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Investigation of the perceptual thresholds of tooth whiteness

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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

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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