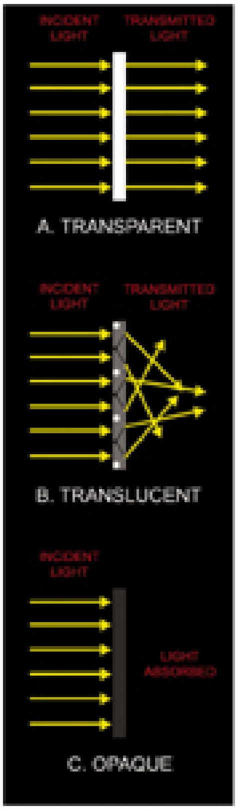

Figure 1-18. A reflective surface can influence the perception of color. A transparent medium allows visible light to pass through almost unaltered [a]. A translucent medium scatters, transmits, and absorbs portions of visible light [b], and an opaque medium does not transmit light but reflects and absorbs various wavelengths of visible light [c].

The Observer

Visible light enters the eye through the transparent area of the cornea, and is focused by the crystalline lens on the retina. The retina is composed of two types of specialized photosensitive cells and is the receptor system for vision. These specialized receptor cells are called rods and cones, and they contain photosensitive pigments.[8,10,25,27]

Cone cells comprise the majority of receptor cells in the macula lutea, which is the focal area of vision on the retina and is located along the optical axis. These cones cells are divided into three types that contain different forms of the photosensitive pigment opsin with spectral sensitivity to the wavelengths of the three primary colors—blue (wavelength of 448 nm), green (wavelength of 528 nm), and red (wavelength of 567 nm).[8,10,27] Because of the presence of these three different light-sensitive pigments, human vision is primarily trichromatic. The proportionate intensity of the stimulation at these three receptor cells determines the impression of the color in the brain.[10] When visible light stimulation occurs, the pigments are photodecomposed to create an electrical impulse for nerve excitation. A phenomenon called cone cell fatigue occurs when cone cells are overstimulated by staring at a colored object for long intervals. The cells produce a negative afterimage in the complementary color.[25] In dentistry, cone fatigue can be useful in enhancing efforts at color-matching. The basic shade of natural teeth varies from white-yellow and yellow-orange to orange-brown.[33] The complementary color to a yellowish hue is blue; therefore, the cone cells can be sensitized to the appropriate color range by staring at a blue card or object for several seconds.

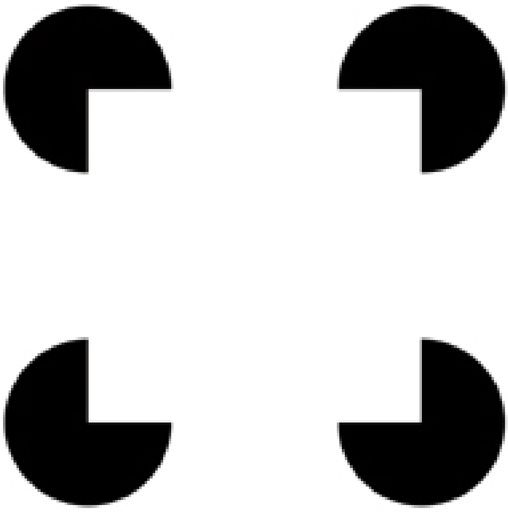

Figure 1-19. The creation of a mental concept (a complete square) results from the complex central nervous system's interpretation of retinal stimulation.

Information from the retina is relayed via the optic nerve to the visual cortex, which is located in the posterior pole of the occipital cortex. The images are processed in several stages by many interconnected cortical areas. The left hemisphere senses shapes and colors and relays the information via a communication channel, the corpus callosum, to the right hemisphere for conceptual interpretation.[25,34] The brain converts the images into a unified visual perception, or gestalt, using complex computations from past experiences and, while the mind is not aware of this computational event of visual consciousness, it responds to the effect.[8,35,36] As an example, the following figure, known as a Kanizsa square, gives the illusion of a complete square despite the obvious absence of luminence differences necessary to make a complete figure (Figure 1-19).

Therefore, it becomes apparent that visual perception is more than just light striking and activating the neuro-ophthalmologic axis; it involves the creation of a mental concept resulting from the complex central nervous system interpretation of retinal stimulation.[8,25,28]

Subjective Approach

The subjective approach is considered a means of color comparison to a standard (eg, shade guide) or to a sample of the restorative material, which can be used as a reference to describe the position on the tooth that the color should be placed. This may require a combination of several shade tabs from multiple shade guides to reduce the coverage error component during shade determination.[37] While the subjective approach continues to be the most common practice of color determination,[38] it is limited in that the perception of color can vary between individuals and even the eyes of the same individual.[39-42] These findings support the importance of patient involvement and self-assessment to ensure patient satisfaction as the final treatment goal.

Instrumental Color Determination

Another method for color determination in dentistry is computer-aided color imaging/analysis. Instrumental measurements (eg, with digital cameras, spectrophotometers, or colorimeters) of subtle differences that occur in varying degrees, angles, and areas of the teeth can quantify color for a more uniform, repeatable, and precise objective assessment. This objective approach overcomes many of the previously discussed human factors for error in visual color determination.

Digital cameras provide a mathematical analysis by measuring the appearance of color images. One system (ShadeScan, Cynovad, Montreal, Canada) analyzes tooth images and objectively infers their appearance properties based on color and translucency. This digital image can be cross-referenced with a database of shade tabs and guides (ie, Vitapan 3-D Master, Vident, Brea CA; Chromascop, Ivoclar Vivadent, Amherst, NY). Such systems yield an objective analysis of translucency and opacity distributions, texture, and a detailed visual description of the differences in hue, chroma, and value.

The spectrophotometer measures the fundamental reflectance of an object across the visual light spectrum. This technology is most commonly used in the research of dental materials and is the most accurate measuring device for shade evaluation.[26,43] Spectrophotometers use multiple data point references of information from across the visible light spectrum (300 nm to 800 nm) to extrapolate color determination (Spectro Shade, MHT International, Newton, PA).[44,45] The spectrophotometer can determine CIE Lab or CIE Lch values, which allows it to be used to calculate metamerism.[46] Another spectrophotometer-based shade determination system (Shade Eye EX Chroma Meter, Shofu, Menlo Park, CA) measures only single-point sources of reference of information to extrapolate color determination.

Studies have indicated there is significant variation in the data obtained from the human eye to the results from the colorimeter.[43,47] A colorimeter is designed to directly measure color as perceived by the human eye. As light is projected in the additive spectral colors of red, green, and blue (RGB), the color wavelengths in the visible light spectrum are measured with great accuracy. These devices are trichromatic and can also measure in CIE Lab or CIE Lch. Precise colorimeter is difficult to design, however, because the filters must be carefully controlled and the characteristics of the light source must be maintained. Any alterations can cause inconsistent color determinations over time.[17,46,48] One colorimeter system (ShadeVision, X-rite, Grandville, MI) filters light in three or four areas of the visible spectrum to determine the color of an object.

Both methods of color determination, visual and instrumental, provide the clinician and technician with alternatives to enhance their color-matching skills. Beyond color matching skills, the process of aesthetic shade determination for a resin restoration requires a further mastery of color analysis, communication, interpretation, fabrication, and verification.[17]

Controlling Color Variables

Many other factors contribute to the perception of color, influence the triad of color, and should be considered during shade determination. These variables include the viewing angle of observation, light and dark adaptation,[26] the size of the field of view, previous eye exposure/fatigue,[49] environmental and lighting conditions,[17,29,30-32] and environment changes (ie, dehydration, temperature changes of light). Also involved are surrounding colors, physiological and psychological responses to radiant energy stimulation,[32-34] patient's clothing and makeup,[42] metamerism,[23,26,27,40] mood, drugs and medications, age and gender. While time and space prevent a thorough discussion of each, all factors should be given weight in final shade determination or aesthetic shade matching.

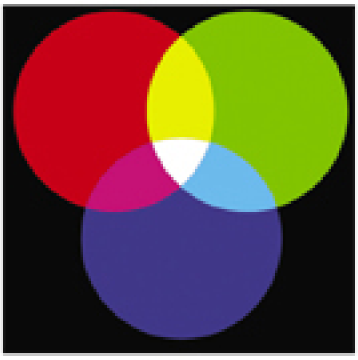

Figure 1-20. The primary spectral colors: red, green, and blue. A combination of all three primary spectral colors produces white light through "the additive theory."

Additive and Subtractive Theories of Visible Light

When light "paints" an object, it adds the light rays of different colors. The primary colors of the human visual system are red, green, and blue (Figure 1-20). Combining any of these three colors yields a wider range of colors than can be reproduced by any other three colors. A combination of all three primary colors will produce white light through the "additive theory," but only for light transmission—not for pigments.[27] These primary colors follow the principles of additive color mixing when combined in equal amounts to make the secondary colors of the human visual spectral system (Figure 1-21).

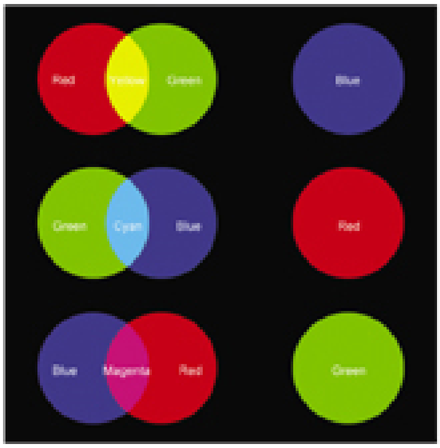

Figure 1-21. The primary spectral colors follow the principle of additive color when combined in equal amounts to make the secondary colors (left) of the human visual spectral system. The secondary spectral colors are deficient one primary spectral color, which is their complementary color (right) and recombines in equal ratios as white light.

- **blue light + green light = cyan**
- **red light + blue light = purple (magenta)**
- **green light + red light = yellow**

The secondary color is the complement of a primary color.

- **White – red = cyan**
- **White – green = purple (magenta)**
- **White – blue = yellow**

Every primary color is the complement of a secondary color.

- **White – cyan = red**
- **White – magenta = green**
- **White – yellow = blue**

Combining complementary colors of light of equal quantities produce white light.

- **Red + cyan = white**
- **Green + magenta = white**
- **Blue + yellow = white**

Figure 1-22. Primary color pigments are the secondary colors of the human visual spectral system—cyan, purple (magenta), and yellow. A combination of all three primary pigments in a certain ratio will produce black.

The opposite occurs when mixing pigments. The secondary colors of the human visual spectral system are classified as the primary color pigments (Figures 1-22 and 1-23).

- **Cyan**
- **Purple (Magenta)**
- **Yellow**

These primary pigments follow the principles of subtractive color mixing when combined in equal amounts to make the secondary color pigments.

- **Cyan + magenta = blue**
- **Magenta + yellow = red**
- **Yellow + cyan = green**
- **Cyan + magenta + yellow = black**
- **no pigment = white**

While the primary colors of the painter's color wheel are red, yellow, and blue (similar to primary pigments), a greater range of colors can be reproduced using cyan, magenta, and yellow than with red, yellow, and blue.[4,55]

Figure 1-23. The primary pigment colors follow the principle of subtractive color mixing (when combined in equal amounts) to make secondary color pigments (left). These secondary color pigments lack one primary pigment color, which is their complementary color (right) and, mixed in a certain ratio, produce black.

Reflection, Refraction and Light Transmission

When light rays strike an object, the light is reflected at the same angle as the angle of incidence. The angle of refraction is proportional to the refractive indices of the materials crossed by the light ray. When light rays are completely reflected by the surface, the angle of incidence exceeds the angle for which all rays will be reflected, known as the critical angle. This event explains the whitish areas that appear on teeth. The white demarcations at the incisal edge of teeth, known as the "halo effect," are the results of the total reflection of light rays from these areas (Figure 1-24).[9]

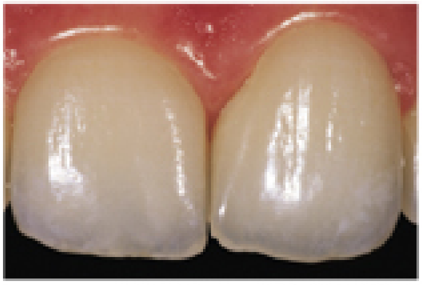

Figure 1-24. White demarcations at the incisal edge of these maxillary central incisors are known as "the halo effect." They result from total reflection of visible light rays from these areas.

Surface geometry modifies the visual aspect of the surface. When light strikes a smooth, flat, opaque body, the reflected rays will be parallel. If the surface is rough, there will be scattering of these reflected rays. When light strikes a smooth, flat, transparent medium, the transmitted rays will be parallel. If the transparent medium is rough, the transmitted rays are directed in multiple directions or diffused (Figure 1-25). The optical scattering of light has an effect on color perception and should be considered during shade matching between a restorative material and natural tooth. Accordingly, the surface characteristics of teeth and restorative materials have a considerable impact on the reflection of light, which influences the surface gloss, and plays a significant role in the appearance and vitality of teeth and aesthetic dental materials.

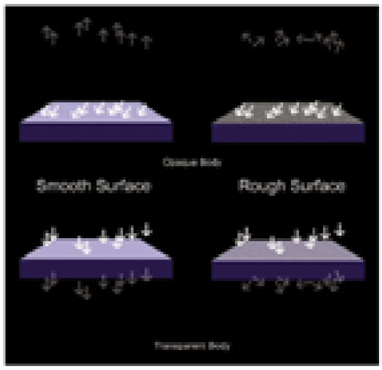

Figure 1-25. When light strikes a smooth, flat, opaque body, the reflected rays will be parallel. When the surface is rough, there will be scattering of these reflected rays.

Metamerism

Metamerism occurs when the perception of color of two objects is different because one of the variables of the color triad (object, light source, or observer) is altered while the other two remain the same.[23,26,27,40] There are two types of metamerism: object metamerism and observer metamerism.[23]

Object metamerism occurs when the two items appear the same in one lighting condition, but appear differently when the light source is changed.[36] To prevent metamerism, objects should have the same spectral reflectance curves, since only materials with identical spectral energy distribution curves will match under all light sources (Figure 1-26).[26] Color match does not require the light source and object to have the same reflectance spectrum. Therefore, to obtain an acceptable shade determination, it is advisable for the viewer (technician, clinician, and assistant) to observe the color matching under three different lighting conditions—daylight, color-corrected light, and dim light.[9,26,29]

Figure 1-26. The color coordinates of the custom shade tab and the maxillary dentition are identical in both images. The tab and the natural teeth, however, appear to match under one lighting but not under a different light source. The metamerism is attributed to the different spectral energy distribution curves of each object.

Observer metamerism occurs when the light source remains the same and the observer changes, caused by either human visual stimulus or instrumental stimulus. Since color perception is dependent upon physiological spectral response sensitivities of the cones in the fovea and psychological interpretation by the brain, it is recommended that a third observer (assistant, technician, friend, or family member) evaluate the selected color prior to cementation of any final restoration.[9,23]

In instrumental visual stimuli, color perception is dependent on the illumination, measuring modes, and the type of light source. Spectrophotometers, for example, operate using two different measuring modes: specular component included (SCI) mode and specular component excluded (SCE) mode. When using instrumental color measurements, the methods employed should be standardized because the resultant color coordinates may depend on the mode that is being used.[37]

Contrast

The phenomenon known as contrast effect can alter the perception of color and one's ability to evaluate color. The utilization of colors in dentistry requires an understanding that value, chroma, and hue contrasts between an object and its surrounding background can influence color perception. Simultaneous contrast occurs when two objects are observed simultaneously and can be subdivided into three categories: hue contrast, light/dark contrast, and chroma contrast.[37]

Simultaneous hue contrast is discerned when two chromatic colors are combined and the perceived hue varies closer to the complementary color than to the surrounding background. Each color appears to modify the other in the direction of its complementary or afterimage. When the colors to be combined are closer to being complementary colors, they appear more intense and vibrant (Figure 1-27). The clinical significance of this phenomenon occurs as was previously discussed in sensitizing the cone cells to blue prior to shade taking in order to see tooth shades more discriminately. In shade determination for dentistry, the perceived color of an object is influenced by the color of the surrounding background.[23] Therefore, an ideal environment for proper color assessment is when the surrounding background is neutral gray.

Figure 1-27. The closer the colors to be combined are to the complementary colors, the more vibrant they appear from mutual repulsion.

Simultaneous light/dark contrast[26] or brightness or lightness constancy[23] occurs when the relative brightness of an object is affected by the brightness of the contrasting surrounding background. This can be demonstrated when the same shade tab of equal value is placed on a black and white background. The shade tab on the white background will appear darker or lower in value because the background reflects more light than the shade tab, whereas the shade tab on the black background appears significantly lighter or higher in value because the background absorbs more light than the shade tab (Figure 1-28). The clinical significance of this phenomenon occurs during the shade selection process of a tooth with the black oral cavity as the background, which causes the tooth and shade tab to appear lighter. To avoid this visual illusion, value should be determined with a surrounding neutral gray background.[23]

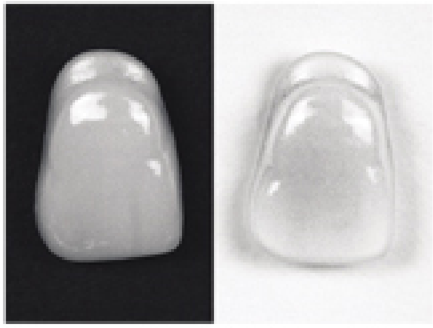

Figure 1-28. Simultaneous lightness contrast or brightness or lightness constancy can be demonstrated by a shade tab of equal value, which appears brighter or higher in value on a black background and darker or lower in value on a white background. This illusion is similar to chromatic adaptation.[23]

Simultaneous chroma contrast follows the effects generated from hue and light/dark contrast. For example, the image against the gray background appears brighter (light/dark contrast) since it has low chroma, whereas the image against the same hue background appears dull (light/dark contrast) from the increase in chroma of the background and the blue presence in tone (hue contrast) (Figure 1-29).[37]

Adaptation

Sensory adaptation is a reduced sensitivity of the eye to a continued or unchanging stimulus.[23] Chromatic adaptation occurs when an object is viewed in two different light sources and is perceived as the same color. This can be illustrated when a white card is perceived in the daylight as white and later, under incandescent light, the card appears the same color. Such a condition occurs because the brain stores the color of the object in short-term memory, then recalls the initial memory of the color of the object, and automati-

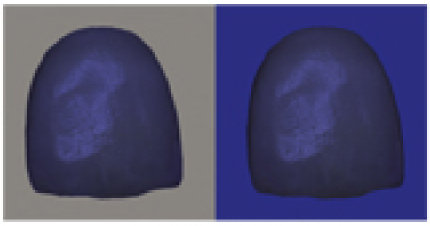

Figure 1-29. Chroma contrast effects are influenced by light/dark contrast and by hue contrast. Note that the color of the background is close to the color of the tooth, muting the color of the tooth.

cally assigns the same color. To prevent the influence of chromatic adaptation during color matching, the object must be viewed within a minimum threshold of time. The brain requires the image to be visible for 60 ms to 70 ms for the eye to detect a stimulus. The chromatic assessment period is the maximum amount of exposure time that can occur without the influence of chromatic adaptation. The maximum time interval is 5 seconds, and shade determination should be performed within this time interval to prevent an inaccurate shade match.[23]

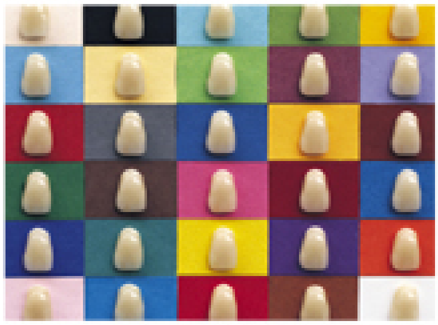

Figure 1-30. Although the shade tab remains constant, the perceived color is altered by the reflected hue of each background.

Environmental Influences

The setting in which an object is viewed can influence the perceived color. The background and surroundings can affect the saturations and the hues perceived (Figure 1-30). The patient's complexion, make-up, and even reflection from the operatory equipment and walls can modify the color of the oral environment and the shade sample, which can influence the shade determination. Therefore, it is advisable to remove the patient's make-up and utilize a neutral gray background in the operatory to reduce the influence of surrounding colors and to prevent an inaccurate shade determination (Figure 1-31).[23,25]

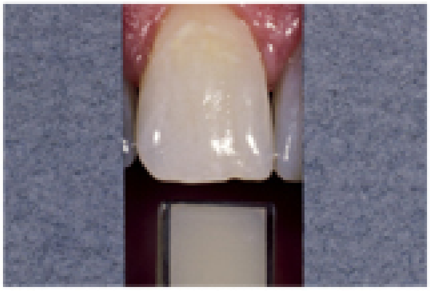

Figure 1-31. A neutral gray background is used in shade determination to reduce the influence of surrounding colors.

In the general population, color defects occur in 8% of males. One study found that 9.9% of dental professionals had some form of color deficiency.[38] These findings suggest that it would be prudent to screen the restorative team (assistants, technician and clinician) for color blindness deficiencies.[25,32,34]

The successful determination and transfer of color to an aesthetic reproduction of the natural dentition relies on many interdependent relations. The restorative team's understanding of the optical characteristics of light, the anatomical morphology of the tooth, the interrelation of the optical properties of light with the different refractive indices of the tooth structure, and the restorative material, may still be hampered by physical and psychological limitation. By developing the senses through observation, one can begin to notice the variations in the parameters of these optical properties that produce the infinite possibilities of color rendering and the polychromatic effect within the tooth and restoration.

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