Evaluation of Whiteness Formulae for Teeth

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ABSTRACT

In this study, various whiteness and yellowness indices were compared on their performance of measuring the whiteness of human teeth. Psychophysical experiments were conducted by 9 observers on teeth whiteness perception. According to visual results, the Pearson correlation coefficient and '% wrong decision' method were applied to determine the best index for teeth whiteness measurement. A modified version of whiteness formula (WIO) was introduced by optimising the original CIE whiteness formula (WIC) and it was found that WIO is the most suitable index for predicting the whiteness of teeth.

1. INTRODUCTION

Whiteness is an attribute of colours of high luminous reflectance and low purity situated in a relatively narrow region of the colour space along dominant wavelengths between 570nm and 470nm[1]. Whiteness is recognised as being a special colour attribute and much work has been carried out to defining whiteness colorimetrically. Literally hundreds of whiteness formulas exist and have been applied in the past. There are many industries in which the whiteness index is a useful measure of manufactured products. In order for a whiteness index to be valid, it must be used on the type of materials for which it was intended. Also, when items are being compared using a whiteness index, they must be similar in gloss, texture, translucency, and other physical attributes. The three most widely used indices currently are the CIE Whiteness Index (WIC), the whiteness index according to the ASTM E-313-73 (WI), and the Z% index.

As tooth whitening is becoming more popular and a routine dental or home procedure, there is a growing requirement for quantification of perceived tooth whiteness.[2] Some work has been carried out to assess whether the CIE whiteness formula can predict the perception of tooth whiteness[3]; however, there is still some uncertainty of its applicability since the formula was designated to be used only with samples whose colour coordinates were within a narrow range[4] and the colour of teeth appear to be outside this range[5]. In this study a psychophysical experiment was conducted to rank samples of the Vita 3D Shade Guide in order of perceptual whiteness. Various candidate metrics were evaluated in terms of their ability to predict the psychophysical results. Since some researchers[6] consider that changes in yellowness are the most important component of whiteness, two widely used yellowness indices and CIELAB b* were also investigated.

2. METHOD

A total of 9 observers were asked to rank 26 teeth samples of the Vita 3D shade guide in order of perceived whiteness when viewed on a neutral gray background under a light source approximating the CIE D65 illuminant. The ordinal-scale rank data were then converted into interval-scale z scores[7]; the higher the value of the z score, the greater the perceived whiteness.

In order to calculate the whiteness and yellowness indices, the tristimulus values of teeth were first obtained. The spectral reflectance of each of the teeth was measured using the Minolta CS1000a spectroradiometer. This instrument recorded the spectral power at each wavelength interval and this was divided by the spectral power of the light source to yield the spectral reflectance factors. This non-contact measurement technique was preferred to the use of a contact reflectance spectrophotometer because of the curved surfaces and translucent nature of the teeth. The CIE XYZ values for each of the teeth were computed (D65 illuminant; 1931 CIE standard observer). The candidate metrics considered were three whiteness indices (WIC, Z%, WI), the CIELAB b* value (b*), and two yellowness indices (E313, D1925).

The CIE whiteness formula (WIC) is given as equation (1), where (x, y) and (x_n, y_n) are the chromaticity coordinates of the sample and the reference white respectively, thus,

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

The Z% whiteness index is computed from the CIE Z value, where Z_n is the CIE Z value of the reference white, thus,

$$Z\% = 100\frac{Z}{Z_n} \quad (2)$$

A whiteness index (WI) that combines Z% with luminance factor was also evaluated thus,

$$WI = 4Z\% - 3Y \quad (3)$$

The E313 and D1925 yellowness indices were also evaluated.

$$YIE313 = 100\left(1 - \frac{0.847Z}{Y}\right) \quad (4)$$

$$YID1925 = \frac{100(1.275X - 1.057Z)}{Y} \quad (5)$$

A modified version of the CIE Whiteness Index (WIO) was tested where the numerical coefficients in equation (1) were optimized to give the best fit with the visual data. Ganz[8] formulated a general formula as shown in Equation 6 and the values of P and Q were optimized,

$$W = Y + P(x_n - x) + Q(y_n - y) \quad (6)$$

The Pearson correlation coefficient between the linear z scores and the whiteness or yellowness indices was computed as a measure of goodness of fit between the visual data and the models.

3. RESULTS

Figure 1 shows the plot of the z scores against the WIC for the 26 porcelain tooth samples. The correlation coefficient (r^2) was about 0.87. Table 1 lists the correlation coefficients (r^2) for all the indices that were tested. The higher value indicates better correlation between the index and the visual result. The CIE Whiteness Index (WIC) gave the best performance of the various published indices.

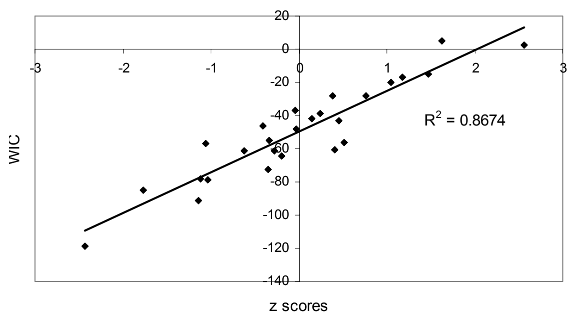


Figure 1: The visual results (z scores) vs. CIE Whiteness Index (WIC).

The optimized version of the CIE Whiteness Index WIO, shown in equation (7), was tested and its performance was compared with the other indices.

$$WIO = Y + 1075.012(x_n - x) + 145.516(y_n - y) \quad (7)$$

Table 1: Pearson correlation coefficients between the various indices and z scores from visual assessment.

Indices	WIO	WIC	Z%	Y(D1925)	Y(E313)	CIELAB b*	WI
r^2	0.93	0.87	0.85	0.85	0.81	0.62	0.56

After optimization of the coefficients of the WIC formula according to the visual results, the new formula (WIO) gave a correlation coefficient of 0.93.
Although the correlation coefficients of all of the formulae are quite high, it is difficult to infer whether the use of any of the whiteness formulae would be adequate in practical terms. An additional analysis based upon the statistical method called '% wrong decisions' was used in this study. In this method the rank data were analysed in terms of pair-wise comparisons; for the 26 teeth there were 325 possible paired combinations. For each pair the individual observer rankings were used to assess which sample would be perceived to be whiter. The consensus of the visual assessments was considered to be the standard (correct) answer. The performance of each observer was then computed (in terms of per cent wrong decisions) and was found to be in the range of 1.85~12% with an average about 5.71%. The same method was applied to the indices (comparing the instrumental decision with the visual consensus) and the per cent wrong decisions are listed in Table 2.

Table 2: The average percent wrong decisions for observers and various indices using 325 teeth pairs.

325 pairs	Observer	WIO	WIC	Z%	Y(D1925)	Y(E313)	CIELAB b*	WI
% error	5.71	5.85	13.54	8.92	12.31	16.00	22.46	25.54

The benefit of this analysis is that it becomes apparent that if any of the indices were used for predicting whiteness, the performance would be worse on average than that of a human observer selected at random. For example, the use of b^* would result in four times as many wrong decisions as the average observer. We argue that although the CIE Whiteness Index (WIC) strongly correlates with the visual assessments ($r^2 = 0.87$) it still cannot be considered to be adequate since its use would generate about 13.5% wrong decisions (compared with an average visual performance of 5.7%). However, since the optimized formula WIO yields only 5.8% wrong decisions it may be considered adequate for the assessment of tooth whiteness.

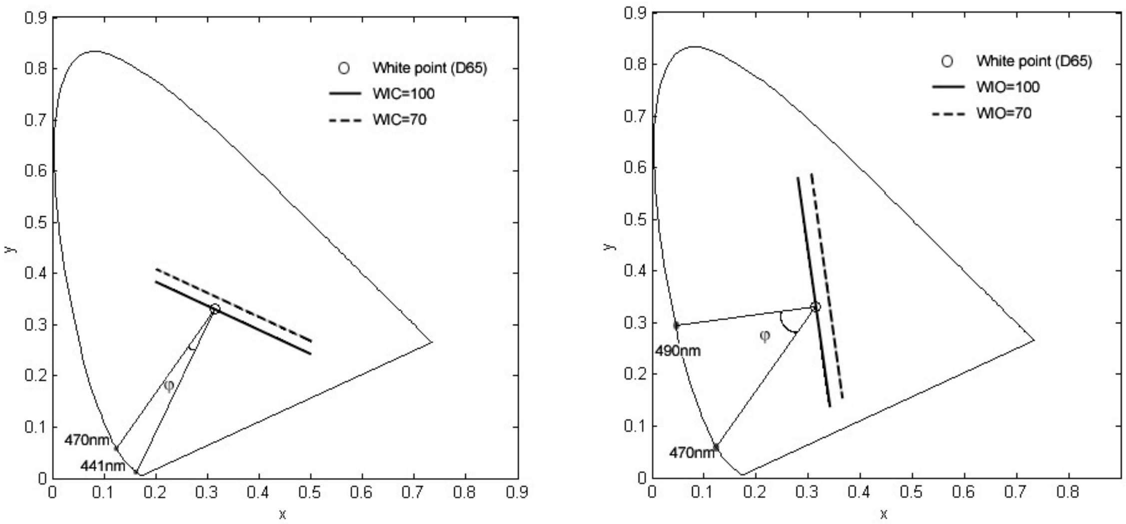
The low values in Table 2 are caused by the fact that many of the pairs included samples that were very different in terms of whiteness, e.g. Vita 3D tooth tab 1M1 (the lightest one) versus 5M3 (the darkest one), and so were, perhaps, unrealistically easy to judge. The analysis was therefore repeated with just 25 paired comparisons where each pair consisted of the adjacent samples in the average visual ranking. For this analysis the visual per cent wrong decisions were in the range 0~20% with an average of 8.44%. From Table 3 it can be seen that apart from the modified formula (WIO) the performance of all of the indices is worse than that of the average observer. Only the performance of the optimized formula (WIO) can be said to be adequate.

Table 3: The average percent wrong decisions for observers and various indices using 25 adjacent teeth pairs.

25 pairs	Observer	WIO	WIC	Z%	Y(D1925)	Y(E313)	CIELAB b*	WI
% error	8.44	8.00	16.00	16.00	24.00	28.00	32.00	32.00

In order to investigate why the optimized formula (WIO) performs better than the original CIE Whiteness Index (WIC) the formulae were rearranged to allow loci of iso-whiteness to be plotted in the CIE chromaticity diagram.

Figure 2 shows the iso-whiteness lines at two levels of whiteness for both the WIO and WIC formulae. In this diagram each line represents samples of constant whiteness but of different hue. It was found that these lines are all parallel and shift along their perpendicular line from higher to lower whiteness values. Since Ganz found that variations in whiteness of neutral tint caused by changes in colorimetric saturation are observed in range of dominant wavelengths of approximately 465-475nm, λ_d = 470 nm was selected as the reference dominant wavelength for neutral whites[8]. The angle φ between the dominant wavelength line and the perpendicular to the iso-whiteness lines is the hue preference angle. The angle φ of WIC is about 9.6 ^{o}, the dominant wavelength of its perpendicular is about 441nm (the intersection point of the perpendicular and the spectral locus) which indicates that bluish colours are considered to be whiter than yellowish colours in the WIC formula system. However, for the WIO equation, the hue preference angle is about -45^o; the dominant wavelength of the perpendicular is about 490nm, which is a cyan colour; this indicates that, for teeth, the greenbluish whites appear whiter than reddish whites. Therefore the effect of optimizing the coefficients in the WIO equation was to rotate the lines iso-whiteness compared with the original CIE whiteness index in chromaticity space. This indicates that the hue preference of observers when assessing the visual whiteness of teeth is different from that of observers when viewing other white objects for which WIC has been found to be quite satisfactory.



(a) (b)

Figure 2: The comparison of (a) the CIE Whiteness formula (WIC) and (b) the modified version (WIO) in the CIE chromaticity diagram with illuminant D65 and CIE 1931 2^o observer. Based on a dominant wavelength for neutral whites of 470nm the WIC formula can be shown to have a hue preference φ of 9.6^o whereas the new WIO formula has a hue preference of -45^o.

4. CONCLUSIONS

Various whiteness and yellowness indices were compared for their performance of predicting human teeth whiteness. According to visual results, it was found that the CIE whiteness formula (WIC) has the best performance among the existing published formulae that were tested. However, a further analysis showed that the predictions of tooth whiteness using the WIC formula may not be acceptable in they are less reliable than visual assessments made by the average human observer. A modified version of the whiteness formula (WIO) was developed which outperformed the WIC formula and which was shown to be acceptable in that it was as reliable as the average human observer.

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