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Pan, Q and Westland, S orcid.org/0000-0003-3480-4755 (2018) Tooth Color and Whitening - Digital Technologies. Journal of Dentistry, 74 (Supplement 1). S42-S46. ISSN 0300-5712

https://doi.org/10.1016/j.jdent.2018.04.023

Tooth color and whitening – digital technologies

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Keywords: Tooth Whiteness, Tooth Yellowness, Whiteness Index, Visual Assessments, CIE Color Space

Declarations of interest: None

Abstract

Objectives: To review the key concepts of color in the dental domain with specific reference to the use of digital technology to measure color and color appearance. **Materials and Methods:** The literature on color assessment in dentistry is considered and methods for assessing whiteness, yellowness and color appearance are collated and described. **Results and Conclusion:** A variety of methods for assessing color have been shown to exist and be viable including digital imaging. Equations to predict whiteness are identified; there is evidence that they are effective but further evaluation may be needed.

Introduction

Tooth color is important to both dental professionals and consumers [1]. Professionals may wish to select the correct shade for a dental restoration or to measure the efficacy of tooth-whitening systems whereas consumers seek improved tooth color to enhance their confidence and self-esteem. Although visual assessment of tooth color is widely used, digital technologies are increasingly being preferred. This paper reviews the key concepts of color (including whiteness and yellowness) in the dental domain and then describes the use of digital technology to measure color and appearance.

Color, Whiteness and Yellowness in Dentistry

It is important to understand what is meant by the term color. Figure 1 shows two teeth that are presented on two differently colored backgrounds. Physically the two teeth are identical but most observers would see them as being different in color. It is helpful to distinguish between physical color and perceptual color. According to this distinction, the two teeth have the same physical color but different perceptual color. However, it is the perceptual color that is almost always of interest to consumers.

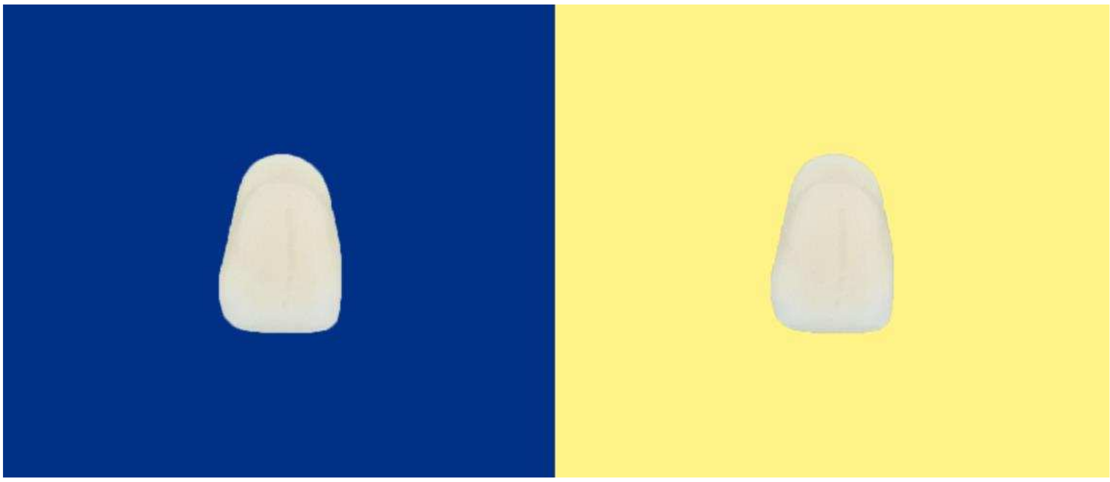


Figure 1: The two teeth are physically identical but the one on the left looks lighter and yellower than the one on the right because of the contrast effect with the background.

The physical signal that is the source of color perception is the spectral distribution of light that reaches the eye when a tooth is illuminated. This spectral distribution is a product of the tooth's spectral reflectance factors and the spectral power distribution of the light source. However, the third component that needs to be considered is the observer. The perceptual dimensions of color are lightness, chroma and hue [2, 3]. Figure 2 demonstrates these three perceptual attributes using digitally manipulated teeth as examples.

Lightness is the attribute of teeth whereby they appear to reflect more or less light relative to a similarly illuminated white sample. Chroma is the attribute by which teeth appear to be more colorful relative to the brightness of similarly illuminated white sample. Hue is the attribute by which teeth look redder, yellower or bluer, for example. Perceptual color is influenced by a number of factors including the background against which the samples are viewed and a number of background effects such as contrast [4], assimilation [5] and crispening [6] have been documented.

Change in lightness

Change in chroma

Change in hue

Figure 2: Variations in lightness (top row), chroma (middle row) and hue (bottom row). The middle tooth is all three rows is the same and teeth to the right and left show increasing and decreasing amounts of the attributes respectively. Note that a change in a single color attribute (as shown in each of the rows) with no change in the other attributes is very unlikely to happen as the result of a real physical process such bleaching, staining or ageing.

The terms whiteness and yellowness have specific meanings and changes in whiteness and yellowness are usually associated with changes in more than one of the perceptual color attributes (lightness, chroma and hue) at the same time. In dentistry an increase in whiteness is traditionally attributed to teeth that increase in lightness and decrease in chroma. A decrease in whiteness naturally occurs due to changes in absorption and scattering of the dentine and enamel of the tooth (intrinsic staining) or when materials attach to the tooth surface (extrinsic staining) [7]. Extrinsic staining can be removed by brushing and use of toothpaste [8, 9] whereas intrinsic staining can be reduced by bleaching. Yellowness is another perceptual term that is sometimes used in dentistry. In general yellowness will increase with staining (or aging) and will be associated with an increase in chroma and a decrease in lightness; it is also likely to be reduced by bleaching. It is possible that yellowness and whiteness are antonyms in practice; however, research is needed to explore this more fully. Note that the terms whiteness and yellowness are perceptual terms and quite distinct from the terms whitening and yellowing which refer to physical processes (such as bleaching and ageing). Note that a change in a single color attribute (as shown in each of the rows of Figure 2) with no change in the other attributes is very unlikely to happen as the result of a real physical process such bleaching, staining or ageing. Figure 3 shows the sorts of perceptual changes that typically results from actual physical processes such as bleaching or the deposition of a blue colorant on the surface of a tooth.

In dentistry there are several reasons why it is useful to assess tooth color [1]. Tooth color is assessed in order to enable a prosthetic (crown) to be produced that will be aesthetically pleasing to the patient [10]. Tooth color (particularly whiteness) is also assessed in order to quantify the efficacy of tooth-whitening systems [9]. Measurement of tooth color is used to assess clinical outcomes in a range of dental procedures including avulsion and replantation

[11]. A number of tooth shade guides are available and are routinely used to visually assess tooth color. Although visual assessment using shade guides is very useful there are some limitations [12-14]. Firstly, the visual assessment made by one operative may differ from that made by a different operative (the subjective problem). Secondly, the visual assessment may be influenced (see Figure 1) by the lighting or by the surround against which the tooth is viewed (the environment problem). Thirdly, the shade guide itself may not be optimal for the task in that the samples may not be uniformly spaced (the reference problem). For these reasons, methods to instrumentally assess tooth color are increasingly being used [15] and these are described in the next section.

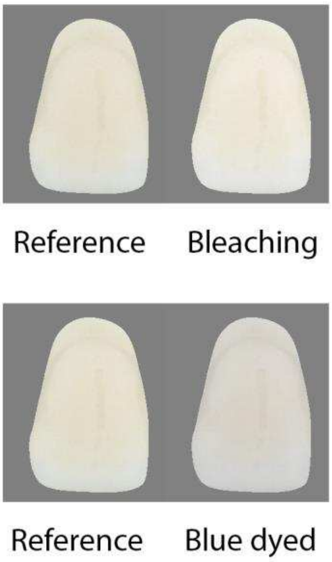


Figure 3: The top row shows the typical effect of bleaching where L* is increased and a* and b* are decreased. The bottom row shows the typical effect of the deposition of a blue colorant where L* is decreased and b* is decreased. Both processes result in a reduction in perceptual yellowness and an increase in perceptual whiteness. In order to address the question of which of the right-most teeth is whiter it is necessary to develop whiteness.

Traditionally shade guides have been used to assess tooth color. The Vitapan Classical shade guide, consisting of 16 shade guide tabs, is routinely used to assess tooth color. When arranged from lightest to darkest, this shade guide can be used for visual evaluation of tooth whitening [16]. The Vita Toothguide 3D-Master consists of 29 tabs that are ordered around the parameters of lightness, chroma and hue and has a broader color range than the Vitapan Classical shade guide [17]; however, it is less widely used for assessing tooth whitening because of the three-dimensional non-linear arrangement of the tabs [16]. The Vita Bleachedguide 3D-Master, which has 15 tabs (that consist of the odd numbers, 1, 3, 5, etc., in a 29-point scale) ordered in terms of whiteness, has been shown to be effective for the visual evaluation of changes in tooth whiteness [16].

Instrumental Measurement of Tooth Color

The reflectance properties of teeth can be defined by spectral reflectance factors that are normally measured at regular intervals in the visible spectrum of radiation. The reflectance factor at a certain wavelength is the proportion of incident light at that wavelength that is reflected and for teeth is almost always in the range 0-1. It is important to note that most of the light that is incident on the tooth surface penetrates the dentine and may be absorbed and scattered by the tooth enamel and dentine and any staining therein.

Commercially available reflectance spectrophotometers are able to measure reflectance factors (typically at intervals of 10 nm in the range 400 – 700 nm) and generally provide the most accurate measurement of color [2]. However, for teeth, it is not clear that they are the most accurate measurement method because the tooth surface is non-planar and also can be difficult to access in vivo. Although the spectral reflectance factors define the tooth physically, a psychophysical measurement of color requires the use of the CIE system of colorimetry. The CIE system allows the calculation of three numbers, known as tristimulus values XYZ. The CIE XYZ values depend upon the spectral power distribution of the illumination, the tooth spectral reflectance factors and the properties of the observer (the CIE system uses a standard observer obtained from the average visual responses of a number of individual observers).

Table 1: A comparison between different devices for measuring color that are used in dentistry.

Device	**Spectral data**	**Colorimetric data**	**Spatial data**	**Contact based**	**Comments**
Spectroradiometer	Yes	Yes	No	No	Measures spectral radiance which, with appropriate calibration, can be used to calculate spectral reflectance (and hence CIE XYZ and CEILAB values).
Colorimeter	No	Yes	No	Yes	Measures CIE XYZ and can compute CIELAB color coordinates.
Spectrophotometer	Yes	Yes	No	Yes	Measures spectral reflectance factors (and hence CIE XYZ and CIELAB values)
Digital Camera	No	Yes	Yes	No	Records RGB and these can be converted to approximate CIE XYZ values. Spectral data may be estimated with difficulty.

Three other types of measurement devices for tooth color are also used; spectroradiometers, colorimeters, and digital cameras (see Table 1). Spectroradiometers are spectral devices that measure light. Unlike the spectrophotometer they are not placed in contact with the tooth surface but rather measure spectral radiance from a distance. Unlike a spectrophotometer they do not have a built-in light source but use the ambient illumination. Appropriate calibration can allow the calculation of the CIE XYZ values for a color stimulus. Colorimeters measure the amount of light reflected using three broadband filters and yield CIE XYZ directly. Colorimeters are not considered to be as accurate as spectrophotometers (and certainly provide less information) but can nevertheless be useful devices. Recent years have seen the use of digital color cameras as color-measurement devices. The advantage of cameras is that they can provide color information at each spatial position on the tooth whereas the other three devices are limited to recording spatially averaged color.

All four of the devices in Table 1 are able to produce CIE XYZ values with varying degrees of difficulty and accuracy. The CIE XYZ system is a system of colorimetry (two samples with the same XYZ values will visually match under the viewing conditions specified in the CIE standard) whereas many dental researchers have more familiarity with the CIE (1976) L*a*b* or CIELAB system. The CIELAB system is a non-linear transformation of the XYZ system and is a color-appearance space. The CIELAB system also uses three numbers to represent a color. The Cartesian representation specifies color by L*, a* and b* but the polar representation specifies color by L*, C* (chroma) and h* (hue). The Cartesian representation has some advantage because it better maps on to the visual attributes lightness, chroma and hue.

The XYZ color space is often represented by chromaticity coordinates x,y where $x = X/(X+Y+Z)$ and $y = Y/(X+Y+Z)$. For a full specification it is necessary to also cite the luminance Y. The CIE chromaticity space formed by plotting x against y is illustrated in Figure 4.

Although general-purpose color-measurement instruments are sometimes used, the last couple of decades have seen the introduction of a number of instruments that are specifically designed for use in the oral cavity [18].

Equations that Predict Perceptual Whiteness

It is possible to measure color instrumentally using the devices listed in Table 1 but it is not trivial to denote each shade guide tab with a unique set of CIELAB values. The reason for this is the tabs are translucent and inhomogeneous in color in addition to having curved surfaces and being small in size; all of these factors mean that different color-measurement devices will likely produce slightly different CIELAB values. However, the more significant challenge is to relate changes in CIE XYZ, Yxy or CIELAB values to changes in perceptual whiteness. Figure 5 shows the variation in CIELAB values for the 16 classical shade guide tabs. Generally, whiteness increases with decreasing a* and b* (and C*) and increasing L*. Changes in whiteness that result from bleaching tend to produce correlated changes in a*, b* and L*. However, it is also possible to affect perceptual whiteness by a different whitening method such as the deposition of a blue colorant to the surface of the tooth [19]. Such use of blue colorants typically result in a decrease in b* and a decrease in L* (the tooth becomes bluer, or less yellow, but darker). Metrics are required to predict how changes in L*, a* and b* will affect perceptual whiteness.

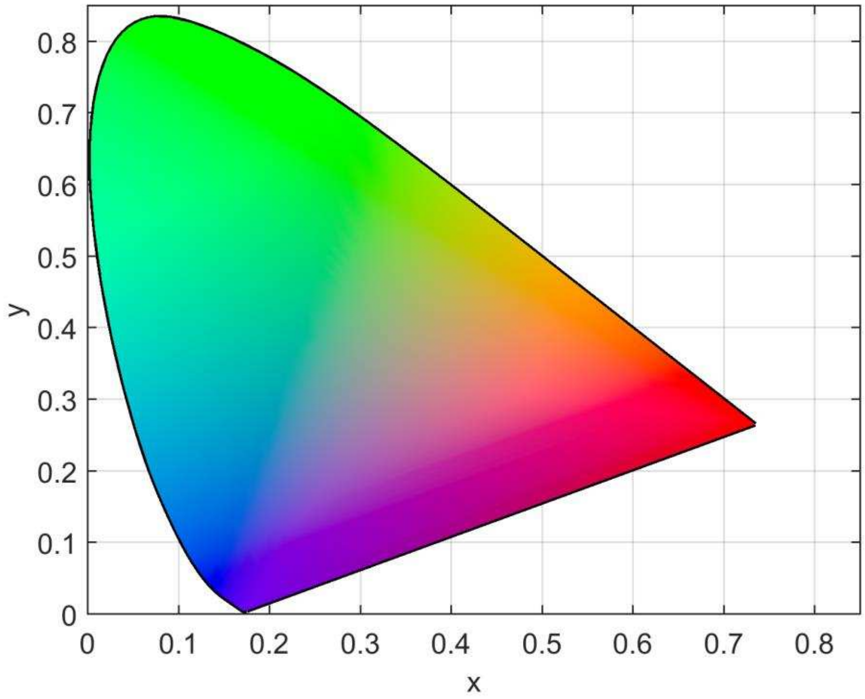


Figure 4: The CIE chromaticity diagram.

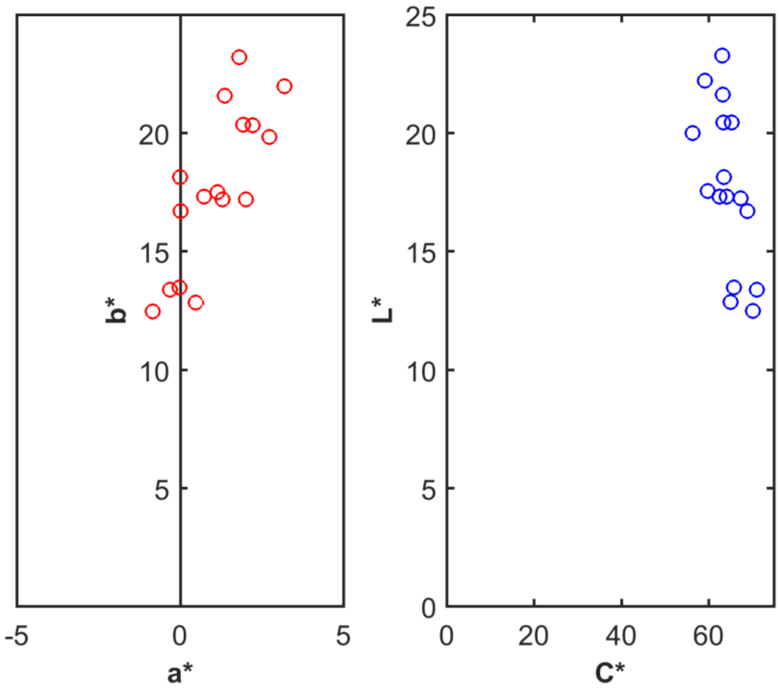


Figure 5: The CIELAB a*-b* (left) and L*-C* (right) coordinates of the 16 tabs in the Vita Classic Shade Guide [22]. Note that the changes in color attributes tend to be correlated (for example, L* increases as C* decreases).

The percept of whiteness has traditionally been assessed by a univariant metric known as a whiteness index [20]. A number of such whiteness indices have been developed for various industries, most notably for paper and textiles, and the CIE whiteness index WIC [21, 22] is widely used. Thus

$$WIC = Y + 800(x_n - x) + 1700(y_n - y) \qquad (1)$$

where Y, x and y are the colorimetric properties (luminance and chromaticity values) of the sample and x_n, y_n are the chromaticity values of the reference white (usually the light source used to view the samples). The CIE whiteness formula was modified and optimized for use with dentistry and is known as the WIO whiteness formula [23, 24]. Thus

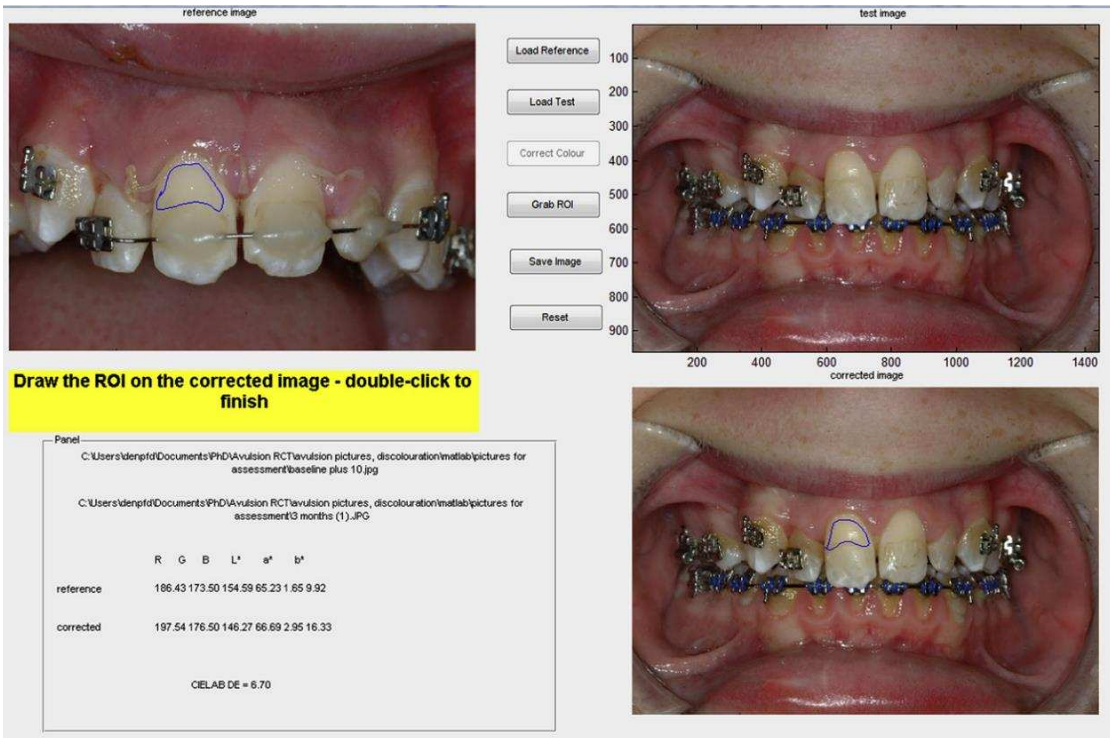
$$WIO = Y + 1075.012(x_n - x) + 145.516(y_n - y). \qquad (2)$$

The WIO formula was developed to predict perceptual whiteness under daylight (specifically the D65 illuminant) and therefore the values of x_n and y_n are 0.3138 and 0.3310 respectively. It is not clear whether and how the equation should be used if visual assessments are made under a different lighting condition. The WIO equation has been shown to be effective [25] and has been used in a number of clinical studies [25, 26]. However, one limitation is that it requires the user to understand about the XYZ color space and the associated chromaticity values xy. Many dental researchers are very familiar with CIELAB color space but are less confident in using CIE XYZ color space even though the calculations to move between the two spaces are trivial [27]. Recently, a new equation has been developed for use in dentistry that is based upon CIELAB color space and is referred to as WI_D [25]. Thus,

$$WI_D = 0.511L^* - 2.24a^* - 1.100b^* \qquad (3)$$

It is interesting to note that this equation weights changes of L* as being less significant in terms of whiteness than changes in b* (yellow-blue) which in turn is weighted less than a* (green-red). The performance of the WI_D equation was compared with that of several other whiteness indices (including WIO and WIC) using data from four psychophysical experiments [25]. The WI_D equation was shown to perform better than any other previously published whiteness equation based on CIELAB. WI_D performance was comparable to WIO (in one of the psychophysical experiments WI_D performed slightly better and in another WIO performed slightly better).

The application of digital imagery to the assessment of tooth color arguably provides a more accurate method to assess tooth color than other digital techniques or shade guides. However, in order to obtain accurate and precise color information from cameras requires substantial expertise and calibration processes [27, 28]. Cameras may have an advantage where the tooth is difficult to access or where the tooth surface is curved and also easily allow the color of different regions of the tooth to be recorded (e.g. gingival and incisal). A further important advantage of the digital camera (if calibrated correctly) is that it provides a visual record of how tooth color changes over time. For example, the image in Figure 6 is from a study to quantify discoloration after avulsion and replantation [11] and requires images to be collected at baseline and then after one year (or longer).



Draw the ROI on the corrected image - double-click to finish

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C:\Users\denpfd\Documents\PhD\Avulsion RCT\avulsion pictures, discolouration\matlab\pictures for
assessment\baseline plus 10.jpg

C:\Users\denpfd\Documents\PhD\Avulsion RCT\avulsion pictures, discolouration\matlab\pictures for
assessment\3 months (1).JPG

                R    G    B     L*    a*    b*

reference       186.43 173.50 154.59 65.23 1.65 9.92

corrected       197.54 176.50 146.27 66.69 2.95 16.33

                    CIELAB DE = 6.70
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Figure 6: MATLAB software used to facilitate accurate color measurement in an avulsion and replantation study [11].

Conclusion

Tooth color, and changes in tooth color, are important to both dental professionals and consumers. The whiteness and yellowness of teeth are two particularly important visual attributes. It is important to distinguish between visual attributes, such as whiteness and yellowness, and physical processes (such as bleaching and ageing) that may be associated with the visual attributes. Bleaching of teeth, for example, will usually result in an increase in lightness and a decrease in chroma, and an increase in whiteness. However, an increase in whiteness may also occur even if lightness decreases if there is a suitably large change in yellowness (this can occur, for example, in the application of blue-dye whitening technologies). As increasingly diverse physical processes are developed to modify tooth color, the assessment of changes in perceptual whiteness may become more difficult. Traditional color-measurement instruments (such as reflectance spectrophotometers and colorimeters) and digital cameras can be used and allow the objective assessment of color changes. Equations that can predict changes in whiteness have been specifically developed for use in dentistry but their robustness to a variety of whitening methods needs to be explored.

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