Color Science and Shade Selection in Operative Dentistry

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Editor

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Essential Elements for Clinical Success

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Preface

This book aims to provide information and guidance on color selection and color matching in Dentistry.

Generally speaking, color science has always been an essential and trending topic in Dentistry but never fully explored. Color science in Dentistry is usually briefly explored in book chapters. This book is looking forward to fully exploring all theories and clinical guidance to fulfill clinical success.

This book is addressed to all groups from undergraduate to postgraduate students, clinicians, and researchers. The content embraces to attend all groups but written in a way all groups can understand. The topics include the basic color science concepts till bleaching, color selection, color matching using schematic drawings, and the many different restorative techniques using resin composites and stratifications, and much more.

I appreciate all authors for their contribution to this book, their effort, and their dedication that made it all possible. It was a pleasure to collaborate with such an amazing group. Thank you so much for making this book come true!

Gainesville, FL, USA Dayane Oliveira

Contents

1 Color Science

Dayane Oliveira and Mateus Garcia Rocha

1.1 Color Definition

"Color is defined as the property of producing a visual perception as a result of the way an object reflects or emits light." Although it seems simple, color is best described as an abstract science in which it appears to be highly subjective.

In 2005, neuroscientists from University of Rochester had found that the number of color-sensitive cells in the human retina differs among people by up to 40 times; yet people appear to perceive colors the same way. These findings indicated that visual perception of color is controlled much more by the human brain than the eyes [1].

A practical example of the influence of the human brain on visual perception is shown in Fig. 1.1. Observing the square, how many shades do you see? If you see two different shades of gray, cover the line blocking the darker and lighter shading across the middle, and your brain will begin to realize that the cube actually has only one shade. This is a color illusion from Tom Cornsweet, who is best known for his work in visual perception. Color illusions are images where the surrounding colors trick the human brain into an incorrect interpretation of color [2].

Indeed, the visual perception of different colors is a subjective process whereby the brain responds to the stimuli that are produced by color-sensitive cones localized in the human retina. However, it proves the importance of color education in Dentistry [3].

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1.2 Color and Its Dimensions

Color can be specified based on three color appearance parameters, also known as the three color dimensions: hue, value (or lightness), and Chroma (Fig. 1.2).

1.2.1 Hue

Hue is defined as the visual perception of the stimuli of a wavelength. As illustrated in Fig. 1.3, the main pure hues are red, blue, and yellow. The main pure hues are also called primary colors. However, the mixture of pure hues can generate different visual perception stimuli, also called secondary colors. For example, the mixture of blue (primary color) and yellow (primary color) generates the visual perception of green (secondary color). The mixture of a primary color and a secondary color can also generate a different visual perception stimulus, called a tertiary color.

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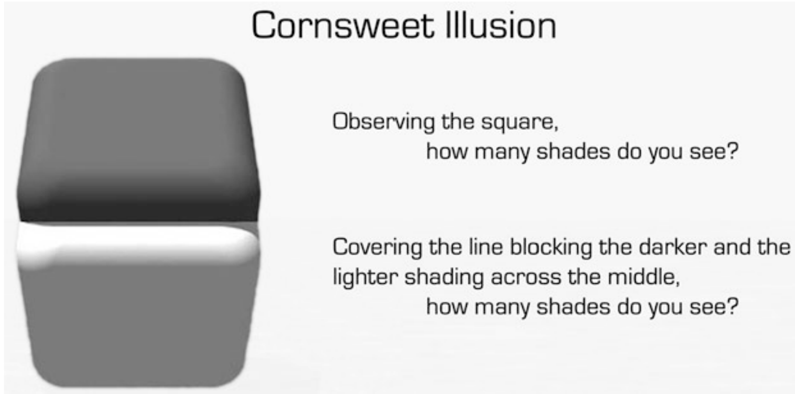

Fig. 1.1 Cornsweet illusion: color illusion designed by Tom Cornsweet

1.2.2 Value

Value, also known as lightness or tone, is referred to the lightness or darkness of a color. In other words, it indicates the quantity of the light that is reflected.

1.2.3 Chroma

Chroma is defined as the purity, intensity, or saturation of a color. Thus, a lower Chroma would indicate less intensity of the color, as in pastel colors. In contrast, a higher Chroma is related to more vivid color.

1.2.4 Translucency

Translucency is the physical property that allows light to pass through the material. The material can be considered transparent, translucent, or opaque according to the degree of light that is transmitted rather than absorbed or reflected (Fig. 1.4). When the material allows most light to pass through it, it is considered transparent. This means that it is possible to clearly see through it. On the other hand, when the material allows some light to pass through it, it is considered translucent. This means that it is still possible to see through it, but not as clearly. Last, when no light is able to pass through it, the material is considered opaque. This means that it is not possible to see through it.

Clearly, a mistake in translucency may compromise the natural appearance of a restoration in comparison to the natural teeth as the background changes. This is the reason why some authors describe translucency as the fourth dimension of color [4].

1.3 Color Perception

Color is not a property of light, but the visual perception of light by an observer. In order for the color to be perceived, three elements must be simultaneously present: illumination, an object, and an observer.

1.3.1 Light

1.3.1.1 Concepts of Illumination

Although white light is colorless to the human eye, it contains all colors in the visible wavelength spectrum (Fig. 1.5). Thus, when the white light hits an object, the different wavelengths can be absorbed, transmitted, or reflected. The reflected wavelengths will be responsible for the color perception of the object (Fig. 1.6).

However, different light sources can emit different wavelengths. This means that not all visible wavelength spectra are being absorbed, transmitted, or reflected by the object under different light sources. Thus, the color of one object can look different under different illumination.

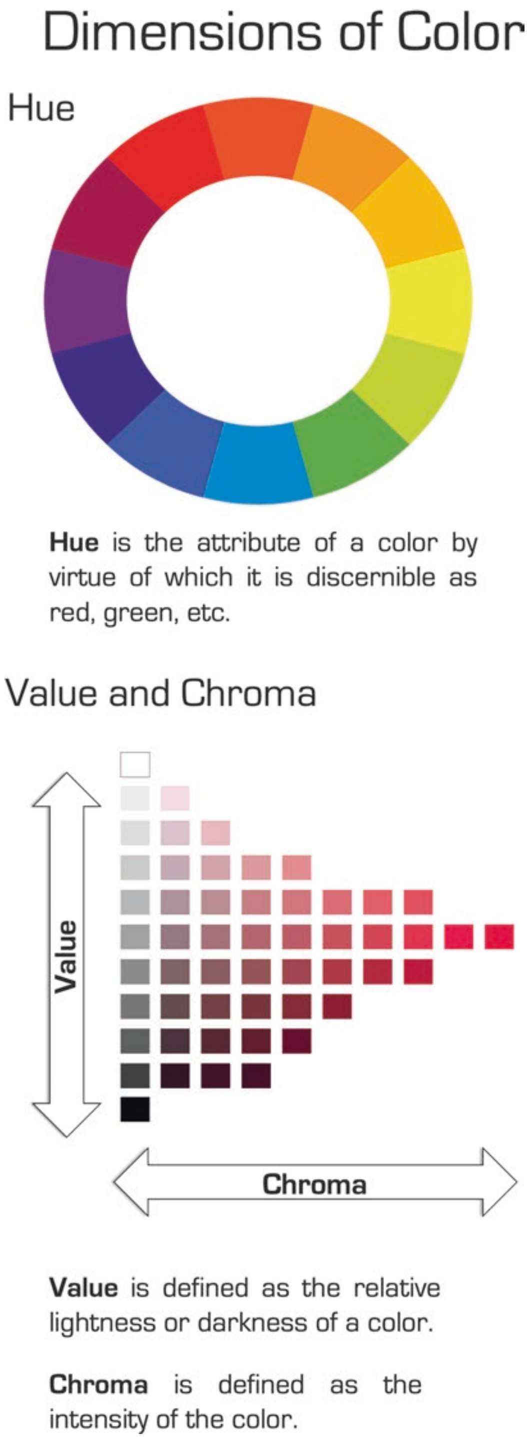

Fig. 1.2 Color dimensions: hue, value, and Chroma

1.3.2 Object

As previously explained, when the light hits an object, the different wavelengths can be absorbed, transmitted, or reflected, and the reflected wavelengths will be responsible for the color of the object (as illustrated in Fig. 1.6). It means that when the object is yellow, it absorbs and/or transmits all wavelengths, but yellow, which is reflected.

1.3.2.1 Light Reflection, Light Absorption, and Light Transmittance

> As stated by Lavoisier, in nature, nothing is created, nothing is lost, everything is transformed.

The understanding of light reflection, light absorption, and light transmittance through an object follows this rationality.

The light reflection is the change in the direction of the electromagnetic radiation at an interface between two different media. Technically, different media have different refractive indexes. The refractive index is the ratio of the speed of light in the vacuum to its speed in a specific medium. Higher the difference between the refractive indexes of the two mediums, the higher the light reflection.

Then, the amount of electromagnetic radiation that is either not reflected is absorbed or transmitted through the object. The light absorption is defined as the electromagnetic radiation energy that is transformed into the internal energy of the object (also called absorber). The reason the electromagnetic radiation is absorbed by the object while trying to pass through the object is that when it vibrates, the electrons interact with neighboring atoms in such a manner as to convert its vibrational energy into thermal energy. Thus, the light wave with that given frequency is absorbed by the object, never again released in the form of light. In contrast, the light transmittance is the electromagnetic radiation energy that was not reflected nor absorbed, being able to pass

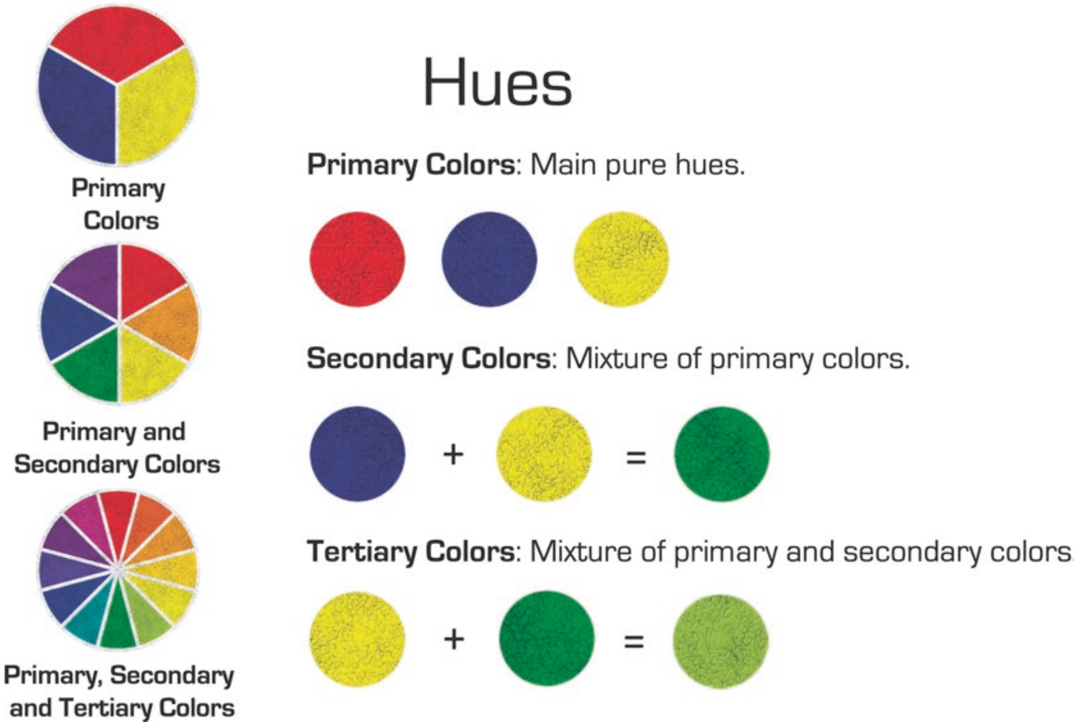

Fig. 1.3 Hues: primary, secondary, and tertiary colors

Fig. 1.4 Definition of transparency, translucency, and opacity

through the object. And in the end, how an observer perceives an object's color depends on which wavelengths are reflected by this object.

1.3.2.2 Opalescenceand Counter-Opalescence

As previously mentioned, objects can be transparent, translucent, or opaque according to the degree of light that is transmitted rather than absorbed or reflected (as illustrated in Fig. 1.4). In highly translucent materials, the light that is scattered through the material can create dichroism, in which the material appears blue from the front side (opalescence), but yellowish-red shines through the backside (counter-opalescence) (Fig. 1.7). This phenomenon occurs due to a specific type of light scattering known as the Tyndall effect. Under the Tyndall effect, the longer-wavelength light, yellow-red, is more transmitted while the shorter-wavelength light, blue, is more reflected.

Enamel is a highly translucent tissue responsible for the opalescence of the incisal halo. This

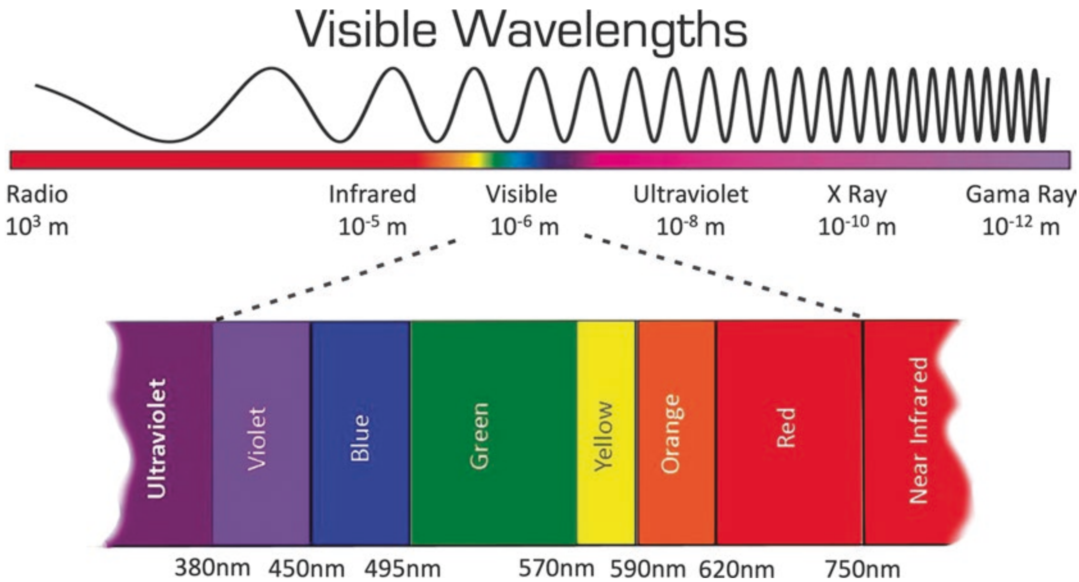

Fig. 1.5 Visible wavelength spectrums and color perception

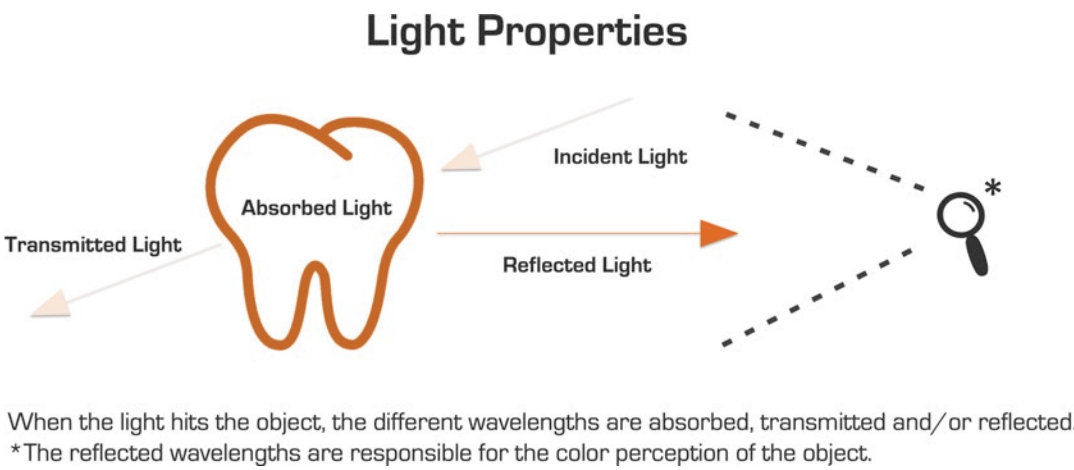

Fig. 1.6 Light absorption, reflection and transmission, and color perception

effect is not perceptible in the cervical and medium thirds of the teeth due to the presence of dentin in between, which is highly opaque [5, 6]. However, in the incisal third, it is possible to observe an opalescent halo that follows the incisal outline of the mamelon of dentin. Specific composites called “translucent” or “opalescent” can be used to reproduce this effect.

Also, the translucent multilayering characteristic of the teeth can make its color be perceived differently at different angles. This phenomenon is called goniochromism [7].

1.3.2.3 Fluorescence

On the other side, the dentin is responsible for another natural effect in the tooth: fluorescence. The fluorescence is the emission of a visible wavelength after absorption of radiation in the ultraviolet region of the spectrum, which is invisible to the human eye. Then, when exposed to ultraviolet light, the fluorescence of dentin gives a distinct color that glows. Thus, if the restorative material did not have this property, the difference between the natural teeth and the restorative material would be perceived when exposed to ultraviolet light (Fig. 1.8). However, nowadays, all dental composites have fluorescence properties due to the addition of rare earths to the composition.

1.3.3 Observer

1.3.3.1 Visual Phenomena

The human eye is responsible for capturing stimulus from different wavelength spectra of light and discharging nerve impulses that are conducted to the brain. There are three types of cone cells in the human eye that are more sensitive to either short (blue), medium (green), or long wavelengths (red) (Fig. 1.9).

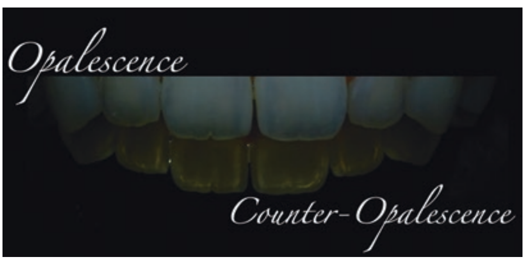

Fig. 1.7 Tyndall effect: opalescence and counter-opalescence

Despite called “blue,” “green,” and “red” cone cells, each type of cell does not sense only one color but a broad range of wavelengths in varying degrees of sensitivity. Because of this, different specific selective cones can be stimulated by similar wavelength spectra but in different levels. Thus, when the cone cells are exposed to a certain wavelength spectrum, the most sensitive cone cell for this specific wavelength spectrum is stimulated first.

1.3.3.2 Visual Fatigue

However, as previously mentioned, when a specific selective cone is stimulated for prolonged viewing, it causes the fatigue of these cone cells. Then, the other color receptor, which is not fatigued, receives the stimulus, and the brain incorrectly perceives the other color.

1.3.3.3 Gender

Human beings are capable of perceiving hundreds of shades equally; however, although findings are ambiguous, gender may have an influence on color perception. Thus, men and women may experience the appearance of color differently. Generally, women are expected to experience more shades of color than men. What may be simple “purple” to a man, but it could be “lavender” to a woman. Neuroscience says women are better at distinguishing among distinctions in color. On the other hand, linguistic researchers say that women possess a larger vocabulary of

Fig. 1.8 Fluorescence effect of different composites

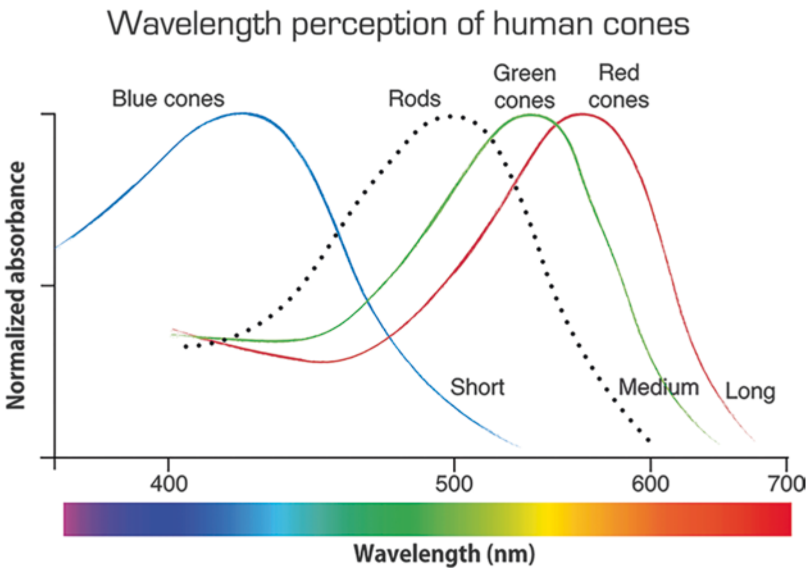

Fig. 1.9 Different wavelengths absorbance of sensory cells on human retina

Fig. 1.10 Bleaching shade guide shades tabs with saturation in a crescent scale

shades to describe color than men. But women proved slightly better at detecting tiny differences between shades that look the same to men. The scientists believe the answer lies in the differences in men's and women's hormones that can alter development in the visual cortex. In contrast, children are more likely to sort the col-ors more randomly. However, the reason is probably due to the smaller exposure to color groups and general education of color [8, 9].

1.3.3.4 Expertise

As mentioned in the previous topic, exposure to color groups and general education of color directly affect how color is perceived and called. Thus, although human beings can perceive hundreds of shades equally, as more educated they are on the topic, they tend to be more attentive, percept smaller differences in nuances, and even accept those differences less. Figure 1.10 illustrates side by side different shades from a bleaching shade guide with saturation in a crescent scale; try to identify the differences in Chroma.

1.3.3.5 Age

The sensitivity of retinal cells declines with age, causing different shades of color to be less noticeable [10]. At the same time, certain neural pathways of the brain compensate it, so color perception remains constant over some time [11]. Because of this, color vision abnormalities are very uncommon in people younger than 70. However, as there is no treatment for this age- related loss of color perception, in mid-70s, dentists should be aware of this limitation.

1.3.3.6 Phenomena That Affect Color Perception

– Metamerism

  As previously explained, when the light hits an object, the different wavelengths in it can be absorbed, transmitted, or reflected. The reflected wavelengths will be responsible for trated in Fig. 1.6). However, different light sources can emit different wavelengths, and the color of the object can look different under different illumination.

In some cases, the color of two different colored objects can match under one set of illumination but fail to match under a different set (Fig. 1.11). This phenomenon is known as the metamerism effect [12–14]. It shows the importance of illumination during color selection in Dentistry [15].

– Bezold–Brucke effect
  Hue perception can change as light intensity varies. This phenomenon is known as the Bezold–Brucke shift [16, 17]. As the light intensity increases, the color perception shifts more toward blue or yellow, depending on the original color of the object. Then, if the object is yellow, it tends to look more saturated than it really is (Fig. 1.12). It can influence the color selection to a more saturated color rather than the original color of the teeth. At lower intensities, however, the color perception shifts more toward the red/green axis.
– Stiles–Crawford Effect
  The Stiles–Crawford effect is the phenomenon where light reaching the eye near the edge of the pupil produces a lower photoreceptor response compared to light of similar intensity reaching the eye near the center of the pupil. This phenomenon is so vital in Dentistry because teeth color is multichromatic, and depending on the angle that the color is observed, color perception can vary [18].
– Aubert or Abney Effect
  The Aubert or Abney effect is also known as the purity-on-hue effect. This effect described the perceived hue shift that occurs when white light is added to a monochromatic light source. The addition of white light causes a desaturation of the monochromatic light, as

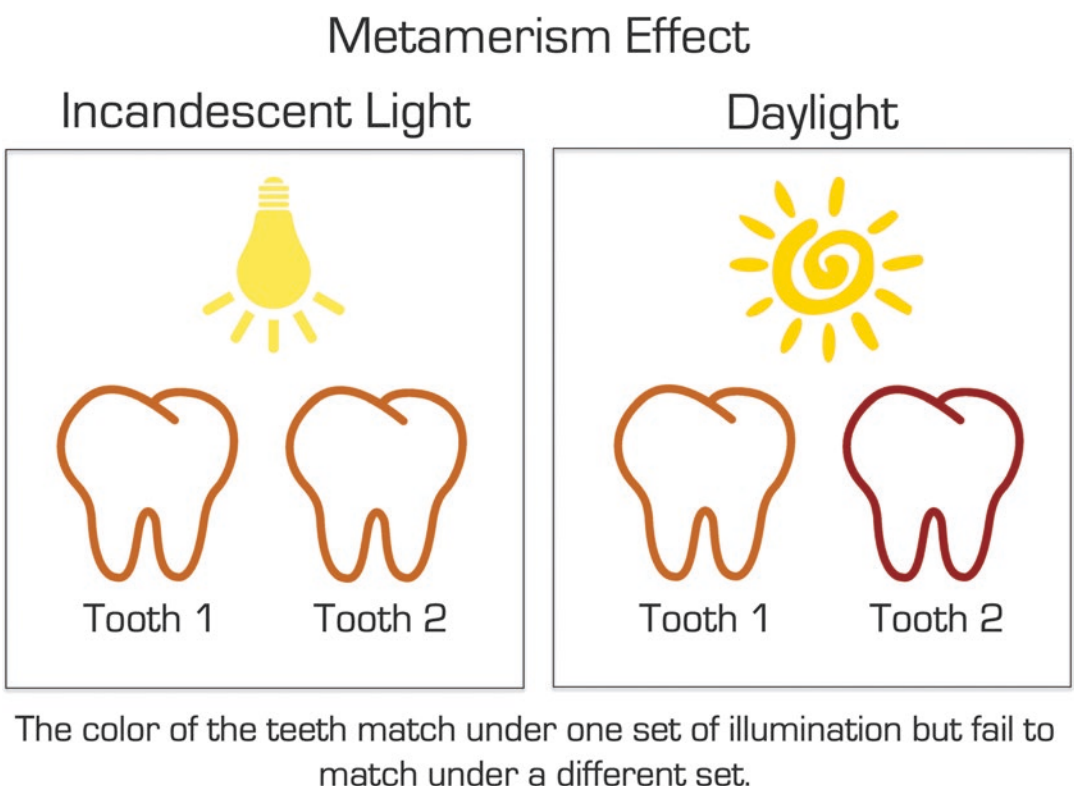

Fig. 1.11 Metamerism phenomenon

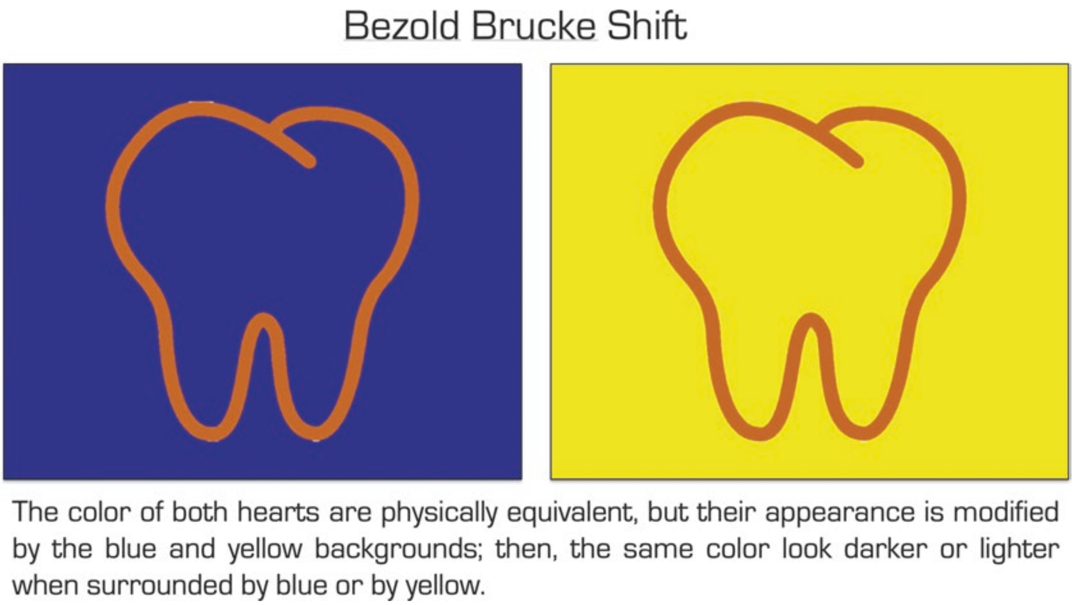

Fig. 1.12 Bezold–Brucke phenomenon

shift phenomenon is considered more a physiological effect than a physical effect [19].

– Helmholtz–Kohlrausch Effect
  The Helmholtz–Kohlrausch effect is another physiological effect in which colored light appears brighter than white light of the same luminance [20]. This phenomenon can also be observed in colored pigments and printing, although less pronounced. When the colors are more saturated, the human eye interprets it as the color's luminance and Chroma, thus tricking the brain into believing that the colors are brighter (Fig. 1.13).

  Notice that brightness and lightness are different concepts. Brightness is the intensity of the object regardless of the light source. Lightness is the brightness of the object with respect to the light reflecting on it. An exception to this is when the human observed is red–green colorblind, thus not being able to distinguish differences between

– Opponent-Color Theory
  The human eyes receive stimulus from different wavelengths by different sensory cells on the retina, the cones. There are specific selective cones for different wavelength ranges. However, when a specific selective cone is stimulated for prolonged viewing, it causes the fatigue of these cone cells. Then, the opponent-color receptor, which is not fatigued, receives the stimulus, and the brain incorrectly perceives the opponent color. This phenomenon is known as the opponent-color theory.

  This phenomenon can be observed in Dentistry. As the rubber dam is usually brightly colored, it may alter the color perception of the tooth and lead to an incorrect color selection. This is the reason why shade selection should be made before the dam is applied [4]. Otherwise, prolonged exposure to the bright color of the dam can desensitize a specific selective cone

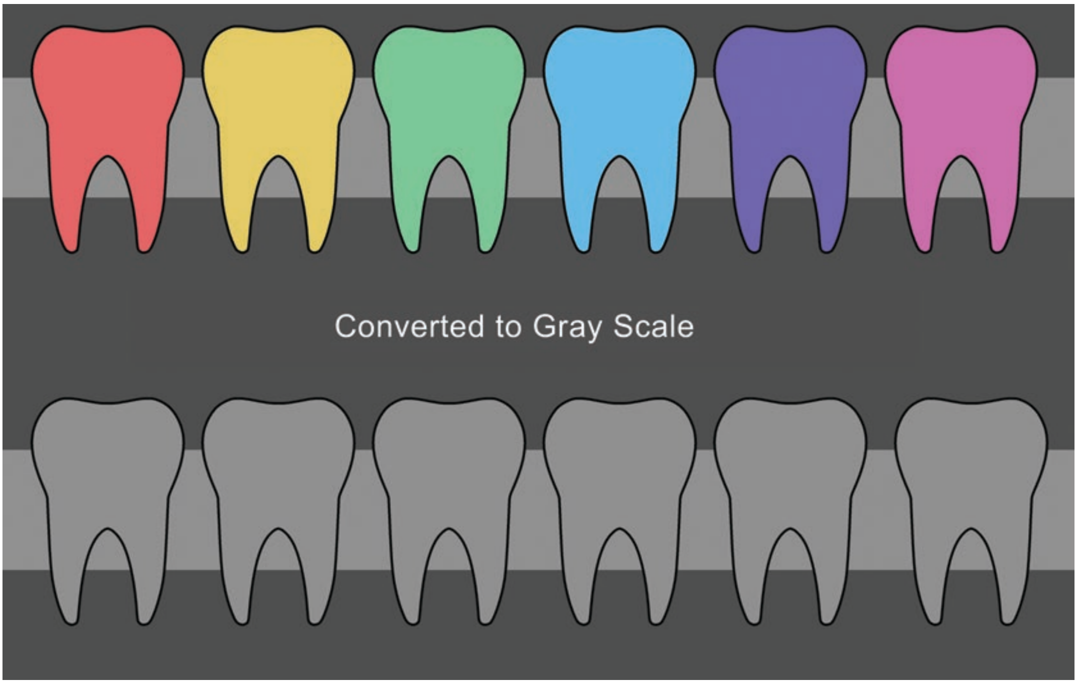

Fig. 1.13 Helmholtz–Kohlrausch effect

under absolute operatory field isolation. The opponent colors are blue and yellow, red and green, and black and white (Fig. 1.14). Toward a better understanding of this theory, a practical example is given in Fig. 1.15.

It is worthwhile to mention that the absolute operatory field isolation also causes the dehydration of the teeth. Natural teeth exhibit high gloss reflection when wet. Thus, the color appearance looks vivid. However, in the absence of saliva, the roughness of the teeth surface scatters the light, and the color appearance looks more pastel.

– Von Kries Law

Chromatic adaptation the human visual ability to adjust to changes in illumination in order to preserve the appearance of object colors. Various theories explain the color constancy phenomena under illuminant changes. The Von Kries law describes the relationship between the illuminant and human visual

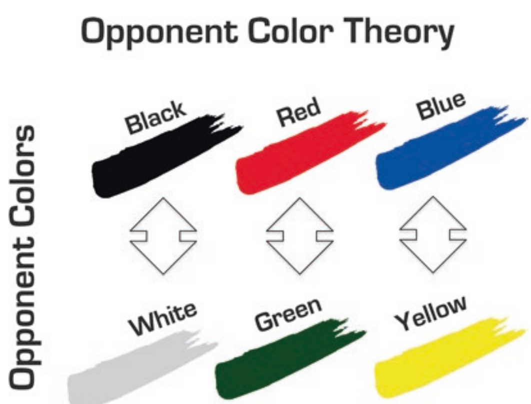

Fig. 1.14 Opponent-color theory: opponent colors

The Von Kries law is frequently used in-camera image processing. Cameras with no adjustments for light may register color differently. Thus, a correction, also known as white balance, is used to simulate this feature of chromatic adaptation by the human eye.

Fig. 1.15 Opponent-color theory test: practical example

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2 Natural Tooth X Composites Biomimetics

Dayane Oliveira, Rodrigo Rocha Maia, and André Figueiredo Reis

2.1 Optical Properties of the Natural Tooth

The tooth color is determined by the absorption and reflection of the incident light in the different natural tooth structures: the enamel and the dentin [1, 2]. These tissues have different structural characteristics and, consequently, exhibit different optical properties (Fig. 2.1).

2.1.1 Composition of the Natural Tooth Structures

2.1.1.1 Enamel

The enamel is composed of inorganic and organic components. The inorganic part is hydroxyapatite, 96% mineral by weight, and more than 86% by volume is hydroxyapatite. The hydroxyapatite crystals are colorless and organized in a hierarchical and organized way above the dentin. included in the intercrystalline spaces and a network of micropores opening to the external surface. These microchannels allow a dynamic connection between the oral cavity outside and the dentin underneath the enamel. These characteristics give the enamel a slight whitish color look with high translucency [2].

2.1.1.2 Dentin

Dentin is a unique mineralized avascular connective tissue. It constitutes a hydrated biological tissue—composed of 70% inorganic material, 18% organic material, and 12% water, by weight—whose structural properties and components vary according to the area analyzed. Its inorganic part consists of crystals of hydroxyapatite, while the organic portion contains mainly type I collagen and fractions of type III and V collagen, glycoproteins and proteoglycans, non-collagen proteins, and water [1]. Different from the enamel, the dentin is not colorless; its hue naturally varies among yellow, orange, and brown shades with low translucency. Also, the low translucency of the dentin compared to the high translucency of the enamel is due to the lower amount of inorganic content and increased amount of organic content.

2.1.1.3 Dentin–Enamel Junction (DEJ)

The dentin–enamel junction (DEJ) is a thin layer constituted of partially mineralized collagen protein fiber bundles in between the enamel and the

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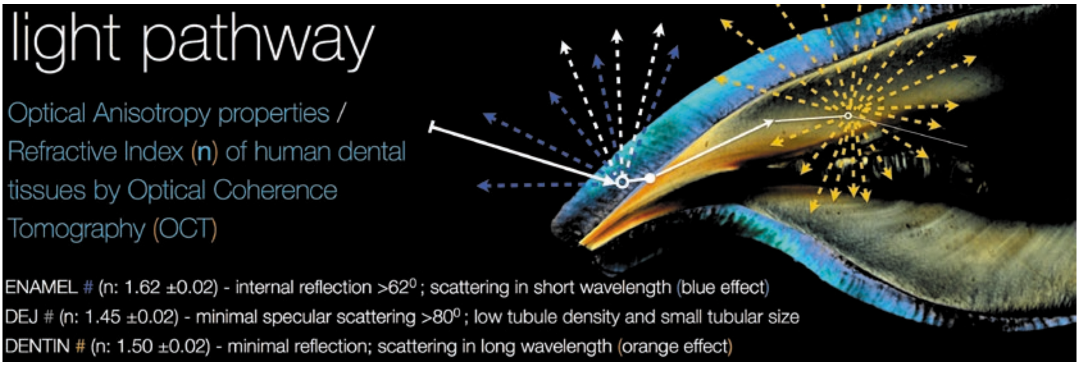

Fig. 2.1 Natural tooth structures: enamel and dentin layers, and the opalescence and counter-opalescence phenomena in the tooth structure

dentin that penetrate and connect both tissues. This junction gives the natural appearance of the tooth color, which depends on the hue of the dentin and the translucency of the enamel [3].

2.1.2 Optical Properties

There are three optical properties that directly influence on the color of the tooth structure: translucency, fluorescence, and opalescence.

2.1.2.1 Translucency

Translucency is described as the ability to allow an underlying background to show through. As previously described, the enamel has a higher translucency than the dentin [4]. The materials can be considered transparent, translucent, or opaque according to the degree of light that is transmitted rather than absorbed or reflected. For further details, consult Chap. 1.

The translucency of human dental enamel has been determined by total transmittance at wavelengths from 400 to 700 nm. Total transmission of light through human dental enamel increases with increasing wavelength. Human tooth enamel is more translucent at higher wavelengths. Translucency is influenced by many factors, thickness (of enamel and dentin), the surface texture, and the hydration of the dehydration occurs, then translucency decreases [3]. For this reason, it is extremely important to evaluate the color of the tooth when hydrated. When performing a restoration under isolation, the tooth dehydrates and tends to look lighter and opaquer, causing a mismatch in color. For this reason, it is recommended to wait for the tooth to hydrate to check the final color appearance.

2.1.2.2 Fluorescence

The fluorescence is the emission of a visible wavelength after absorption of radiation in the ultraviolet region of the spectrum, which is invisible to the human eye. Then, when exposed to ultraviolet light, the fluorescence of dentin gives a distinct color that glows. Of course, such property is only observed under ultraviolet illumination. However, if the restorative material does not have this property, a difference in appearance between the natural teeth and the restorative material would be perceived when the tooth is exposed to ultraviolet light (as previously illustrated in Chap. 1, Fig. 1.8).

In natural teeth, fluorescence occurs mainly in the dentin because of the greater amount of organic material. However, it is important to mention that the enamel is also fluorescent, although it presents a smaller fluorescence index than dentin due to the lower amount of organic material in its composition. Additionally, in many cases, the enamel pres-

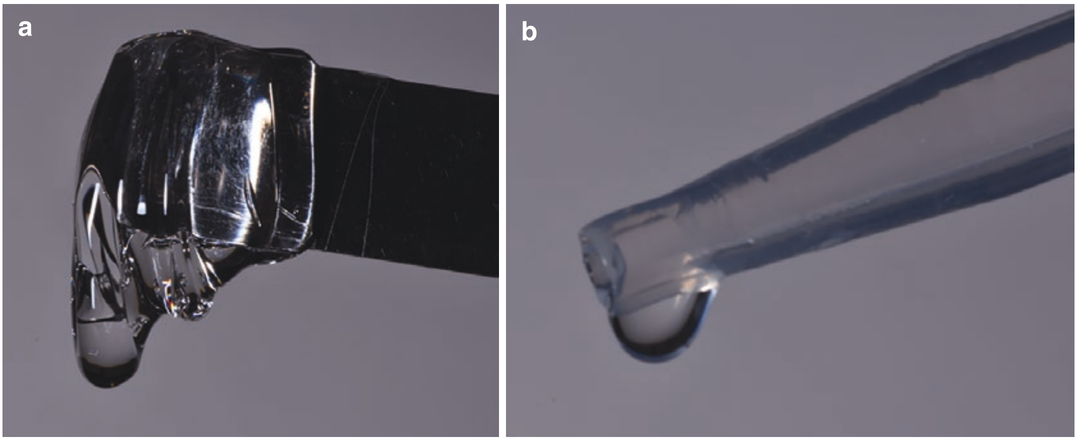

Fig. 2.2 Dental monomers used in the composition of resin composites: (**a**) BisGMA and (**b**) TEGDMA

ents higher fluorescence than several of the resin composites available on the market [5].

2.1.2.3 Opalescenceand Counter-Opalescence

Opalescence and counter-opalescence are phenomena in which tooth enamel appears one color when refracting light and a different color when reflecting light. As previously explained in Chap. 1, in highly translucent materials, the light that is scattered through the material can create dichroism, in which the material appears blue from the front side (opalescence), but yellowish-red shines through the backside (counter-opalescence).

The natural opal is an aqueous disilicate that breaks down transilluminated light into nine spectral components by refraction. Opalescence acts like prisms and refracts different wavelengths to varying degrees. Shorter wavelengths bend more and require a higher critical angle to escape an optically dense material than red and yellow ranges of the spectrum. In this case, the hydroxyapatite crystals of the enamel act as the prisms. Thus, when the enamel is illuminated, it will transilluminate red shades and scatter blue shades from their bodies; therefore, the enamel appears bluish from the front side and reddish from the backside, even though it is colorless (Fig. 2.2) [5].

2.2 Optical Properties of the Resin Composites

2.2.1 Composition of Resin Composites

The resin composites are basically composed of three main components: an organic portion, the monomers, an inorganic portion, the fillers, and a coupling agent, an organosilane, responsible for linking both organic and inorganic portions. Other than these three main components, additives are added to give specific functions or characteristics to the resin composite, eg.: photoinitiators, pigments, and rare earths.

2.2.1.1 Monomers

The organic portion of the resin composites comprises the combination of different types of monomers, such as the bisphenol A diglycidyl ether dimethacrylate (Bis-GMA), the bisphenol A ethoxylated dimethacrylate (Bis-EMA), the triethylene glycol dimethacrylate (TEGDMA), and the urethane dimethacrylate (UDMA), among others [6]. The different monomers are combined due to their differences in viscosity, refractive index, and other properties. However, all monomers are colorless liquids (Fig. 2.3).

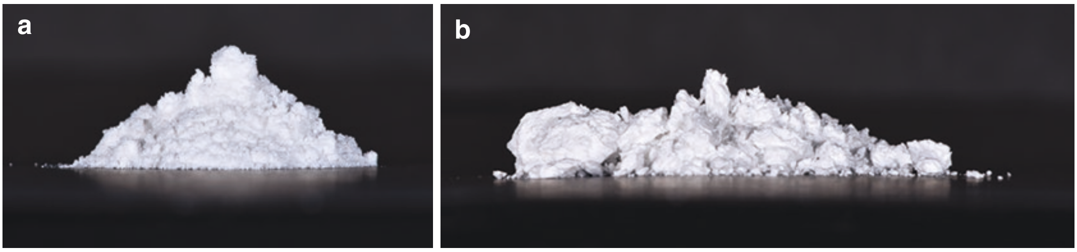

Fig. 2.3 Dental filler particles used in the composition of resin composites: (**a**) silica and (**b**) glass

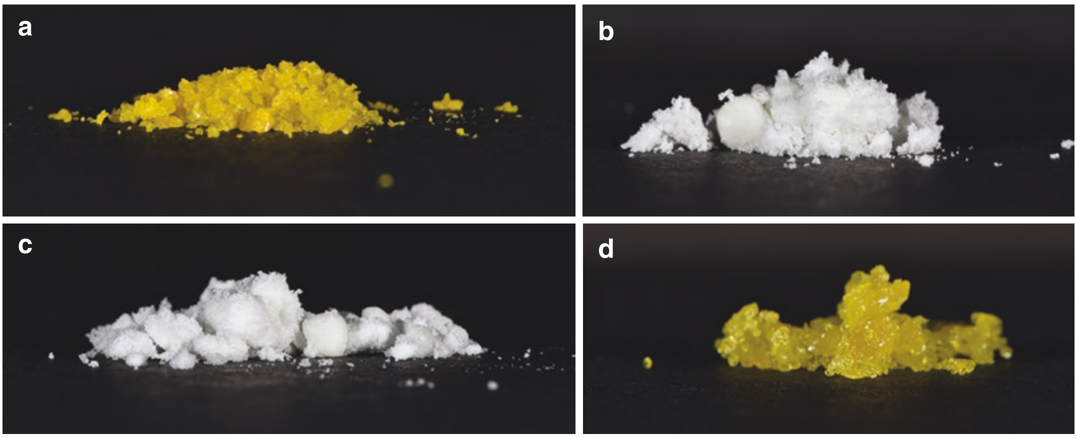

Fig. 2.4 Dental photoinitiators: (**a**) camphorquinone; (**b**) BAPO; (**c**) TPO; (**d**) ivocerin

2.2.1.2 Fillers

The inorganic portion of the resin composites, on the other hand, consists of particles of quartz (SiO_2), silica (SiO_2), zirconia (ZrO_2), barium aluminosilicate ($BaO{\cdot}Al_2O_3{\cdot}2SiO_2$), or a combination of these particles [6]. All these filler particles are whitish powders (Fig. 2.4). The different particles or their combination can be used according to the type of monomers used in the formulation of the resin composite. The reason for this is because all different monomers and filler particles have different refractive indexes.

As previously explained in Chap. 1, the refractive index is the ratio of the speed of light in the vacuum to its speed in a specific medium. Higher the difference between the refractive indexes of the two mediums, the higher the light reflection. Thus, the type and amount of these components can affect the way the light is reflected, absorbed, or transmitted [7], thus affecting its color perception. It is important to mention that the manufacturers can also use different filler particle sizes to adjust this variable. However, it is known that better polishing, lower surface roughness, and higher gloss retention are achieved with smaller particles [8–10]. The reason is that when white light shines on any solid, some of the light is directly reflected from the surface and remains white. However, most of it is absorbed and transmitted, reflecting only a few wavelengths giving the perception of the color of the object. As a result, an extremely rough surface appears lighter than a smooth surface of the same material. The reason is that most of the white light will be directly reflected from the surface. This problem is associated with unpolished composite restorations that appear lighter and less chromatic (grayer) before polishing [5].

2.2.1.3 Coupling Agent

Coupling agents are meant to link dissimilar materials. As previously described, the resin com-