Journal of Dentistry 67 (2017) S11–S14

Contents lists available at ScienceDirect

Journal of Dentistry

journal homepage: www.elsevier.com/locate/jdent

Investigation of the perceptual thresholds of tooth whiteness

Stephen Westland[a], Wen Luo[b,*], Yuan Li[a], Qianqian Pan[a], Andrew Joiner[b]

[a] University of Leeds, Woodhouse Lane, Leeds, LS2 9JT, UK
[b] Unilever Oral Care, Quarry Road East, Bebington, Wirral, CH63 3JW, UK

ARTICLE INFO

Keywords:
Tooth whitening
Tooth colour
Perceptual threshold
Visual assessment

ABSTRACT

Objective: To investigate the tooth whiteness perceptibility thresholds of the average observer to changes in the CIELAB values and an optimised whiteness Index for dentistry (WIO) based on psychophysical studies.
Methods: A psychophysical experiment based on visual assessments of digital images of teeth on a calibrated display with a group of observers (n = 32) has been conducted to determine the perceptual thresholds in tooth whiteness. Digital simulations of a tooth that is identical in shape to the left incisor in the image of teeth were superimposed on to images. The colour of the simulated tooth was varied and observers were asked to respond whether there was a difference in whiteness between the left incisor and the simulated tooth. Thresholds for detection of differences in whiteness were independently determined in four conditions: ΔL*, Δa*, Δb* and a blue optical whitening direction. Raw data were fitted using a non-parametric approach and thresholds of CIELAB and WIO for each conditions were calculated.
Results: Estimates of the threshold of the four conditions of ΔL*, Δa*, Δb* and a blue covarine optical tooth whitening direction were 1.14, 3.24, 1.11 and 1.51 respectively, with the corresponding WIO thresholds of 2.77, 6.52, 3.09 and 1.99 respectively.
Conclusions: The thresholds for tooth whiteness perception in CIELAB space and WIO space were determined. The findings demonstrate that for a whitening treatment with a blue covarine optical technology, a colour change of about 2 WIO units would be noticeable.
Clinical significance: This study gives a better understanding of the tooth whiteness perception threshold, and will help clinicians identify perceivable differences in tooth colour during matching and whitening procedures.

1. Introduction

Tooth whitening has become increasingly popular as a routine dental or home procedure [1]. This trend has been driving the development of tooth whitening methods and materials, including bleaching agents and whitening toothpastes [2–5]. Whitening toothpastes typically contain an optimised abrasive cleaning system to remove and control extrinsic stains and may contain other materials to enhance this process [6]. One approach to improving the intrinsic colour of teeth is via blue optical technologies, such as blue covarine, which when deposited onto the tooth surface help to reduce the yellowness of teeth and make them appear whiter [7].

The requirement for quantification of tooth colour, whiteness and its perception has also grown [8]. Traditionally, dentists and dental professionals assess tooth colour using a shade guide which provides a reference standard for visual comparison [9,10]. However, the consistency of different human assessors is hard to guarantee because of the variations in illumination, experience, age, fatigue of the human eye and colour blindness [11]. Alternatively, instrumental assessments are widely applied for tooth colour measurements, like colorimeters, spectrophotometers, spectroradiometers and digital cameras [5].

The colours measured by instruments are usually represented by Commission Internationale de l´Eclairage (CIE) XYZ tristimulus values or CIELAB values. In both CIE XYZ and CIELAB colour systems, three numbers are required to fully define any colour [12]. In the CIELAB system, the variable L* represents the difference in lightness between light (L* = 100) and dark (L* = 0); the variables a* and b* represent colour values on red-green and yellow-blue axes respectively. Both systems are widely used in dentistry to evaluate tooth whiteness. It is, however, not trivial to relate changes in L*a*b* or XYZ values to perceptual changes in whiteness. Whiteness is generally considered to be a one-dimensional percept defined by Ganz as 'an attribute of colours of high luminous reflectance and low purity situated in a relatively narrow region of the colour space along dominant wavelengths of 570 nm and 470 nm approximately'[13]. Many whiteness formulae have been developed and are widely used in industry including the CIE Whiteness

* Corresponding author at: Unilever R&D Port Sunlight, Quarry Road East, Bebington, Wirral CH63 3JW, United Kingdom.
E-mail address: Wen.Luo@unilever.com (W. Luo).

http://dx.doi.org/10.1016/j.jdent.2017.09.013
Received 17 July 2017; Received in revised form 20 September 2017; Accepted 25 September 2017

Index (WIC), the whiteness index according to the American Society for Testing Materials (ASTM) E-313-73 whiteness index, and the Z% index [14]. Most of these formulae were intended for general use or for use in fields outside of the dental industry (such as for use with papers and textiles). However, the WIO index was developed specifically to predict whiteness for teeth and has shown superiority over some of the more general formulae [15,16]. Recently, Pérez *et al.* [17] developed a customised whiteness index WI_D based on CIELAB colour space. WI_D was shown to have a performance comparable to WIO.

Currently, it is less clear what the perceptual threshold of tooth whiteness change is and therefore what degree of whitening is required in order that the change may be noticeable or acceptable. The threshold is difficult to determine because it may depend upon, for example, whether the criterion is one of perceptibility or acceptability. The just-noticeable difference between two coloured samples in general is also known to change with the size of the samples and, for example, whether they are viewed in such a way that they are perfectly adjacent or separated by a small difference in space. The just-noticeable difference can also depend upon the colour of the background against which the samples are viewed. These parametric effects have been rarely studied in the dental field and for application to whiteness thresholds specifically. In addition, practically, a patient or consumer may be interested in whether they can notice a difference in the colour of their teeth between a before-treatment condition and an after-treatment condition which brings in an additional parameter of colour memory. A study involving 30 observers and 58 tooth-coloured ceramic discs reported acceptability thresholds for lightness, chroma and hue of 2.92, 2.52 and 1.90 respectively but the units were in terms of the CIEDE2000 colour-difference equation [18]; differences in CIELAB units were not reported which makes their comparison with other studies difficult.

The objectives of the current study are to establish the visual perceptibility thresholds of tooth whiteness for the average observer to changes in CIELAB values individually and in a direction relevant to a blue covarine optical tooth whitening technology, and relate the threshold values to the tooth whiteness index (WIO).

2. Materials and methods

2.1. Image preparation

A digital image of teeth was taken using a colour-calibrated tooth imaging system [19,20]. The system allows the CIE XYZ values to be estimated at each pixel position. The image was cropped to reveal the oral cavity and gum area but excluding the lips (which were held back using lip retractors). A realistic shade-guide tab was added to the image and placed next to the upper left incisor (Fig. 1). For image display, the physical display unit (a LaCie ElectronBlue IV CRT cathode ray tube monitor) was characterised using standard methods in colour science [21]. The XYZ values at each pixel were therefore converted into RGB values that were specific to the characteristics (and settings) of the display so that accurate colorimetric data could be displayed.

Fig. 1. Typical image used in the experiment showing the shade-guide tab for the case where the stimulus (colour difference between the tooth and the tab) is zero.

The mean CIELAB values of the left upper frontal incisor were 63.90, 5.24 and 30.81, which were calculated from the captured image. The colour of the shade guide tab was varied in four different colour directions: changing L*, a*, b* individually and changing L*, a* and b* at the same time in a blue optical whitening direction. In the latter condition, the changes ΔL*, Δa* and Δb* were in the fixed ratio of 0.25:0.22:0.54. This ratio was based on an average tooth colour change as measured in several clinical studies of a blue optical technology where L*, a* and b* values were reduced after one brushing with an instant whitening toothpaste containing blue covarine [7,22].

2.2. Psychophysical experiment

Ethical clearance for the study was obtained from the Ethical Review Committee of University of Leeds. Observers were invited to the visual experiment and asked to take an initial colour-blind test. All of the observers were staff and students in the School of Design, none of them have received dental related training and therefore were considered as naive observers to tooth colour. According to a pilot study, the minimum number of observers was identified. In the formal study, thirty-two observers with normal colour vision participated in the study and were presented with the image as shown in Fig. 1. They were asked to respond, by clicking on the screen with a mouse, as to whether the shade-guide tab was whiter than the teeth to its immediate left. This is a classic yes-no task where the observer is asked whether they perceive a difference in whiteness [23]. The stimulus levels for all four conditions were 0, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, 2.25, 3.00 and 4.00. So, for example, in the case where L* was varied, the shade-guide tab was adjusted to be 0.75, 1.00, 1.25 etc. L* units lighter than the tooth next to it. For all except the 0-stimulus level (where there was no difference between the tooth and the shade-guide tab) each observer undertook eight repeats; the 0-stimulus level was repeated 16 times. Each observer was presented with 352 trials (4 conditions × 88 images) so that a total of 11,264 observations in total were made. For each observer the 352 trials were presented in a random order and the observers viewed the screen in a darkened room from a distance of about 80 cm.

2.3. Data analysis

Table 1 shows some typical results for one particular observer. These are presented to make the experimental details clear. The left-most column shows the stimulus levels (the difference between the simulated tooth and the comparison tooth). In the other columns, the proportion of times that the observer responded yes (that they could see a difference) is recorded for the conditions of L*, a* and b*, as an example.

The data from Table 1 defines a psychophysical curve that characterises the observer's responses. When the stimulus is 0 the proportion of times that the observer responds yes tends towards 0; when the stimulus is very large, the proportion of times that the observer

Table 1
Example psychophysical data for one observer for the L*, a*, b* conditions.

Stimulus	△L*	△a*	△b*
0.00	0.375	0.375	0.500
0.75	0.500	0.125	0.500
1.00	0.250	0.375	0.750
1.25	0.375	0.000	0.625
1.50	0.875	0.375	0.250
1.75	0.875	0.125	0.750
2.00	0.625	0.000	0.875
2.25	0.750	0.125	0.625
3.00	1.000	0.000	1.000
4.00	1.000	0.000	1.000

responds yes tends towards 1. The detection threshold can be defined as the stimulus level for which performance is at 50% detection rate. The observer task in this study is to ask the observer if the simulated tooth is whiter than the original one, which is referred to as 2afc (two-alternate forced choice) and the observer will perform at 50% even when they cannot detect the difference between the two stimuli. Therefore, in a 2afc task the chance performance is 50% and detection performance is therefore considered to be at 75% (halfway between chance performance and perfect performance). In order to determine the threshold for a set of psychophysical data it is standard practice to fit a function to the data [24]. It is normal to fit the data with a curve in order to provide the estimate of threshold. However, Zychaluk and Foster [25] have pointed out that different models typically result in different estimates of the threshold. Zychaluk and Foster [25] have developed a non-parametric approach to fitting the psychometric function and have provided MATLAB (MathWorks Inc., USA) code online to allow the implementation of their method [26]. This method has been used to analyse all of the data obtained in this study. Note that the Zychaluk and Foster software also yields estimates of the standard deviation of the threshold.

3. Results

A total of thirty-two observers took part in the experiment. The data was pooled for all observers and is shown in Fig. 2. The psychometric data was fitted using the nonparametric method of Zychaluk and Foster [25].

Table 2 lists the average thresholds in the CIELAB colour space for the four conditions generated by analysing the psychophysical data for the 32 observers. The corresponding WIO thresholds were calculated from the thresholds in CIELAB space. The thresholds for the four conditions ΔL*, Δa*, Δb* and the blue direction are 1.14 (0.04), 3.24 (0.33), 1.11 (0.04), 1.51(0.06) respectively. The values in parentheses are the standard deviations.

Table 2
Thresholds with standard deviations in the CIELAB and WIO colour space.

Directions	L* Direction	a* Direction	b* Direction	The Blue Direction
Thresholds in L*, a* or b*	1.14 (0.04)	3.24 (0.33)	1.11(0.04)	1.51(0.06)
Thresholds in WIO	2.77	6.52	3.09	1.99

4. Discussion

The results from this study suggest that thresholds for discrimination of whiteness are approximately in the range of 1.10-1.15 units for L* and b*, 3.24 for a* and 1.51 units for the combined change in L*, a* and b* together with the fixed ratio for the blue optical technology. The psychometric curve showed an unexpected shape for a* indicating the thresholds for a* may be considered less reliable. This may be due to the observers having difficulty in perceiving whiteness along the a* direction alone, as this may not be a natural direction for tooth whitening.

The corresponding WIO was calculated based on the baseline tooth colour and the thresholds identified for L*, a* and b*. When only changing the lightness (L*) of tooth colour, the just noticeable difference in whiteness is 2.77 WIO units, whereas when only changing the b* direction, the just noticeable difference in whiteness is 3.09 WIO units. These two thresholds are close in values, which suggests that when only changing L* or b* on their own with the same amount, the perceived whiteness change is in a similar range. However, tooth

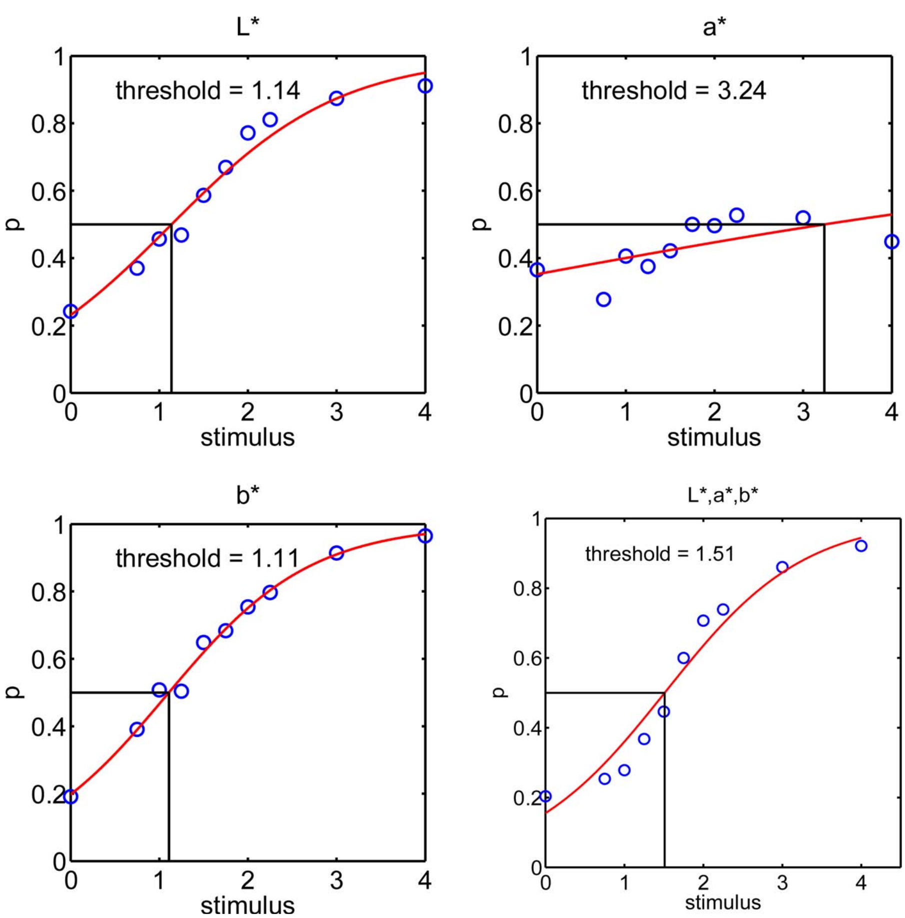

Fig. 2. Data for all four conditions pooled over all 32 observers. The psychometric data have been fitted using the nonparametric method of Zychaluk and Foster [25] and estimates of the threshold obtained for p = 0.5.

whitening procedures do not change only one of the L*, a* and b* values, but will change all three simultaneously, the exact ratio of change in L*, a* and b* depending on the whitening procedure used. Indeed, tooth whitening following use of a blue covarine containing toothpaste changed all three values of L*, a* and b* simultaneously, as measured in clinical studies [7,22]. The threshold for just noticeable difference in whiteness for the blue direction is 1.99 WIO units, which is smaller than the individual thresholds for the L*, a* and b* directions. This demonstrates that when changing tooth colour in the three dimensions of colour space at the same time, which is the normal situation for tooth whitening procedures, the whiteness changes will be easier to detect visually than when changing only one CIELAB colour co-ordinate.

A previous study about the perceptibility and acceptability of small colour differences found that the average CIELAB colour difference for 50% of the observers to perceive a colour difference was 1 ΔE^*_{ab} unit [27]. Although this study was not specific for dental materials, it tested a wide colour spectrum that may cover a range of tooth colours. In addition, there was a trend suggesting that colour perceptibility thresholds were generally lower than colour acceptability thresholds. Another study [28] evaluated colour perceptibility using translucent colour porcelain disks with a group of dental professionals, their results suggested that colour difference in porcelain disks of about 2 ΔE^*_{ab} units or greater would be detected 100% of the time, and for 80% probability of observers reporting a colour difference was about 0.5–1.0 ΔE^*_{ab} units.

In a more recent study, computer-generated pairs of tooth-shaped patches of colour embedded in simulated gingiva were shown to observers consisting of dental professionals and dental patients. The results indicated that colour differences of about 1.25, 1.25, 2.8 ΔE^*_{ab} units in the L*, a*, and b* directions respectively of CIELAB colour space were perceivable [29]. The threshold in the L* direction in the current study of ΔE^*_{ab} 1.14 is consistent with previously published data. However, the thresholds in the a* and b* directions varies from study to study. This is most likely to be due to differences in the test protocols, conditions and stimuli used in the different studies. In the study by Lindsey and Wee [29], teeth stimuli shown to observers were two uniform colour patches, rather than images taken from real teeth; and the layout of the stimuli was a side-by-side pair comparison, rather than a simulated tooth beside an incisor in the image as per the current study. These latter conditions can be considered closer to the procedure used for tooth colour matching procedures. In a study with smiling facial images showing anterior teeth [30], the perceptible thresholds for the teeth were in a similar range of 1.45-2.9 ΔE^*_{ab}. For these facial images, the a* and b * thresholds were comparable, whereas the L* depended on portrait type with the Caucasian face having a significantly higher threshold than the African-American face. This indicates the importance of background and context in determining tooth colour perceptibility and acceptability thresholds.

5. Conclusions

The threshold values for tooth whiteness perception in CIELAB space and WIO space were determined. The findings demonstrate that for a whitening treatment containing a blue covarine optical technology, a colour change of about 2 WIO units would be noticeable.

Conflict of interest statement

Wen Luo and Andrew Joiner are employees of Unilever Plc.

References

[1] S.R. Kwon, P.W. Wertz, Review of the mechamism of tooth whitening, J. Esthet. Restor. Dent. 27 (2015) 240–257.

[2] A. Joiner, Tooth colour: a review of the literature, J. Dent. 32 (Supplement 1) (2004) 3–12.

[3] A. Joiner, I. Hopkinson, Y. Deng, S. Westland, A review of tooth color and whiteness, J. Dent. 36 (Supplement 1) (2008) 2–7.

[4] S.R. Kwon, M. Meharry, U. Oyoyo, Y. Li, Efficacy of do-It-Yourself whitening as compared to conventional tooth whitening modalities: an In vitro study, Operative Dent.: Jan./Feb. 40 (No. 1) (2015) E21–E27.

[5] A. Joiner, W. Luo. Tooth colour and whiteness: a review. Journal of Dentistry, this supplement.

[6] A. Joiner, Whitening toothpastes: a review of the literature, J. Dent. 38S (2010) e17–e24.

[7] A. Joiner, C.J. Philpotts, C. Alonso, A.T. Ashcroft, N.J. Sygrove, A novel optical approach to achieving tooth whitening, J. Dent. 36 (2008) S8–14.

[8] S. Westland, Review of the CIE system of colorimetry and its use in dentistry, J. Esthet. Restor. Dent. 15 (Suppl 1) (2003) S5–12.

[9] S. Paul, A. Peter, N. Pietroban, C. Hammerle, Visual and spectrophotometric shade analysis of human teeth, J. Dent. Res. 81 (2002) 578–582.

[10] C. Igiel, M. Weyhrauch, S. Wentaschek, H. Scheller, K.M. Lehmann, Dental color matching: a comparison between visual and instrumental methods, Dent. Mater. J. 35 (2016) 63–69.

[11] A. Watts, M. Addy, Tooth discolouration and staining: a review of the literature, Brit. Dent. J. 190 (2001) 309–316.

[12] Colorimetry, 2 ed., Central Bureau of the CIE, Vienna, 1986 (Publication No. 15.2).

[13] E. Ganz, Whiteness: photometric specification and colorimetric evaluation, Appl. Opt. 15 (1976) 2039–2058.

[14] E. Ganz, Whiteness measurement, J. Color Appear. 1 (1972) 33–41.

[15] W. Luo, S. Westland, P. Brunton, R. Ellwood, I. Pretty, N. Mohan, Comparison of the ability of different color indices to assess changes in tooth whiteness, J. Dent. 35 (2007) 109–116.

[16] W. Luo, S. Westland, R. Ellwood, I. Pretty, V. Cheung, Development of a whiteness index for dentistry, J. Dent. 37s (2009) e21–e26.

[17] M. Pérez, M. del, R. Ghinea, M.J. Rivas, A. Yebra, A.M. Ionescu, R.D. Paravina, L.J. Herrera, Development of a customized whiteness index for dentistry based on CIELAB color space, J. Dent. 32 (2016) 461–467.

[18] M. Perez, M. del, R. Ghinea, L.J. Herrera, A.M. Ionescu, H. Pomares, R. Pulgar, R.D. Paravina, Dental ceramics: a CIEDE2000 acceptability thresholds for lightness, chroma and hue differences, J. Dent. 39 (2011) e37–44.

[19] R.N. Smith, L.Z. Collins, M. Naeeni, A. Joiner, C.J. Philpotts, I. Hopkinson, C. Jones, D.L. Lath, T. Coxon, J. Hibbard, A.H. Brook, The *in vitro* and *in vivo* validation of a mobile non-contact camera-based digital imaging system for tooth colour measurement, J. Dent. 36 (2008) S15–20.

[20] ASTM, Standard Test Method for Colorimetry of Teeth Using Digital Still Camera Technology, (2011), pp. E2466–E2506.

[21] S. Westland, C. Ripamonti, Computational Color Science Using MATLAB, 1st ed., Wiley, 2004, 2017.

[22] L.Z. Collins, M. Naeeni, S.M. Platten, Instant tooth whitening from a silica toothpaste containing blue covarine, J. Dent. 36 (2008) S21–5.

[23] M.R. Leek, Adaptive procedures in psychophysical research, Percept. Psychophys. 63 (2001) 1202–1279.

[24] B. Treutwein, H. Strasburger, Fitting the psychometric function, Percept. Psychophys. 61 (1999) 87–106.

[25] K. Zychaluk, D.H. Foster, Model-free estimation of the psychometric function, Attention, Percept. Psychophys. 71 (2009) 1414–1425.

[26] Foster DH. (2016), http://personalpages.manchester.ac.uk/staff/d.h.foster/software-modelfree/latest/home, (last accessed 3rd May 2016).

[27] R.G. Kuehni, R.T. Marcus, An experiment in visual scaling of small color differences, Color Res. Appl. 4 (1979) 83–91.

[28] R.R. Seghi, E.R. Hewlett, J. Kim, Visual and instrument colorimetric assessments of small color differences on translucent dental porcelain, J. Dent. Res. 68 (1989) 1760–1764.

[29] D.T. Lindsey, A.G. Wee, Perceptibility and acceptability of CIELAB color differences in computer-simulated teeth, J. Dent. 35 (2007) 593–599.

[30] D.T. Lindsey, A.G. Wee, Assessing tooth color differences in digital facial portraits, J. Dent. 89 (2010) 1254–1258.