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# A review of tooth colour and whiteness

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ABSTRACT

*Objectives:* To review current knowledge on the definition of tooth whiteness and its application within dentistry, together with the measured range of tooth colours.
*Methods:* 'Medline' and 'ISI Web of Sciences' databases were searched electronically with key words tooth, teeth, colour, colour, white and whiteness.
*Conclusions:* The application of colour science within dentistry has permitted the measurement of tooth colour in an objective way, with the most common colour space in current use being the CIELAB (Commission Internationale de l'Éclairage). Indeed, many investigators from a range of different countries have reported $L^*$, $a^*$ and $b^*$ values for teeth measured *in vivo* using instrumental techniques such as spectrophotometers, colorimeters and image analysis of digital images. In general, these studies show a large range in $L^*$, $a^*$ and $b^*$ values, but consistently show that there is a significant contribution of $b^*$ value or yellowness in natural tooth colour. Further developments in colour science have lead to the description of tooth whiteness and changes in tooth whiteness based on whiteness indices, with the most relevant and applicable being the WIO whiteness index, a modified version of the CIE whiteness index.



## 1. Introduction

Tooth colour is an important topic not only for the professional who wants to select the correct tooth shade for aesthetic restorations or tooth bleaching procedures but also for patients and consumers who wish to enhance their smiles. Indeed, it has been reported, depending on age, that 12.1–15.5% of UK adult study population were dissatisfied with the appearance of their teeth and 17.9–21.3% were dissatisfied with their tooth colour.[1] In the USA it is reported[2] that 34% of an adult study population were dissatisfied with their current tooth colour and in China this figure was found to be 52.6% in an urban study population.[3]

Tooth colour is influenced by a combination of intrinsic colour and the presence of extrinsic stains that may form on the tooth surface.[4,5] Light scattering and absorption within enamel and dentine give rise to the intrinsic colour of the teeth and since enamel is relatively translucent, the properties of dentine can play a major role in determining the overall tooth colour.[6] Extrinsic stains tend to form in areas of the dentition which are less accessible to tooth brushing and the abrasive action of a toothpaste,[7] and are often promoted by smoking, dietary intake of tannin-rich foods (e.g. red wine) and the use of certain cationic agents such as chlorhexidine, or metal salts such as tin and iron.[4,8,9]

There are a number of methods and approaches to successfully improving the colour of teeth including whitening toothpastes, professional cleaning to remove stain and tartar, internal bleaching of non-vital teeth, external bleaching of vital teeth, microabrasion of enamel with abrasives and acid, and the placement of crowns and veneers.[10–13]

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The use of products for the bleaching of vital teeth has grown considerably over recent years and typically such products contain hydrogen peroxide or carbamide peroxide as the tooth whitening agents. They are either applied to the teeth under professional supervision or supplied as mass market products for home use. These latter products usually contain lower levels of the whitening agent (e.g. 3–6% hydrogen peroxide) and are self-applied to the teeth via gum shields, strips or paint-on product formats and usually require twice-per-day application for up to 2 weeks.[13]

Whitening toothpastes are based on formulations with enhanced physical and chemical cleaning ability in order to effectively remove and prevent extrinsic stains.[10,14,15] For example, the use of perlite as a cleaning and polishing agent has been added to both silica- and chalk-based toothpaste formulations to give enhanced extrinsic stain removal versus non-whitening toothpaste formulations, without causing an undue increase in abrasive wear towards enamel and dentine.[10,14]

With the continued interest in tooth whitening, the aim of this paper is to introduce aspects of colour science pertinent to teeth, including relevant whiteness indices and perception aspects of tooth colour together with a review of the range of tooth colour measured in different populations.

## 2. Colour science

Colour science[16] seeks to link the fundamental properties of light and matter to our perception of colour and our ability to capture and generate colour. As such, colour science has long been important to a wide range of manufacturing industries. We can divide the colour science problem into three domains: the colour properties of the lighting (illuminant), the colour properties of the object and the colour response of the detector (or observer).

Visible light comprises of photons whose wavelengths fall in the range between 360 nm and 780 nm. Light at the shorter wavelengths (~400 nm) appears blue whilst that at longer wavelengths (~700 nm) appears red. The Commission Internationale de l'Éclairage (CIE) defined[16] a range of standard illuminants which describe the intensity of a light source as a function of wavelength. One of the more commonly used is the D65 illuminant which corresponds approximately to the spectrum of midday daylight in Western/Northern Europe. Photons from the illuminant interact with materials, where they may be absorbed or scattered. Wavelength-dependent absorption in the visible region normally arises from the excitation of electronic transitions in molecules, although it is also possible to observe wavelength-dependent absorption and scattering through interactions with microscopic structures—such as the iridescent sheen seen in thin films of oil on water or on certain butterfly wings.

The amount of light absorbed or reflected by a material at each wavelength in the visible part of the spectrum can be measured using devices such as reflectance spectrophotometers which typically contain a diffraction grating that splits light into its constituent wavelengths. Typical instruments split the visible region into 10 nm bands giving a total of 31 wavelength readings (known as reflectance factors) across the visible region.

Spectrophotometers are not the only measurement devices for visible light; the most familiar alternative is the human visual system. Unlike a spectrophotometer the human eye is sensitive in only three channels corresponding to three different types of cone cell. These have peak *in vivo* sensitivities at short (440 nm), medium (545 nm), and long (565 nm) wavelengths, although each type of cell has some sensitivity over quite a broad wavelength range. To compute the visual response for a given spectrum of reflectance factors the reflectance factors are first multiplied by the appropriate illuminant data at each wavelength to give what is known as the colour signal $S(\lambda)$. The product of the colour signal $S(\lambda)$ and the response function for each of the three visual channels are then computed and the sum for each of these products to give three values are calculated. The CIE provide colour-matching functions (closely related but not identical to the response functions). The resulting sums of the products are known as the CIE tristimulus values $X$, $Y$ and $Z$ and are usually normalized such that $Y = 100$ for a white (an object with whose reflectance factor is 1 at every wavelength) irrespective of the colour or intensity of the chosen illuminant.

The tristimulus values are useful in physical calculations since they are linear with the spectral intensity. However, their perceptual meaning can be difficult to interpret. To complement the tristimulus values the CIELAB values are defined[16]:

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16, \quad \text{for } \frac{Y}{Y_n} < 0.00856,$$

$$L^* = 903.3\left(\frac{Y}{Y_n}\right),$$

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{1/3} - \left(\frac{Y}{Y_n}\right)^{1/3}\right],$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{1/3} - \left(\frac{Z}{Z_n}\right)^{1/3}\right]$$

where $X_n$, $Y_n$ and $Z_n$ are the tristimulus values for the chosen illuminant. The CIELAB, or CIE (1976) $L^*a^*b^*$ values have a perceptual meaning: $L^*$ is the lightness which relates to the physical intensity of a colour, whilst $a^*$ and $b^*$ are coordinates on the red–green and yellow–blue colour axes respectively. This scheme is designed such that a constant difference in colour, $\Delta E$, defined by the Euclidean distance in CIELAB space, thus:

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}}$$

should give a constant 'perceived' colour difference—regardless of the location in the colour space. The smallest perceivable difference for two coloured patches contacting one another is approximately 0.5–1.0 $\Delta E$ units.

Cameras and displays, in common with the human eye, usually have three sensors (or emitters) with principle sensitivities (or emission) in the red, green and blue.

## 3. Whiteness indices

In spectral terms a white material is one whose reflectance across the visible wavelength range is constant and high (i.e. close to 100% or reflectance factor of 1). Varying shades of gray to black have a constant reflectance with the perfect black having a reflectance of 0%.

Quantifying whiteness has long been of importance in the paper, laundry and paint industries. Several whiteness indices have been developed to address the needs of these industries, one is defined within the CIE nomenclature (WIC) along with a tint measure (T)[16]:

$$WIC = Y + 800(x_p - x) + 1700(y_p - y),$$
$$T = 900(x_p - x) - 650(y_p - y)$$

where $x$ and $y$ are the chromaticity coordinates defined from the tristimulus values:

$$x = \frac{X}{X+Y+Z}, \qquad y = \frac{Y}{X+Y+Z}$$

the subscript 'p' refers to the chromaticity of the white point for the colour space.

Perceptually whiteness has two components, one is luminance—i.e. the brighter something is the whiter it appears, the second component is the 'tint': generally shades that deviate too far from the white point are deemed to be less white than those of the same luminance. However, humans have a marked preference for 'bluish' white. This preference is not unbounded, ultimately when increasing the bluish tint of a sample it will cease to be described as 'white'. Whiteness indices capture both of these components. It is worth noting that the whiteness indices are typically only valid for a range of tint values so that outside this range they should not be used.

The use of whiteness indices to describe the whiteness of teeth in dentistry has, in general, received only limited attention in the literature. The CIE whiteness index (WIC) has been used *in vitro* to describe the whiteness of a series of porcelain teeth samples.[17] In another *in vitro* study,[18] WIC has been used on extracted teeth to investigate the whitening effects of either 15% hydrogen peroxide bleaching treatment for 1 h or brushing with toothpaste for 2 min. Tooth colour was measured by spectrophotometry and image analysis of digital images and WIC was calculated. It was shown that the bleaching protocol gave a significant increase in whiteness whereas the brushing protocol did not. In another study,[19] the shade tabs of the Vitapan Master 3D Shade Guide have been ranked in terms of WIC value from the whitest to the least white shade tab using image analysis techniques. In addition, the application of WIC in forensic dentistry has been considered for determining the age of dental skeletal remains.[20]

A whiteness index ($W^*$) has been described[21] based on the distance of a colour value from a nominal white point, represented in CIELAB colour space as $L^* = 100$, $a^* = 0$ and $b^* = 0$, and defined as

$$W^* = [(a^*)^2 + (b^*)^2 + (L^* - 100)^2]^{1/2}$$

Changes in the closeness to white ($\Delta W^*$) following a tooth whitening treatment can be calculated as

$$\Delta W^* = W^*\,(\text{treatment}) - W^*\,(\text{baseline})$$

This whiteness index has been used, together with $\Delta L^*$, $\Delta a^*$ and $\Delta b^*$ values, in a number of tooth bleaching studies to describe changes in tooth colour, for examples, after the use of 6.5% hydrogen peroxide product for 3 weeks[22] or a 6% hydrogen peroxide product for 7 days.[23]

Luo et al.[17] have recently proposed a modified version of the CIE whiteness index (WIO), based directly on observers scoring of the Vita 3D Shade Guide, defined as

$$WIO = Y + 1075.012\,(x_p - x) + 145.516\,(y_p - y)$$

This index has the same functional form as some previous whiteness indices but the parameters are different and are optimized specifically for the evaluation of whiteness in teeth. Indeed, it has been shown to be the most suitable index for predicting the whiteness of teeth and most appropriate for assessing changes in tooth whiteness.[24,25] In a clinical study[24] with 46 subjects, the changes in WIO index values were determined using digital image analysis techniques following 2 weeks use of either a non-whitening toothpaste or a 6% hydrogen peroxide tooth bleaching product. It was found that the bleaching product gave a larger increase in tooth whiteness than the toothpaste and the product difference was of statistical significance.

## 4. Tooth colour range

The colour of teeth has been measured *in vivo* in many different study populations using a number of techniques including spectrophotometers and colorimeters (Table 1).

From Table 1 it can be seen that there is a large range in the reported mean $L^*$, $a^*$ and $b^*$ values for anterior tooth colour, even from study populations from the same country. For example, in the USA based studies, the mean $L^*$ values were found to range from 51.1 to 73.3. This broad difference is most likely due to the difference in measurement techniques and conditions used. For example, colorimeters have been reported to be prone to significant edge-loss effects so absolute colour measurements will be subject to errors.[36] A further criticism of colorimeters is that systematic errors are difficult to manage and can be expected to adversely affect instrument accuracy regardless of degree of precision or control of environment.[28] In other words, inter-instrument agreement is relatively poor in comparison with intra-instrument reliability. Despite these issues, colorimeters have been shown to be highly sensitive when measuring tooth colour differences and changes.[37] The effect of different instrumental techniques giving rise to greatly different $L^*$, $a^*$ and $b^*$ values is further exemplified by the study of Cho et al.[32] (Table 1), where the tooth colour of the same study population was measured with both a colorimeter and a shade vision system.

From Table 1 it can be seen that, when reported, there is a large range in $L^*$ values within a study population. For examples, Gozalo-Diaz et al.[29] and Zhu et al.[34] report that $L^*$ values ranged from 38.0 to 89.5 and 21.89 to 83.75, respectively. In terms of reported $a^*$ values, these are generally more consistent across populations and the mean $a^*$ values ranged from −1.69 to 5.4. Further, the overall reported range of $a^*$ values is relatively small, with the largest reported range being −8.07 to 9.21.[34] In terms of reported mean $b^*$ values, these ranged from −0.2 to 19.4 depending on population, with the

**Table 1 – Reported $L^*a^*b^*$ values for anterior maxillary incisors measured *in vivo***

| Reference | Method | Subject demographics | | | Mean colour co-ordinates (S.D.) | | |
|---|---|---|---|---|---|---|---|
| | | Country | Number | Age (years) | $L^*$ | $a^*$ | $b^*$ |
| Rubino et al.[26] | Colorimeter | Spain | 600 | 15–50 | 67.6 (7.0) | 4.3 (2.1) | 12.1 (3.3) |
| Russell et al.[27] | Spectrophotometer | Ireland | 7 | Dental students | 48.31 | −1.35 | 2.73 |
| Russell et al.[27] | Spectrophotometer | Ireland | 7 | Dental students | 41.31 | −0.91 | 4.91 |
| Douglas[28] | Colorimeter | Canada | 7 | ? | 54.76 (4.16)<br>46.23–60.83 | 0.06 (0.75)<br>−0.72 to 2.02 | 6.37 (3.65)<br>1.92–14.70 |
| Gozalo-Diaz et al.[29] | Spectroradiometer | USA | 120 | >18 | 73.3 (7.7)<br>38.0–89.5 | 4.7 (2.3)<br>0.3–12.2 | 18.8 (4.9)<br>5.7–35.7 |
| Gegauff et al.[30] | Colorimeter | USA | 20 | 20–27 | 51.1 | −0.1 | −0.2 |
| Odioso et al.[2] | Spectrophotometer | USA | 180 | 13–64 | 69.3 (5.92) | 5.4 (1.33) | 18.7 (3.37) |
| Hasegawa et al.[31] | Spectrophotometer | Japan | 87 | 13–84 | 73.1 (5.6) | 3.4 (1.2) | 16.4 (3.9) |
| Cho et al.[32] | Colorimeter | Korea | 47 | >19 | 57.8 (3.5)<br>39.0–65.8 | −1.0 (0.9)<br>−5.1 to 4.0 | 6.7 (3.1)<br>−1.0 to 15.1 |
| Cho et al.[32] | Shade vision system | Korea | 47 | >19 | 74.0 (3.4)<br>64.5–83.2 | 5.0 (1.5)<br>1.6–9.8 | 19.4 (4.0)<br>10.4–29.0 |
| Zhao and Zhu[33] | Spectrophotometer | China | 70 | 18–70 | 51.48 (8.02) | 0.62 (0.14) | 0.15 (0.02) |
| Zhu et al.[34] | Spectrophotometer | China | 162 | 20–73 | 54.91 (6.39)<br>21.89–83.75 | −1.69 (1.56)<br>−8.07 to 9.21 | 9.19 (5.65)<br>−6.53 to 59.89 |
| Zhou et al.[35] | Colorimeter | China | 181 | 15–67 | 56.0–81.0 | −2.5 to 6.0 | 2.0–28.0 |
| Xiao et al.[3] | Colorimeter | China | 405 | 13–64 | 70.67 (1.91) | 4.29 (2.05) | 17.51 (4.13) |

largest reported range within a population of −6.53 to 59.89.[34] The vast majority of studies reported mean $b^*$ values greater than 6.

## 5. Perception of tooth colour

The perception of tooth colour is a complex phenomenon and can be influenced by a number of factors, including the type of incident light, the reflection and absorption of light by the tooth, the adaptation state of the observer and the context in which the tooth is viewed. For example, a study by Dagg et al.[38] showed that different light sources significantly reduced the accuracy of visual shade selection and a study by Curd et al.[39] showed that the ability of dental students to conduct shade matching improved under certain lighting conditions. Reflection and absorption of light by the tooth can be influenced by a number of factors including specular transmission of light through the tooth; specular reflection at the surface; diffuse light reflection at the surface; absorption and scattering of light within the dental tissues; enamel mineral content; enamel thickness; dentine colour, and the presence of extrinsic and intrinsic stains.[5,40] In terms of the human observer, experience, age, fatigue of the eye and physiological variables such as colour blindness can effect colour perception and colour matching.[5] In terms of the context in which the tooth is viewed, the perceived brightness of the tooth can change depending on the brightness of the background, and the perceived hue of the tooth can change depending on the colour of the background.[41] These latter factors can be influenced by, for example, gum and lip colour. Indeed, in a study by Reno et al.[42] it was shown using computer-generated images that tooth whiteness perception can be increased by adding a magenta hue to the gums.

Despite the reported limitations of visual shade matching of teeth, the use of shade guides is a quick and cost-effective method for measuring tooth colour. Indeed, there are a number of reported studies where shade guides have been successfully used to measure longitudinal tooth colour changes following tooth bleaching procedures.[13,43–45] Further, tooth colour discriminatory ability can be improved with training and it is often reported that investigators undergo a number of colour calibration exercises with shade guides when conducting tooth whitening studies.[13]

The appearance of teeth was found to be more important to women than men and significantly more important to younger people than older in a dental aesthetics attitudes survey involving 250 subjects.[46] In this study it was also found that the notion of having very white teeth as being beautiful significantly decreased with increasing age of the subject; younger subjects expressed a greater preference for white teeth than older subjects. This was in agreement with a study where photographs of four maxillary dentures, identical except for shade, were rank ordered for preference by 150 subjects, where it was found that older subjects preferred darker colours than younger subjects.[47] In a study[2] with 180 subjects, despite the older group (55–64 years) having significantly darker and more yellow teeth than the 13–17 years group, both groups expressed similar levels of dissatisfaction with their tooth colour, 30 and 27%, respectively. It was speculated that differential expectations among the age groups may affect colour satisfaction and that individuals may seek to have whiter teeth within their peer group rather than the whitest teeth possible.

The self perception of tooth whitening by bleaching has been investigated and compared to objective measurements of changes of tooth colour in a study with 50 subjects.[48] The subjective self perception of tooth whitening was investigated by completion of a questionnaire and the tooth colour changes were objectively measured using a digital image analysis system. The data was fitted into a probability model and it was found that the subjective responses to whiteness improvement and satisfaction were significantly correlated with changes in $b^*$ and not $L^*$ or $a^*$. Thus, $\Delta b^*$ (reduction in yellowness) is of primary perceptual importance to the user of vital tooth bleaching products.[49]

## 6. Conclusions

The application of colour science in dentistry has enabled the measurement of tooth colour in an objective way, with the most common colour space in current use being CIELAB. Indeed, many investigators from a range of different countries have reported $L^*$, $a^*$ and $b^*$ values for teeth measured *in vivo* using instrumental techniques such as spectrophotometers, colorimeters and image analysis of digital images. In general, these studies show a large range in $L^*$, $a^*$ and $b^*$ values, but consistently show that there is a significant contribution of $b^*$ value or yellowness in natural tooth colour. Further developments in colour science have lead to the description of tooth whiteness and changes in tooth whiteness based on whiteness indices, with the most relevant and applicable being the WIO whiteness index.

Because of the continued interest in tooth whitening by patients and consumers, the development and evaluation of new tooth whitening methods, technologies and measurement techniques will be a focus of attention for researchers and clinicians in the future, with the likely outcomes being of great value to the field of aesthetic dentistry.

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