Shade Matching in Restorative Dentistry: The Science & Strategies

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Abstract / Introduction
Closely matching natural teeth with an artificial restoration can be one of the most challenging procedures in restorative dentistry. Natural teeth vary greatly in color and shape. They reveal ample information about the background and personality of our patients. Dentistry provides the opportunity to restore our patient's unique characteristics or to replace them with alternatives. Whether we are restoring one tooth or many, the ability to assess and properly communicate information to our laboratory can be greatly improved by learning the language of color and light characteristics. It is only possible to duplicate in ceramic what has been distinguished, understood, and communicated in the shade matching process of the natural dentition. This article will give the reader a better understanding of what happens when incident light hits the surface of a tooth and some strategies for best assessing and communicating this to the dental laboratory.

The Phenomenon of Color
Sir Isaac Newton first observed that sunlight separates into bands of bright colors when projected through a prism. The white light was being "refracted" or separated into the colors of the spectrum (see Fig 1). Colors originate from light waves that represent different wavelengths or oscillations of electromagnetic energy. The visible light spectrum spreads uninterruptedly from red to violet. The physicist Young later performed Newton's experiment conversely. Whereas Newton broke up light into its spectral colors, Young put the light fractions together again. He made the separated rays of light converge through a lens and so regained the white light. He found that any mixture of two or more colors of light yielded a brighter and lighter color leading to white. For example, the sum of the combination of green and red light yields the lighter color yellow. Young also determined that there are three basic colors in the light spectrum (red, green, and blue-violet). These "primary colors" when mixed can reconstruct most other colors of the spectrum and when all three equally combined yield white. When two primaries are mixed, a secondary color is produced. The secondary color therefore lacks only the third primary color (complementary color) to recompose to white. The importance of these concepts will be evident later with hue and chroma selection, when eye fatigue are addressed, and when staining.

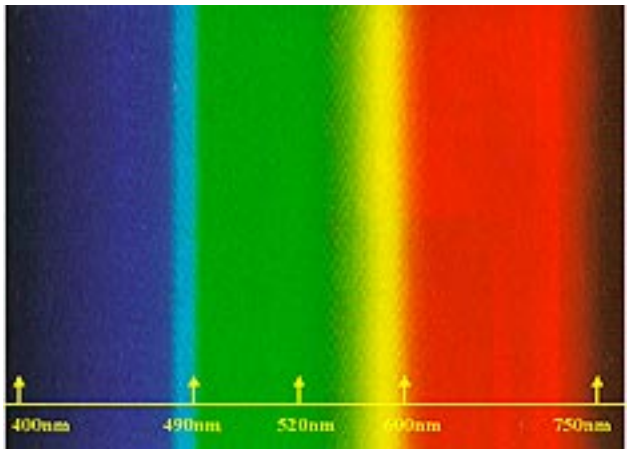


Figure 1

Additive and Subtractive Colors
When light rays of different colors are added together to form a mixture, the eye perceives it as lighter than the original colors that were combined to create it (additive coloration). Mixing colors of light is very different from mixing colors of opaque pigments. Any time you work with colorants like pigments, dye, lacquer, etc., you are dealing with reflected light. When an artist or dental ceramist works with pigments or dental porcelains of varying opacities, the amount of light reflected is decreased with the addition of different colors. Opaque pigments absorb or subtract the light waves of all colors but those perceived by the eye. Each subtractive mixture is darker than the original colors combined to create it. Each pigment absorbs different wavelengths and increases the absorptive ability of the mixture thus decreasing the reflectance. The three primary colors of opaque pigments (Figs. 2 & 3) act differently when mixed, blending to gray or black. The definition of a primary color is that no other colors can be combined to create it. The primary colors of light (additive) are red, green, and blue-violet. The primary colors of opaque pigments (subtractive) are red, yellow, and blue. The additive primaries when combined yield white. The subtractive primaries when combined yield black.

Figure 2 - The additive (light) primaries of red, green, and blue-violet.

Figure 3 - The subtractive (opaque) primary colors of red, blue, and yellow.

Absorption and Reflection
Every opaque object that you see around you is receiving light or is receiving the three primary colors red, green, and blue-violet in some ratio. Some of these objects reflect all of the light they receive and others absorb it almost totally[1]. Most "opaque" objects absorb partially and reflect the rest. The dominant wavelength reflected back to your eye is the perceived color of the object. White paper reflects almost all visible light rays. Black objects absorb most of the light so nothing is reflected back to your eyes. A perfect black body is basically unchanged by shining light on it. A yellow object (like a banana) when illuminated by the three primary colors will actually absorb the blue-violet and reflect back the red and the green which when mixed will appear as yellow.

Albert Munsell described color as a three dimensional phenomenon. He described the three dimensions as hue, value (brightness), and chroma (saturation).

Hue
Hue is the quality that distinguishes one family of colors from another. Hue is specified as the dominant range of wavelengths in the visible spectrum that yields the perceived color, even though the exact wavelength of the perceived color may not be present.[2] Hue is a physiologic and psychological interpretation of a sum of wavelengths. In dental terms, hue is represented by the letter A, B, C, or D on the commonly used Vita™ Shade Guide*.

Figure 4 - Some colors have a more extensive value range than others without losing their identity as they become darker.

Value
Value or brightness is the amount of light that is returned from an object. Munsell described value as a white to black gray scale. Bright objects have lower amounts of gray and low value objects have larger amounts of gray and will appear darker. The brightness of a crown is increased usually in two ways, by using lighter porcelain (lowering chroma) or by increasing the reflectivity of the surface. Lowering value means diminished light returns from the object illuminated, thus, more light either is being absorbed, scattered elsewhere, or transmitted through. Some hues have a more extensive value range than others, retaining their identity as they become darker. For example, blue remains recognizable as blue, even with a significant amount of gray added. Yellow and orange, on the other hand, lose their hue identities as they lower in value (Figure 4). The low value neck of a tooth is a difficult place to assess hue due to this fact.

Chroma
Chroma is the saturation, intensity, or strength of the hue. Envision placing red food dye into a glass of water. Each time you add more of the same color dye, the intensity, saturation, or chroma increases but it is the same red color (hue). As more dye is added, the mixture also appears darker so the change in chroma has a corresponding change in value. As chroma is increased, the value is decreased. Chroma and value are inversely related. Chroma is represented by numbers on the Vita™ Shade Guide.
*Vita Lumin, Vita Zahnfabrik
Bad-Säckingen, West Germany

Translucency

In dental ceramics, we try to imitate the appearance of the tooth as a sum of all its visual dimensions. There is another dimension beyond hue, chroma, and value that is significant when mimicking nature. Human teeth are characterized by varying degrees of translucency. Translucency can be defined as the gradient between transparent and opaque. Pieces of frosted glass or snow can have the exact same chroma, hue, and value but not look the same. Generally, increasing the translucency of a crown lowers its value because less light returns to your eye. With increased translucency, light that enters is scattered within the body of porcelain. When light enters enamel it gets bounced around the enamel like a fiber-optic cable. If you illuminate one side of a tooth with a curing light, the entire crown is lighted. Similar to the fiber-optic cable, enamel is an optically dense material bordered on either side by air or dentin, both with significantly lower optical densities. Normally, increasing opacity or reflectivity increases value. By increasing the optical density of dental ceramics, the fiber-optic properties of natural enamel can be replicated and the prosthetic crown can be bright and translucent at the same time. It is with the translucent enamel layer that the ceramist achieves color depth and the illusion of a vital natural tooth.

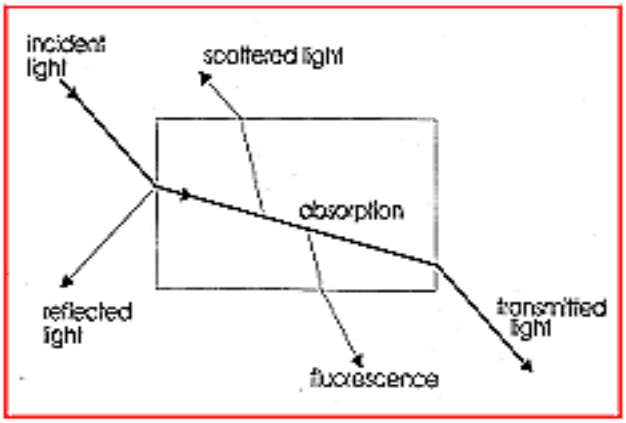
The translucency of enamel is a function of wavelength. The longer the wavelength, the higher the translucency. Therefore, enamel is more translucent in light rich in yellow and red, and will show more dentin making the tooth appear redder with a higher chroma and lower value than it actually is.[3]

Fluorescence

We live in a world of UV light. UV light can have a dramatic affect on the level of vitality exhibited by our restorations. With the characteristic of fluorescence, our restorations look brighter and more alive. So whether the patient is at a disco or at the beach, the crown will look more genuine. Fluorescence by definition is the absorption of light by a material and the spontaneous emission of light in a longer wavelength.[4] Fluorescence in a natural tooth primarily occurs in the dentin due to the higher amount of organic material present.[1,5,6,7] Ambient near-UV light is absorbed and then fluoresced back as light primarily in the blue end of the spectrum but it will occur at all wavelengths. The more the dentin fluoresces, the lower the chroma.[1] Fluorescence is considered a subset of reflectivity. Fluorescent powders are added to crowns to increase the quantity of light returned back to the viewer, to block out discolorations, and to decrease chroma.[8] This is especially beneficial in high-value shades as it can raise value without negatively affecting translucency when placed within the dentin porcelain layers.

Opalescence

Opalescence can be described as a phenomenon where a material appears to be one color when you observe light reflected from it and looks another color when you see light transmitted through it.[9] A natural opal is an aqueous di-silicate that breaks trans-illuminated light down into its component spectrum by refraction. Opals act like prisms and refract (bend) different wavelengths to varying degrees. The shorter wavelengths bend more and have a higher critical angle needed to escape an optically dense material than the reds and yellows. The hydroxyappetite crystals of enamel also act as prisms. As mentioned earlier, wavelengths of light have different degrees of translucency through teeth and dental materials. When illuminated, opals and enamel will trans-illuminate the reds and scatter the blues within its body. This is why enamel appears bluish at the incisal edge even though it is colorless.[1,5,10] The opalescent effects of enamel brighten the tooth and give it optical depth and vitality[11] (see figure 5).



Contrast and Glare

Contrast is caused by a difference between the brightness of an object and its immediate background. Object forms with high contrast are easier to pick out than objects with low contrast. While some contrast is helpful to our visual system, excessive contrast causes glare. An extremely bright object against a dark background or significantly differently colored objects cause discomfort and can interfere with our perception.[1,13,14] This interference is generically called glare. This glare reduces our ability to perceive visual information. Preston et al[15] recommended that the illumination of the teeth should not be significantly brighter than the ambient environment. The “task to ambient light ratio” should not exceed 3:1. With dental photography, the use of a black background increases impact, but it will cause glare. This is counter-productive when matching hue and chroma due to the increase in glare and it will mask shade mismatches.

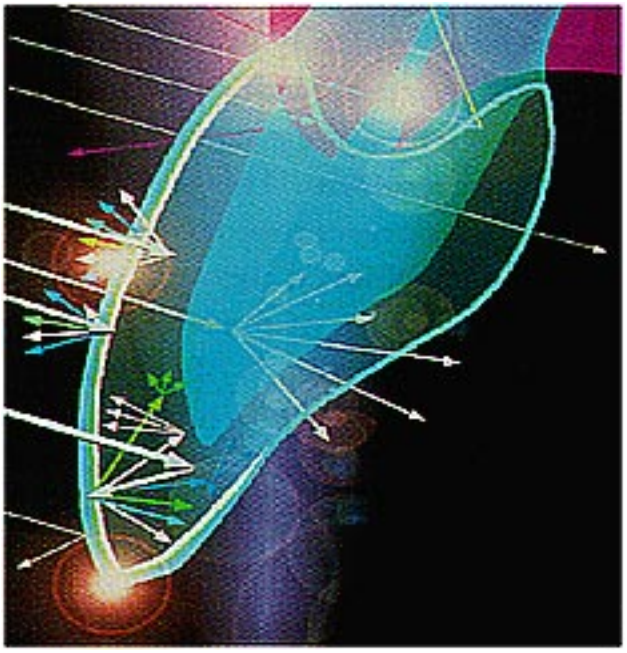


Figure 5 - The appearance of a tooth is the summation of light that is reflected, transmitted, fluoresced, and opalesced.[12]

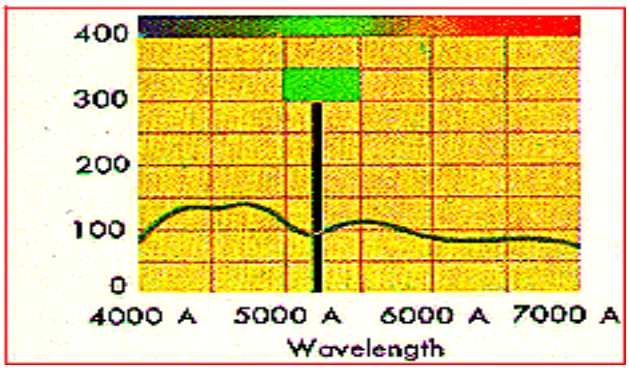


Figure 6a

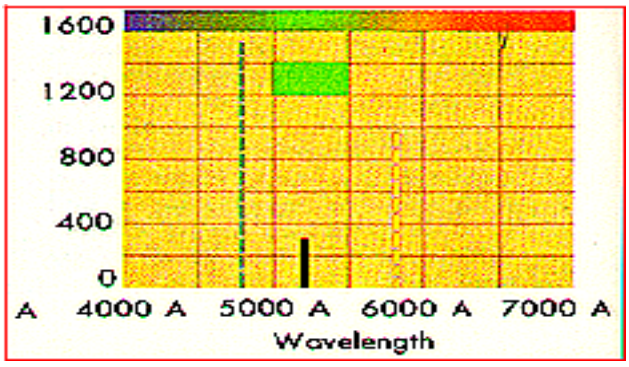


Figure 6b

Color Perception

Color perception depends largely on human physiology. Humans have three visual pigments, each in different cone shaped receptor cells. One pigment senses primarily blue light, one primarily green, and one primarily red. It is thought that impulses from the three types of receptor cones are somehow combined into a coded signal prior to transmission from the eye to higher visual centers in the brain. The combination takes place in the ganglion cells in the retina. Changes in the color stimulus change the patterns of the coded signals.[13] The eye cannot distinguish the component wavelengths in a color sample. Two lights of different colors when mixed produce a third color, and no human eye can detect its composite nature (Figures 6 a, b). Ultimately the perceived hue is the dominant or the average wavelength. The ability to perceive color differences varies from person to person.

Afterimages and Visual Distortions

Afterimages are common and frequent physiologic affects of the cone receptors with normal function that cause alterations in our perceptions. One type of afterimage that commonly affects dentists is called the spreading effect that occurs when light is removed from the retina, the receptors continue for a short time to be active and send a signal to the brain.[1] Under normal circumstances your eyes do not stare fixedly at a single spot but rather roam the visual field continuously. Thus you are constantly creating weak overlapping afterimages of which you are totally unaware. If you are presented simultaneously with two adjacent areas of different color, your eyes will flick back and forth between the two areas involuntarily. The color you see for each will be a combination of the true color of the area and the afterimage of the adjacent area. When holding a shade guide close to a tooth, it is important to decide quickly because the two will soon begin to appear more and more alike.

A negative afterimage occurs due to fatigue of the receptors. The receptors become less sensitive to further stimulation after a period of stimulation. If you were to stare at a red object for some time your red receptors will then become fatigued relative to the green and blue receptors. If you now look away at a white background, the red, green, and blue receptors will all be fully stimulated, but the red receptors will produce a diminished response. Thus you will see a blue-green afterimage. The afterimage will always be the complimentary color of what you had been starring at. If you have strong red lipstick next to the tooth you are evaluating, the red receptors in your roaming eyes become fatigued while the blue and green receptors remain fresh and can be fully stimulated. This can yield a perception of the tooth that is more blue-green than it really is. Give your eyes a break with neutral gray back-

grounds. Kulzer™ sells little gray shields designed by Pensler to screen background color glare out. 18% reflective gray cards are the photographic industry standard achromatic background.[16] Blue backgrounds are not appropriate because they also cause afterimages and will bias your perception to its complementary color, orange. Some advocate use of a blue background[17,18,19,20] to make the eyes more sensitive to yellow–orange but all that is doing is selectively fatiguing one type of cone and not making the others any more sensitive. An 18% reflective gray card is also an excellent background for photographic evaluation of hue and chroma.[21]

Establishing the Proper Environment For Color Rendering

Our ability to perform the task of shade selection depends on how well our eyes perceive the details of teeth. Factors determining the visibility or "seeability" of these details include ambient light quality, luminance (light quantity), size, contrast and glare. Establishing the proper environment for evaluation requires an understanding of these "seeablitiy" factors. Dental unit lights are commonly used for color rendering. Most are incandescent lights that emit light high in the red-yellow spectrum and low at the blue end (Figure 7). Therefore, if we illuminate opaque samples of red, yellow, and blue under the incandescent light source, we will see that red and yellow are quite strong or highly saturated, while blue is weaker and more difficult to see. Under an ordinary cool white fluorescent source, which is high in the green-yellow spectrum with some strong but narrow blue spectrum spikes, the reds and violets are less apparent. There are fluorescent bulbs that have full color content and render color more accurately. The ambient light quality of the operatory must be maintained with artificial lighting (natural light conditions vary). The ambient light quality is commonly measured by the color temperature and the color-rendering index (CRI).

Color Temperature

When black iron is heated gradually, it will begin to glow, first with a red hue, then yellow, white, and blue. If we plot the temperature rise of this black iron radiator, we relate temperature with color change and establish a color temperature scale. Such a scale exists and is commonly used to index color of light sources in degrees Kelvin, which is equivalent to degrees centigrade plus 2730. The ideal color temperature for color rendering is 55000 Kelvin. Light at this temperature can be described as having a medium temperature feel and is considered "white" light. Color temperature is the average wavelength of the ambient light. Because color temperature is an average, it does not

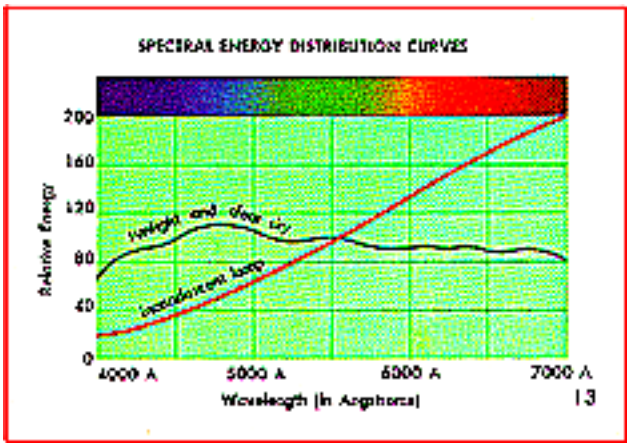


Figure 7

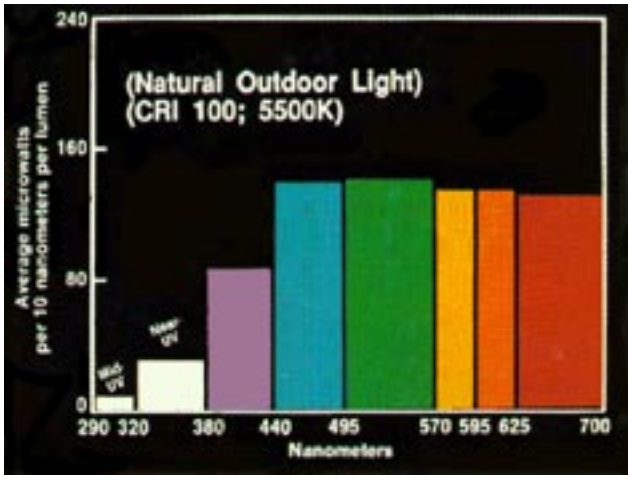
mean that all wavelengths are present nor are they in equal amounts.

Color Rendering Index

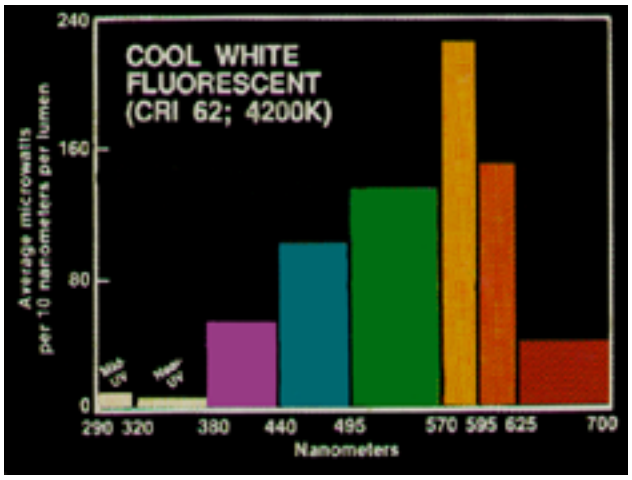
Not all wavelengths need be represented to produce white light. White light can be simply produced by mixing the three primary light colors of red, green, and blue-violet. Ambient light is a varying assembly of many different wavelengths. Artificial lighting can approach white light (5500K) but the full spectrum of wavelengths is not necessarily present. You cannot see the reflected colors (wavelengths) of a tooth if those wavelengths are not present in the ambient light spectrum.[2,18] If ambient conditions have only a small range of the spectrum of light wavelengths, then all you get reflected back are the wavelengths present. If red light is not fairly represented in the spectrum then you will not be able to see the reds in the object to be matched. Color Rendering Index (CRI) is the measure of the completeness of the light spectrum. A measure of 100 indicates that the entire visible and near-UV light spectrum is present. Although we cannot see the close to visible UV spectrum, it is commonly absorbed and fluoresced out at wavelengths in the visible spectrum. Figures 8 and 9 show the wavelength distribution curves for natural light and fluorescent lights. Fluorescent bulbs tend to be at 3000-4200K and although they have some spectral spikes in the blues are too heavy in the reds. The average incandescent dental unit lamp has a CRI of 75 and averages 3800K.[13,20,22] Theoretically, the ideal light to take a shade is with an equal energy mixture of light (Figure 10). The equal energy mixture is a balanced equal mixture of all the visible wavelengths. Realistically, a CRI greater than 93 will be adequate.

Metamerism

Metamerism is the characteristic of restorations where your restoration will match in one light (at your office!) but then display a different color in other light condi-



Figures 8



Figures 9

tions.[16] Perhaps you have matched clothing under one lighting type and were shocked to find the mismatch under different lighting. One object may have the ability to reflect more red than another. However, if there is no red range in the light source, they will appear the same. Then when viewed under a light source containing red, they will appear different. The color we see depends on the nature of the light source illuminating the object. The color of an opaque object is the sum of the wavelengths that reflect off of it. Light spectrum reflectance graphs can be made measuring the percentage of reflectance of all the near UV and visible light spectrum off of a material. Porcelain might reflect light off of its surface exactly as enamel in one part of the spectrum but under different illumination, the two objects that previously looked identical, might look different. When reconstructing a tooth with dental porcelain, mimicking the layers of the tooth employing materials with the same optical properties (spectral reflectance curves) will minimize metamerism. The closer the curves of the two materials to be matched, the more

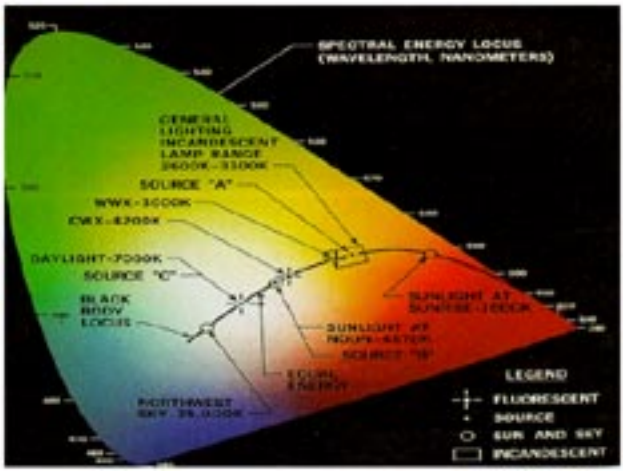


Figure 10 [13]

successful the color matches will be.[23] Ideally, both the dentist and the laboratory technician should have balanced full spectrum lighting conditions. Use of opaque surface stains to correct mismatches will increase metamerism.

Light Intensity

The intensity of the light conditions is important also. If the amount of light (measured in foot-candles or lumens per ft)^2 is too small, fine details are missed and the eye has difficulty perceiving hue. Usually the ceiling lighting in the dental operatory is not intense enough to see everything. With teeth that have subtle color variations, you need the proper intensity. Too great an intensity and glare decreases the accuracy of the color rendering. Dental unit lights should not be used for color rendering. They are too bright and cause glare. Glare will fatigue your eyes thus; rendering shades immediately after using a dental unit light is also contraindicated.

The ideal luminosity for dental shade matching is 75 to 250 ft-candles.[15,17,20,24-26] To have 150ft-candles intensity in the operatory at the level of the dental chair, ten to twelve four foot bulbs would be needed in a 10x10 ft room with 8-foot ceilings.[1,14,15,25] The diffusion panels covering your fluorescent bulbs are important also because they screen out wavelengths. As they age, the panels change what wavelengths they absorb. The best diffusers are those that don't filter out any wavelengths of the spectrum, preferably the egg-crate type. Using ten to twelve color corrected bulbs on the ceiling will yield more light in the operatory than what would be considered comfortable. There are portable high quality light units such as the Vident™ light which are ideal. Shade matching with photography lessens but does not obviate the need for special lighting. The proper shade tabs still need to be selected.

Reflections of Light

Although this article is mainly about shade rendering, it is important to realize that matching the hue and chroma is sixth or seventh in importance on the list of things to match when constructing a prosthetic replacement. You have to be fairly close to someone to detect subtle differences in hue; yet shape, value, surface texture, luster, and opacity disparities can be seen from four or five feet away or more. Violating conformity of the unique characteristics of the natural dentition will cause an unwanted prominence of your restoration.[18,27-29] These characteristics determine how light is reflected, transmitted, or scattered thus affecting its hue, chroma, value, and translucency.[18,30,31] The appearance of teeth is mostly determined by how light interacts with the curved and varied surface. Attractive prosthodontic replacement starts with a consistent silhouette and shape of the buccal surface as the most important aspects of matching because they determine how the majority of light will be reflected. Figure 11 shows an example of in this case sand, which can look so different depending on its contour and angle of illumination.

An observer only sees an object when light comes from that object. Surfaces that are perpendicular to us send the most light back to us. The reflective surfaces of the tooth will not return significant light to our eyes if they are not perpendicular to our eyes. Because we mainly see the surfaces of a tooth that are perpendicular to us, we can manipulate the perceived width and length by bending or flattening surfaces (figure 19). The practitioner can make a tooth look narrower or shorter by decreasing the width or length of the direct buccal reflective surface.[32] Another example would be a maxillary incisor that is tipped lingually. It will not reflect light directly back at you and will appear darker. The smile can be made to appear uniform even without realigning the tooth simply by brightening it up.

Reflection from a smooth, mirror-like surface results in the production of a clear well defined image. This is called specular reflection. A specular reflection returns a high percentage of direct non-diffused light, and if strongly illuminated, will be brighter and stand out (Figures 12,13,14). Smoothing the texture of the buccal surface will make teeth appear lighter and brighter and therefore a primary determinate of value. The more reflective the surface, the more wavelengths return to your eyes and the additive combination of more wavelengths yields whiter light (hue change). Brighter objects appear closer to the viewer. This is the reason why a restoration that is too light appears to “jump out at you”. Lowering the value makes objects appear farther away. Roughening texturally the specular highlights of a too bright crown will make it blend better. Dentists can use this to their artistic advantage

Color is the Music of the Eyes …. Art is Dealing with Perceptions

Most teeth have irregular surfaces with convexities and concavities. The convexities tend to wear and become smooth with specular reflective characteristics. The visual impact of a tooth comes from these specular highlights that give the tooth its visual shape. Concavities tend to collect light by reflecting inwards and tend to be unpolished, thus diffusing the light and less returns to the viewers eyes (figures 17a and b).

Figure 11

Surface Texture

After shape and contour, surface texture and luster are the next most important factors affecting how light interplays with the tooth surface. A roughened surface texture will not yield as well defined an image and will scatter the light and the individual wavelengths will all bend differently yielding a substantially different spectrum returning to the eye.[33] Texture can be broken down into subgroups: vertical, horizontal, and malformations.[34] Vertical surface textures are primarily composed of the heights of contour of the marginal ridges (Figure 15) and the developmental lobes. Perichymata, the fine transverse wavelike grooves believed to be exter-

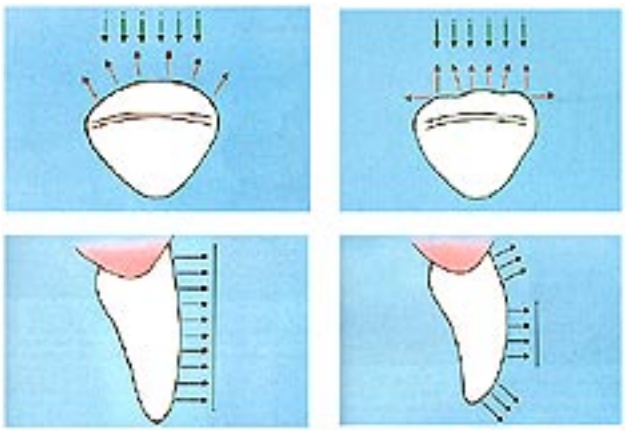


Figure 19 - Rufenacht

nal manifestations of the striae of retzius[7,35] are horizontal textures. The striae or lines of retzius are the result of the layering manner in which the deposition of enamel takes place. Perichymata can be abraded with age, often resulting in horizontal grooves traversing the tooth separated by distances much greater than the original perichymata. These horizontal grooves can be convexities and/or concavities and they stretch in a flat to U shape (bottom of U towards gingival) across the buccal surfaces of the maxillary incisors (Figure 16). These horizontal undulations get flatter and closer together going gingivally.[34] They never cross each other and they go circumferentially. There tends to be more stippling of these textures gingivally. The concentrations of dechromatized white enamel so often found in younger more superficial layers of enamel are often associated with horizontal textures.

Horizontal textures are formed on top of vertical textures, meaning the horizontal patterns follow into the concavities formed by the vertical but the vertical are not affected by the horizontal. When texturizing your restoration, carve the vertical textures first and then

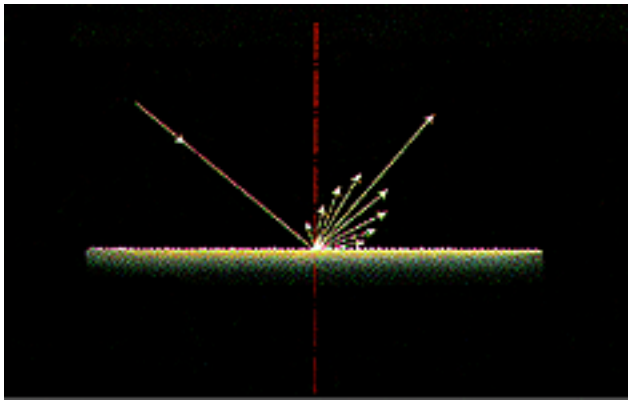


Figure 12[71] *- A roughened surface reduces light.*

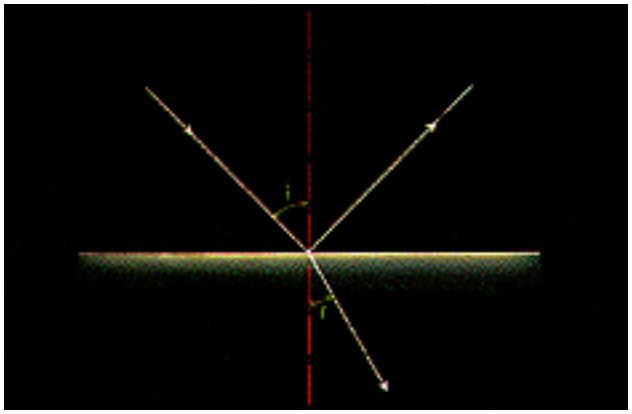


Figure 13[71] *- A smooth polished surface produces a well defined image and can be more translucent.*

Figure 14

Figure 17a - There is a double reflection and absorption of light in the fissures and concavities causing diminution of light coming out of these areas.[71]

Figure 17b - Light is refelcted more in bulging and curved areas, which are generally more worn and polished.[71]

overlay the horizontal ones. Malformations are the third textural group and can be from cracks, chips, and other surface aberrations. Surface texture can be generalized as being heavy, medium, or light. A rough or heavy surface texture will have a lower value because it tends to diffuse light by reflecting it in many directions and less light returns to the viewer. A light surface texture has a higher value due to the increased specular reflection.

At eruption, teeth have their roughest surface texture. With age, these surface features gradually wear. As the wear process continues into the later years of life, all signs of the perikymata are lost and even the definition of the developmental lobes is obliterated and the tooth appears smooth with a highly reflective glassy surface.

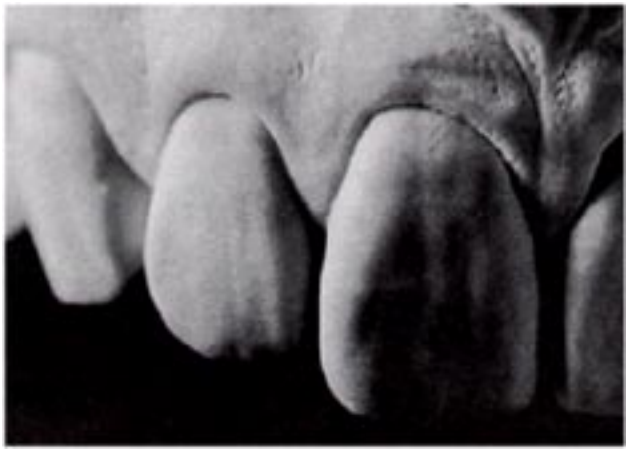


Figure 15

Luster

Reducing the surface luster of a piece of clear window glass by wet sanding or etching will produce a frosty white look. As light hits the surface of the etched glass, it scatters or bends irregularly. This scattering of the light at the surface causes an increase in opacity. The light isn't carried off and away from the surface but rather reflected. As the glass becomes less translucent, the value goes up. The net effect is more light returns to the viewer as the luster goes down. It is important to note that surface texture and not luster determines specular reflection. Although the surface luster has been roughened the glass remains flat and has low texture so it will remain a specular reflector. Polishing the rough glaze off of a porcelain restoration is a subtle way to lower value by making the porcelain clearer and more translucent.[36] Super polished surfaces can appear bright due to the specular reflection but they are also more translucent because the light isn't scattered or bent at the surface.

Figure 16

A surface can have nine different combinations of texture and luster, heavy medium and low texture and high, medium, and low luster. A heavy surface texture will produce a lower value by redirecting reflections away from the viewer or with double inward reflections, and a high surface luster also makes a tooth or crown darker and more translucent. Due to the impact they have on the optical properties of the tooth, the wise practitioner will note them in their lab prescription.

Color Characteristics of Teeth

• In a newly erupted tooth, the superficial layers of enamel are the most opaque. These layers frequently appear as though they have a white frost. This superficial frosted enamel may have a higher organic component[37,38] is less mineralized, and has more empty space between the enamel crystals all of which causes the increased opacity.[10,38] It has a very low luster caused by the pronounced rod endings from enamel deposition. As these top layers wear off, the underlying enamel is less opaque.

• Due to high opacity, the superficial enamel of the young tooth is very reflective.[35] The chroma of a tooth, which primarily comes from dentin, will be lower due to the masking effect of the young enamel. As the enamel gets thinner, the dentin becomes more obvious. The natural thickness of enamel is greatest at the incisal and least at the cervical. Chroma is greatest at the cervical and decreases toward the incisal.[39]

• Young enamel is more permeable. Young teeth dehydrate quickly and older teeth with enamel worn thin will not dehydrate much.

• With age, only the deeper more translucent enamel remains.[36]

• When light enters a tooth, it may reflect off many surfaces within the tooth before it exits substantially changing its character. The more scattering that takes place in the enamel, the higher the value.[6,10]

• Enamel rods and the surrounding interprismatic substances are positioned perpendicularly to the dentin layer. This crystalline structure permits light to pass through, which then reflects the underlying color of the dentin. The prism structure of enamel influences light transmission resulting in anisotrophy, directionally dependant light propagation.[40,41] We sometimes can see a highly pigmented area from one angle but not another angle. The translucency of enamel varies with the angle of incidence, wavelength, and dehydration.
• In the spectrum of the rainbow, the shades (hues) of natural teeth tend to be in the yellow range. If we were to place the rainbow on a line, then the A shade is more towards the red end of the yellow spectrum and the B shade is more to the green end of the yellow spectrum (figure 20). Most teeth are closer to A on the Vita shade guide but there is a much wider spectrum of natural hues than most shade guides provide.[17,42-47]
• The thickness of dentin, the size of the pulp chamber, and the vitality of the pulp tissue are different during different stages of tooth development. Teenagers generally have a larger pulp chamber that adds red. With secondary dentin formation, the pulp chamber decreases in size and the teeth become less red with age.[48]
• Older dentin or sclerotic dentin is darker (higher chroma, lower value) and it has more green and blue. Young dentin is more red-yellow.[39,49] (CIE Lab color spaces[50] a* and b* go negative with age) There is a positive linear correlation between age and chroma of the roots.[51] Though the dentin undergoes a color shift from red yellow towards yellow, the overall color of older teeth is redder than in youth[49] because there is less bright enamel covering the red dentin due to wear.
• Different teeth in the arch can belong to different hue families.[49] a* (red to green gradient) is highest (most red) in canines, then centrals, then laterals.[48] b*(yellow to blue gradient) is highest (most yellow) in canines, then laterals, then centrals.[48]
• Value is mainly determined by qualities of the enamel layer in the form of reflectivity and opacity. As the superficial layers of the enamel surface are worn, the translucency goes up and the dentin becomes more visible and dentinal chroma begins to influence value more.
• To raise the value in a restoration that needs to be highly translucent (translucency normally drops value), the brightness needs to be built into the dentin instead of the enamel.
• Value is typically lowest at the cervical, then at the incisal, and highest in the middle third of the tooth39. Value increases going medially from the maxillary canines to the centrals.[48,49]
• The mammelons and interproximal contact areas usually show the most translucence.
• The cervical hue is always redder than the middle or incisal.[49]
• Translucency is greatest in laterals therefore; opalescence (primarily in translucent enamel) is most evident in the laterals.
• Cuspids show very little translucency.
• Remember that the upper cuspids are often one to two full shades darker in chroma than the maxillary incisors and will sometimes give a better clue to the average hue family.
• The hue and chroma of natural teeth are not constant. If a laboratory uses the same porcelain for all of the teeth in an arch, it will make the mouth look flat.[36] A natural 3-dimensionality can be developed with chroma gradients getting darker from the centrals on back.[52]

Bleached Teeth

Bleaching teeth will cause a change in hue, chroma, value, and translucency. Dehydration and the brightening or removal of pigmented organic material from between the hydroxyappetite crystals significantly changes how light interacts with the enamel and with prolonged beaching, the dentin. Common clear glassware is relatively transparent. When it is crushed into smaller and smaller pieces, the glass that remains, becomes opaque. If you add water to the pile of broken glass, it becomes more translucent again. Dehydration increases opacity of the enamel. Light no longer can go from hydroxyappetite crystal to crystal. Less translucency causes more reflection so the tooth is brighter.[6] The hue changes due to a change in the reflectance spectrum of the enamel.[53]

Figure 20

Recently bleached teeth are not color stable. Shade matching should be delayed for at least one month after bleaching. The rebound of bleaching is mostly due to the rehydration of the enamel. Note that bleached teeth will dehydrate much faster than other teeth so shade rendering should be completed prior to any treatment.

Surface Staining

There are several very good uses for porcelain surface stains. The best use is to help communicate a

look to the lab of a difficult to match tooth. Painting the surface of a shade tab or a mismatched already completed crown is very helpful to the lab and can be a great compliment to photography. Tanaka Dental Products makes a very good porcelain stain that can be painted onto the surface of anything. It can be used for enhancing the beauty of provisionals also. These stains can be sealed on the provisional with Palaseal' (Kulzer) a light cured methyl methacrylate.

• When trying to cover an unwanted color we can use subtractive laws of color mixing and add the complementary color to the unwanted hue. The two colors will cancel each other out blending to gray.[54] Caution, this will lower value.

• We can use complementary hues to control value.

• When trying to change the color by mixing in another pigment, if you are not working with a complementary hue (one of the other primary colors), the value will not change.

• Opaque surface stains increase the likelihood of metamerism.[23,42] Grays attained by mixing complimentary colors are "complex" grays with erratic spectral reflectance curves that increase metameric problems.

• Surface stains are less preferable to internal staining for permanent restorations because they are made of opaque glass that prove to be a light barrier that prevents seeing the color from the internal body of ceramic[55] of the restoration. They also wear off with time.

• Labs should lower value within the dentin layers of the gingival butt joint not with superficial stains. Translucent porcelains are less metameric than the more opaque body porcelains.

• Stains increase the light absorption, and decrease the translucency, reflectivity, and opalescence that are carefully crafted into dental ceramics to correspond to those of natural teeth.[55]

• Painting shade tabs is a great way to convey hue and chroma, but ultimately it can encourage the lab to use surface stains on the restoration thus encouraging metamerism.

• Chroma can be increased easily with surface stain (subtractive darkening) and to a limited extent it can be decreased with bright stains but these will decrease the light coming out of the tooth. Lowering the chroma with surface stains will limit vitality and depth of color of the tooth.

• The addition of proximal and lingual stains can reduce a monochromatic appearance of a restoration without directly visible stains.

• Visual form also can be altered by the use of stains. Long restorations can be shortened in appearance by the use of darker stains at the cervical. Stains can be used in many ways to darken (de-emphasize) or to highlight contours.

• We can make a tooth appear to be leaning out by varying the value the length of the tooth.

The Greatest Art is …. To Disguise the Art

Guidelines for Shade Taking

• When matching teeth, the shape, surface geography, and the value are the most important characteristics.

• Create a neutral colored environment. When looking at a bright red, the cones in our eyes will saturate and fatigue quickly giving an afterimage of the complimentary color blue-green. Your color assessment of the teeth will be too blue.

• The color of the walls in the operatories and lab can alter color perception. In a blue room you see more orange than is actually present since the complement of blue is orange. The ideal background color is neutral gray.[56,57] Neutral gray has no complimentary color and is restful to the cones. This is more critical with aged teeth that have a glossy surface that reflects the shade of any color placed in close proximity.[15,22,35,57]

• Hold the shade tab incisal edge to the incisal edges of the teeth. This effectively isolates the shade tabs from the teeth so they don't reflect onto each other[22,34] reducing afterimages.

• Due to the variability of daylight, blinds should be used, and a color corrected light source of the proper intensity should be used. Use a gray bib to cover the patient's clothes[58] and remove or cover any lipstick.

• The most important circumstance of shade matching is the lighting condition. No matter what technique used, without a light source that approaches 5500K, CRI of 100, with the proper luminosity, for both you and your lab, a superior shade rendering is not possible.

• Viewing teeth under diffuse illumination will minimize the distortion of the reflected light. Reflection from the specular surfaces of a tooth reveals more of the color of the illuminating light than the color of the tooth.[3]

• Value is the most important dimension of shade rendering.[8,27,43,59] Use the value guide first.

• All shade guide selection should be done BEFORE you turn on the dental unit light. This light is too bright and causes eye fatigue due to glare.[52] Consider using a portable Vident light with a rheostat that can control the light intensity and it gives a diffuse illumination. The rods in our eyes are sensitive to lightness/darkness or gray scale. Rods are very sensitive even with small amounts of light. The cones only become activated with higher light levels. When the cones are functioning, then hue and chroma can confuse value discrimination. Low light levels, even if you have to squint are the best for value evaluation.[20,30] If the light is too strong, the high reflectivity of the buccal surface will read high incorrect values.[20]

• Another reason to do shade selection before treatment is due to dehydration. The value increases and the chroma and translucency decrease as the teeth dry out during treatment. This is why restorations fre-

quently are too light. This will happen while doing composites also. If your composite buildup is slightly light when you finish, you know that it will probably be very light when the tooth rehydrates. When in doubt, err to the darker.[60]

• First impressions are the best due to eye fatigue. Don't stare at the teeth for more than 5 seconds to prevent hue accommodation.[20]

• View teeth with lips relaxed (indirect light) and reflected (with direct light at 900). Assessment in muted or non-direct light will determine how much brightness is from the dentin.

• Value sometimes is achieved by decreasing chroma and sometimes it needs to be on the surface of the restoration (increasing reflectivity). If you have a great value drop when shadows cast on teeth with upper lip or with a polarized light filter, then value is superficial, caused by high surface reflectivity.

• When high value exists without help of surface texture, internal value can be raised by placing highly fluorescent porcelain in the dentin layers.

• Miller has suggested using two Vita shade guides.[43] The first guide should have the tabs arranged in order of brightness (value). The order is printed on the back of the shade guide. The second shade guide should be arranged by hue with the A and B hues at opposite ends and C and D in the middle. C and D have hues in between A and B[44] on the linear rainbow (chroma and value are manipulated to yield different looks).

• When choosing the hue family, use the A-4 and B-4 tabs which facilitate the process of elimination by using tabs with the greatest hue spreads.[20]

• The chroma is very low for shades A1 and B1. It can frequently be very difficult to distinguish the proper hue family. Compare highest chroma tab in each hue family with the maxillary cuspids.

• When choosing the hue with a shade tab, look to the mid-buccal of the tooth. Differences between the shade tabs and the natural color of the teeth increase near the root. Compared to the Vita' shade guide, natural teeth exhibit increased redness and lower translucency at the cervical.[22,39]

• The best background for hue and chroma selection is not blue or black but rather gray. The 18% or lighter reflective gray card is the photographic industry standard. A television studio introduced blue because TV cameras can be made blind to blue.[16] The blue card was quietly discarded by its manufacturers because it produces an orange after image, which causes shade errors.

• If in doubt as to the hue family, choose the A family.[61,62] Most natural teeth have more red than B (Figure 21). Perhaps as much as 80% of natural teeth belong to the A hue family.[63]

• When drawing proximal translucence, ask the patient to turn from right to left, which allows a better analysis. Employing a black background will allow you to see the blue of the opalescence in the translucent enamel. Do not use a black background for hue and chroma evaluation.

• If the teeth have prominent surface anatomy, this must be replicated because the surface determines the amount and direction of light reflected to you from that angle. The pre-op models will help duplicate these contours. Although the luster and texture can be determined better photographically, describe it on the prescription form and add the age of the patient.

• Different light wavelengths reflect off a rough surface in different ways. Shades should be evaluated looking at the tooth at different angles. This reevaluation at different angles is called vectoring.[16,27,52] Due to the curved translucent surfaces found on teeth, the anisotrophic properties of enamel, and the complex layering of the tooth structure, vectoring will allow the operator to identify colorations within the layers of the tooth and to visualize the translucent areas. Sometimes the value of the gingival and incisal thirds of a tooth is seen as lower than it actually is due to the natural curvature of the tooth.[57] We only see reflected light if it is perpendicular to us.

• Most humans have eye dominance and one eye will preferentially perceive shade.[52] It is wise to hold the shade guide on both sides of the tooth at each vector.[34] In addition, difficulties can arise where the tooth being examined differs considerably in size from the specimen on the shade guide. A variation in color perception can occur with the relatively larger area appearing brighter and more vivid than the smaller.[64]

• Shade-map all that you see in a three-dimensional drawing. Utilize several views (e.g. 900 straight buccal, 1350 angle from the buccal incisal, and straight incisal/occlusal). Break the labial face of the crown into 9-16 zones.

• Describe surface texture and luster as heavy, moderate, and light therefore giving nine different combinations of surface characteristics. Because these surface features determine the character of light reflection and affect the amount of light that enters the tooth (opacity), the surface texture of a crown must be designed to simulate the light transmission and reflectance pattern of adjacent teeth.[35]

The Use of Photography for Shade Rendering

To be able to communicate your ideas to another is an art. To communicate exactly what you see to another person is a miracle. Many methods have been described in the literature to facilitate the transfer of shade information to the lab. It is difficult to accurately de-

scribe a complex, multi-layered, multi-textured, three-dimensional color scheme of varying opacities with a two-dimensional shade guide system.[44] In addition, 9.3% of male dentists have a color vision defect and most of those do not receive help with their matching by someone trained in color science.[65] The best way to communicate to a laboratory is with color accurate 35mm slides.

• Use a color corrected professional quality film (e.g. Kodak EPN-100, E100-S, or EPP) and have a good photo lab to develop them.
• An accurate clinical photograph can document numerous details that would be missed by the eyes.
• Use a color corrected flash.
• Use as many tabs as you see colors in the tooth. If you see more than one hue family in a tooth/arch, then photo all the tabs that seem to match. Suggest ratios to the lab in the prescription.
• Try to keep the tabs at the same distance as the teeth from the camera, if brought closer, they will appear brighter.
• Tabs should be the same distance as tooth from camera lens.
• Using dual point flashes, take pictures perpendicular to the buccal surface of the tooth for surface texture.
• The teeth should be dry when evaluating value, translucency, and surface geography.
• The teeth can be wetted for hue and chroma evaluation to limit the influence of surface morphology.

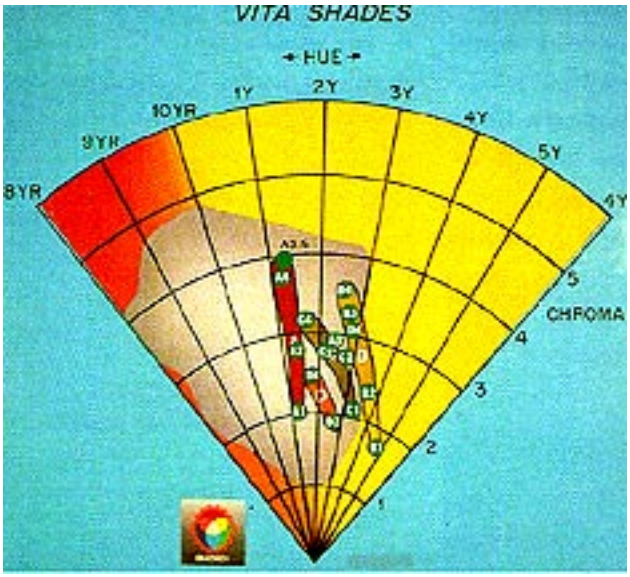


Figure 21 - Colorimetric analysis of Vita™ shade guide. Hue is measured on circumferential lines (going from yellow on the right to orange on the left) and chroma increases along the radial lines going from bottom to top. The gray area represents the natural color spectrum of teeth.

• Saliva must be removed to allow unrestricted observation of tooth surface, its texture, and its degree of luster.
• Surface geography and value shots should be taken at 900 from the surface.
• Vector shots.
• Take pictures at a 65-700 angle looking down with incisal edge away for chroma and hue.[66] The reflections produced at 900 reduce your ability to color render. A ring flash surrounds the camera lens and increases the amount of reflection back at almost any angle. Note that if the pictures are taken below the incisal edge, the flash will light the back of the mouth making it difficult to evaluate hue, chroma, and translucency. The reflected red light will re-enter the tooth and add itself to the light returning from the tooth to the eyes.
• An 18% reflective grey card is a helpful background while selecting hue and chroma.[16,21]
• It is easier to identify the translucent areas of a tooth by placing a black background behind the incisors. A black background will stop any light reflected from inside the mouth from re-entering the enamel that would lessen the visual impact of the bluing in translucent areas.[67]
• Use of the black background will not be useful in hue and chroma selection as it increases glare.[13]
• Due to the confusing influence of hue and chroma in the shade tabs, value can be more easily evaluated by use of black and white film.[67]
• Bracket the camera F-stops. If you close down the lens it increases contrast and helps you see the internal structures better. Lower light helps identify the coloration within the different layers of the tooth and to see the translucent areas better.[68]
• Remember to take incisal or occlusal shots. The older the patient, the higher the chroma of these areas.
• Take photos with shoulder porcelain tabs also. Although the media image of teeth has a limited chroma gradient going gingivally, if you want your single central to disappear you need this information.
• An extension tube allows for more magnification of the characterizations.
• Take photos at 1:1 scale. The technician then can use calipers to measure exactly where to place characterizations.
• Distinguishing the source of value can be sometimes challenging. Use of a polarized light filter will cancel the reflected light making it easier to determine if the brightness is from low chroma or surface reflectivity.[69]
• If an all-ceramic restoration is to be used, photograph the prepared teeth. Keep the teeth wet for these pictures.
• If the crown doesn't match, then re-photo with mismatched crown in the mouth

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