

# Evaluation of colorimetric indices for the assessment of tooth whiteness

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## ABSTRACT

**Objectives:** To evaluate the performance of existing equations that measure perceptual whiteness of teeth.

**Methods:** Three new psychophysical experiments were conducted and combined with two previously published experiments to form a large set of data to test performance of whiteness indices. Three whiteness indices (WIC, WIO, WI<sub>D</sub>) were compared with regard to their ability to measure perceived whiteness. Coefficient of determination ( $r^2$ ) and '% wrong decisions' were used as measures of performance. One of the new experiments involved 500 participants across five different countries to explore the effect of gender, age and culture on whiteness perception.

**Results:** Equations (WIO and WI<sub>D</sub>) that have been optimized for use with tooth whiteness better correlated with visual perceptions of changes in tooth whiteness than the more general CIE whiteness index (WIC). The best performance was given by WIO (in terms of both  $r^2$  and % wrong decisions). No effect of age, gender or culture was found on whiteness perception.

**Conclusions:** WIO is a robust method for assessing whiteness of human teeth.

## 1. Introduction

The assessment of tooth whiteness is important in dentistry both in terms of communication of the benefits of products to consumers and the evaluation and comparison of different oral care products in clinical trials. Tooth whitening may be beneficial to patients because it can lead to better oral-care routines and higher self-esteem [1]. The development of equations that can predict perceptual whiteness is important to quantify the performance of whitening treatments and hence to optimize their efficacy.

Traditionally shade guides have been used to visually assess tooth color with the Vitapan Classical shade guide (which consists of 16 shade guide tabs) and the Vita Bleachedguide 3D-Master (which has 15 tabs that consist of the odd numbers, 1, 3, 5, etc., from a 29-point scale) being used extensively (VITA Zahnfabrik, Bad Sackingen, Germany). When using instrumental methods of assessing tooth color such as spectrophotometers, colorimeters or cameras, color is typically communicated using color systems that use three numbers for the complete identification of a color. There are many such color space systems available such as the CIE XYZ tristimulus values or the CIELAB system [2].

It is complex to relate three-dimensional changes in CIE XYZ or CIELAB values to changes in perceptual whiteness or yellowness,

particularly with respect to the weighting of relative changes for the individual components. Therefore industrial applications of color science for materials such as paper and paint have traditionally assessed whiteness using a univariant metric known as a whiteness index [3]. A number of such whiteness indices have been developed for various industries, most notably for paper and textiles, and the CIE whiteness index WIC [4,5] is widely used. Thus

$$\text{WIC} = Y + 800(x_n - x) + 1700(y_n - y) \quad (1)$$

where  $Y$ ,  $x$  and  $y$  are the colorimetric properties (luminance and chromaticity values) of the sample to be assessed 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 this modified form is known as the WIO whiteness formula [6,7]. Thus

$$\text{WIO} = Y + 1075.012(x_n - x) + 145.516(y_n - y) \quad (2)$$

The WIO formula was developed to predict perceptual whiteness of teeth under daylight (specifically the D65 illuminant) and therefore the values of  $x_n$  and  $y_n$  are 0.3138 and 0.3310 respectively. The WIO equation has been shown to be effective [8] and has been used in a number of clinical studies [8,9]. However, one limitation, as with other whiteness indices, is that it requires the user to understand the XYZ

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color space and the associated chromaticity values  $xy$  when in dentistry the most widely used color space is CIELAB [10]. Recently, a new equation has been developed for use in dentistry that is based upon the CIELAB color space and is referred to as  $WI_D$  [8]. Thus,

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

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). This seems slightly counter-intuitive since increases in whiteness are often particularly associated with changes in  $L^*$  and  $b^*$  [11].

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. The  $WI_D$  equation was shown to perform better than any other previously published whiteness equation based on CIELAB and performance was comparable to WIO (in one of the psychophysical experiments  $WI_D$  performed slightly better and in another WIO performed slightly better) [8].

It is far from clear, however, just how universal the construct of perceived whiteness of teeth is. For example, would observers in China rank a set of teeth samples for whiteness in the same order as observers in UK? In addition it is not known whether males and females share identical concepts of tooth whiteness. For this reason a new large-scale experiment was conducted in which 500 panelists (100 from each of 5 geographical regions) each ranked shade guide tabs in terms of whiteness. Each group of 100 subjects were balanced so that each included 50 male and 50 female and 50 younger adults (aged 18–30) and 50 older (aged > 30). The purpose of this experiment was to assess the validity of WIO and  $WI_D$  using a much larger set of data than has previously been used and to also explore whether a single equation is suitable for people of different age and from different cultures.

One limitation of most of the samples (usually shade guide tabs) that have been used in previous studies of this nature is that there are correlations between the colorimetric values. For example, generally we find that  $L^*$  decreases as  $b^*$  increases; and  $a^*$  decreases as  $b^*$  decreases. This is because the samples represent stages along the locus in color space that is naturally described by bleaching and ageing (that is the locus of tooth color). An example is shown in Fig. 1. The problem with correlations in the data set is that this allows multiple equations to fit the data with similar performance. However, these equations may perform very differently when presented with data that are not correlated. If the only processes that were used to change tooth color were bleaching and the natural ageing process then these correlations would probably always exist. However, recent years have seen the introduction of novel methods of achieving tooth whitening where these correlations may not exist (or where a different set of correlations may

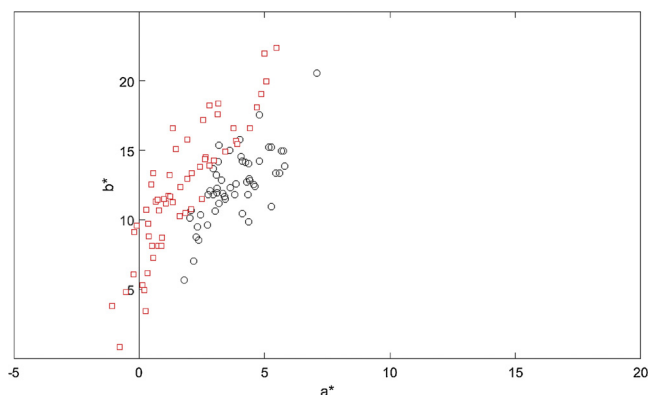


Fig. 1. CIE  $a^*$ – $b^*$  values of 29 Vita 3D Master Shade Guide and 29 Vita Extended Bleachedguide tabs used in PE3 (red squares) and custom-made disks used in PE4 (black circles) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Table 1

Summary of experimental details of the five data sets.

	N of observers	N of samples	Nature of the samples
PE1	9	26	Vita 3D Master shade guide
PE2	9	16	Vitapan Classical shade guide
PE3	500	58	Vita 3D-Master shade guide (29 tabs) Vita 3D Master Extended Bleachedguide (29 custom made tabs)
PE4	80	52	Custom-made ceramic disks (see Fig. 2)
PE5	53	45	Digital simulations on screen

exist) and it is not clear whether the previously published equations will perform well in such cases. Therefore an additional set of data was generated in this study using stimuli that were not correlated in color space. Because of the difficulty in creating such samples as physical shade guide tabs, the stimuli for this experiment were digitally simulated on a color-calibrated display.

## 2. Methodology

### 2.1. Psychophysical experiments

The data from five separate psychophysical experiments (PE1 – PE5) were used in this study. Two of these experiments (PE1 and PE2) were carried out by Luo et al. and have previously been published [7]. The other three experiments were carried out for this study; PE3 and PE4 were carried out with shade guide tabs (or ceramic disks) and PE5 was carried out using digital simulations of tabs presented on a computer display. The materials and methods for the five experiments are summarized in Table 1.

In PE1-PE4, participants were asked to rank the samples in order of perceptual whiteness when viewed under D65 daylight in a viewing cabinet. In PE5 a paired-comparison method was used where participants were asked to select which of a pair of digitally simulated samples was whiter when viewed on a color-calibrated display. The methods to calculate interval scale perceptual whiteness values from paired comparison or from ranking are widely published and understood [12–14]. For all the data sets (PE1-PE5) the raw data were used to calculate interval scale values that represent the relative perceptual whiteness of the samples involved. Two methods ( $r^2$  and %WD) were used to quantify the agreement between these perceptual whiteness values and the values of the whiteness indices that were being studied.

### 2.2. PE1 and PE2

In PE1 and PE2 9 observers ranked the 26 Vita 3D Master shade guide tabs and the 16 Vitapan Classical shade guide tabs respectively. Observations were carried out in a viewing cabinet with D65 illumination and a grey interior. Although the number of participants was small, these data are included in this study because they are the original data on which the WIO formula was developed (the equation was originally validated using a separate experiment with 88 observers). These data were previously published [7] but were available for use in this study.

### 2.3. PE3

PE3 was carried out at 5 distinct geographical locations (UK, India, Brazil, USA and China). In each location 100 participants were recruited in a balanced design to allow the effect of age, gender and culture to be assessed (25 young males, 25 young females, 25 old males and 25 old females). The young group was aged 18–30 and the old group were aged 30–60. Each participant was asked to rank each of 58 shade guide tabs in order of whiteness in a viewing cabinet under D65

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