DENTAL MATERIALS 35 (2019) 292–297

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Whiteness difference thresholds in dentistry

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ARTICLE INFO

Article history:
Received 5 September 2018
Received in revised form
12 November 2018
Accepted 15 November 2018

Keywords:
Whiteness threshold
Perceptibility
Acceptability
Whiteness index dentistry
CIELAB color space

ABSTRACT

Objective. To determine the visual whiteness thresholds for esthetic dentistry using the whiteness index for dentistry based on CIELAB color space (WI_D).

Methods. A total of 60 observers (Dentists and Laypersons; n = 30) from three research sites participated in the study. A psychophysical experiment based on visual assessments of simulated images of teeth on a calibrated display was performed. Images of simulated upper central incisors (SUCI) were consecutively displayed in pairs (60) and the whiteness of each SUCI pair was compared. WI_D was used to calculate the visual thresholds (WPT- perceptibility threshold; and WAT- acceptability threshold) with 95% confidence intervals (CI) and a Takagi-Sugeno-Kang (TSK) Fuzzy Approximation model was used as fitting procedure. Data was statistical analyzed using paired *t*-test ($\alpha = 0.05$).

Results. WPT and WAT were 0.72 (CI: 0.0–2.69; $r^2 = 0.52$) and 2.62 (CI: 0.2-7+; $r^2 = 0.57$) WI_D units, respectively. Significant differences ($p < 0.05$) were found between WPT and WAT, and between dentist (WPT = 0.46WI_D units; WAT = 2.20 WI_D units) and layperson (WPT = 0.94 WI_D units; WAT = 2.95 WI_D units).

Significance. The visual whiteness difference thresholds determined with WI_D index can serve as reference values for research and manufacturing of dental materials, and for clinical practice situations such as assessing the effectiveness of bleaching treatments.

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1. Introduction

Non-invasive teeth whitening procedures are among the most popular treatments currently used in dental practice to improve tooth color and appearance [1–3]. Nowadays, there are many vital tooth bleaching procedures, including in-office bleaching, at-home bleaching and over-the-counter bleaching systems [2,3]. Different bleaching agents and concentrations, product format, application and times of application have been reported [2].

CIELAB color space and its associated color differences formulas are extensively used for color measurement and color evaluation in dentistry. In this sense, whiteness variations are

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https://doi.org/10.1016/j.dental.2018.11.022
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usually evaluated by means of total color differences or differences among one of the three axes that describe the CIELAB color space (ΔL^*: differences in lightness; Δa^*: differences in red–green axis; and Δb^*: differences in yellow–blue axis) [4–8].

Whiteness (level of white) of a material is adequately portrayed using a whiteness index. Whiteness indexes or formulas based on the CIE1931 XYZ color notation system [9], such as the CIE whiteness index (WIC) [10–12] and the whiteness index according to ASTM E-313-73 (WI) [13], have been used in dental research [14,15]. In this sense, an optimized index for evaluation of tooth whiteness (WIO), which preserves the functional form of the CIE WIC index, was developed [16]. Recently, a new customized and easy to use CIELAB-based whiteness index for dentistry (WI_D) was introduced [17,18]. WI_D showed an improved correlation with the visual perception compared to all others CIELAB and CIE1931 XYZ-based whiteness or yellowness indexes tested under laboratory and clinical conditions [17].

Visual thresholds for color discrimination are well-established quality control tools in research and industry. Thus, according to the latest Guidance on color measurements published by the *International Organization for Standardization* (ISO/TR 28642:2016) [19], color variation should be assessed based on comparisons with 50:50% thresholds. Perceptibility difference threshold (PT) represents the lower perceptual limit and it can be applicable to study discernible colors by the human visual system [20]. However, in many practical situations, noticeable to greater differences above the PT are named acceptable color differences or color tolerances. The industrial interest on these differences is justified, mainly by the need of maintaining the differences under an admissible limit in clinical practice or industrial production. Several studies [21–23], showed that the acceptability and perceptibility color thresholds (AT and PT, respectively) values were significantly different using both CIELAB and CIEDE2000 color difference formulas. In addition, it has been shown [23–25] that patients are less discriminating (PT and AT values) than dentists.

A recent study [26] have conducted a psychophysical experiment based on visual assessments of digital images of teeth on a calibrated display to determine the perceptual thresholds for ΔL^* (1.14), Δa^* (3.24) and Δb^* (1.11) in tooth whiteness. Even though these values may be of interest, it is necessary to obtain threshold values based on specific whiteness indexes with a direct application for dentistry. In this context, studies on whiteness thresholds for dentistry that use the recommended CIELAB-based index (WI_D) and a suitable fitting procedure are not available.

Therefore, the purpose of this study was to determine 50:50% perceptibility and acceptability whiteness thresholds (WPT and WAT) using WI_D and the Takagi-Sugeno-Kang (TSK) Fuzzy model, testing the hypotheses that (1) there is a difference between WPT and WAT, and (2) WPT and WAT differ between dentists and laypersons.

2. Materials and methods

2.1. Stimuli

Reported CIELAB color coordinates of pre- and post-bleaching maxillary central incisors [27] were used to represent computer-simulated teeth. The CIE L*a*b* color coordinate range values for simulated teeth were as follows: L* = 59.9–84.1, a* = 1.9–8.1, and b* = 7.4–14.6, while the WI_D value ranged from 0.53 to 19.00 units. Whiteness index values were combined to create images of 60 pairs of simulated upper central incisors (SUCI) with WI_D differences ($\Delta WI_D = |WI_{D2} - WI_{D1}|$) ranging from 0.22 to 7.83 units. Fig. 1 shows the values of ΔWI_D for the 60 SUCI pairs organized by increasing order of ΔWI_D. Human gingiva was simulated based on reported values [28].

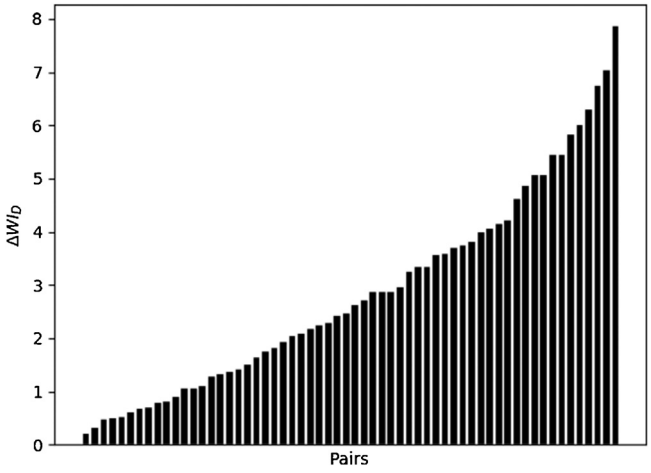

Fig. 1 – Distributionof ΔWI_D values (in increasing order) for the 60 pairs of stimuli used in the present study.

Determination of WI_D difference thresholds was based on computer-generated stimuli presented on a previously calibrated high-resolution 19" RGB monitor (i1Profiler, X-rite Europe GmbH, Switzerland). A custom-made software was used to stimulus presentation control and compilation of observer´s responses (Fig. 2).

2.2. Psychophysical experiments and data processing

Stimuli pairs of two adjacent upper central incisors (SUCI) were judged by a panel of 60 observers: 20 observers (10 dentists and 10 laypersons) from each of the three research sites (two in Europe and one in South America). All observers were screened for normal color vision using the Ishihara charts [29].

Similar to a previous study [28], observers sat in a darkened room, illuminated only by the light from the computer monitor. Prior to the visual judgment, observers viewed a uniform gray screen (mean luminance of 34 cd/m^2 and an approximate perceived reflectance of 0.25) for 10 min. Same uniform gray served as the surround of the stimulus configuration used during testing (Fig. 2). To standardize the observer's viewing distance and geometry, their head was positioned on a headrest, which kept the observer eyes at 30 cm away from the testing screen. Observers were instructed to focus on the stimulus area of the screen.

For perceptibility whiteness threshold (WPT) determination, observers had to answer (clicking a checkbox) the following question: "Can you see a difference in whiteness between the two teeth in the image?" In case of a positive answer, the observer was asked to answer the following question for acceptability threshold (WAT) determination: "Would

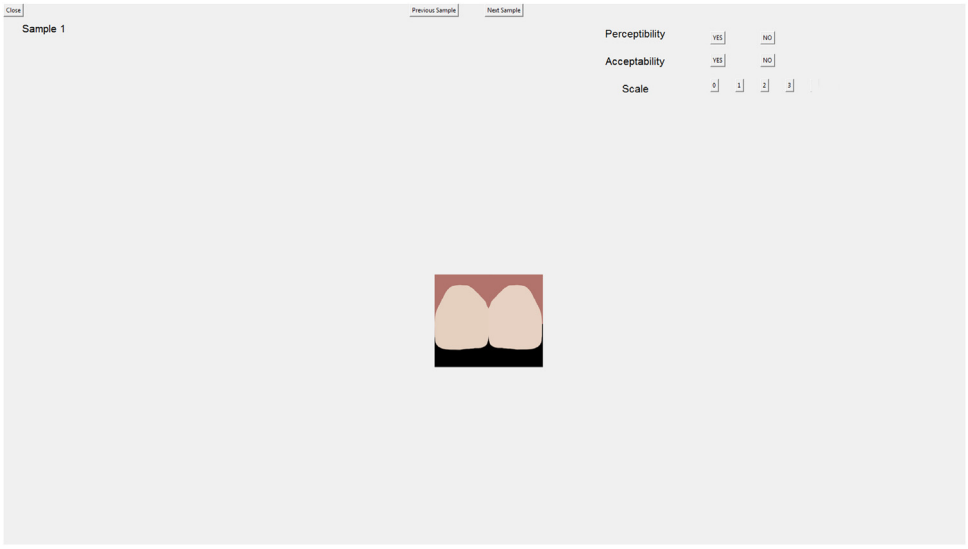

Fig. 2 – Stimulus configuration used to measure WPT and WAT.

you consider this difference in whiteness acceptable in a patient's mouth?" Any SUCI pair with a whiteness difference deemed not perceptible by the observer, it was considered as a clinically acceptable whiteness difference. For further discrimination of perceptible and acceptable whiteness differences [19], observers were requested to grade the whiteness difference as follows: 0- exact match (no difference in whiteness), 1- very good match (small difference in whiteness), 2-good match (fairly acceptable difference in whiteness), and 3-poor match (hardly acceptable difference in whiteness).There was no time constraint to complete the judgments. Observers were instructed on using the software during a pre-experiment training session.

Data was processed and WPT and WAT values were calculated as previous studies [23,28,30]. Similarly, corresponding thresholds were calculated for those sample pairs rated from 0 to 3 (no difference, small difference, fairly acceptable and hardly acceptable), following ISO/TR 28642:2016 [19].

2.3. *Fitting procedure and result processing*

A Takagi-Sugeno-Kang (TSK) Fuzzy Approximation model [22,26] with Gaussian membership functions and constant consequents was used as fitting procedure (Matlab 7.1 Fuzzy LogicToolbox, MathWork, Natick, MA). In the approximations performed, the TSK models took the rule centers equally distributed along the input space, and the rule consequents were optimally obtained using their derivatives with respect to the model output in the minimization of the r value (Least Squares LSE approach) [31]. The number of rules in each case was selected using a 10-fold cross-validation procedure; the number of rules for which the model provided the lowest cross-validation error was chosen to perform the approximation using all data. The 95% confidence intervals (95% CI), 95% lower confidence limit (95% LCI) and the 95% upper confidence limit (95% UCI) were estimated and the 50% of positive answers and 50% negative answers (50:50% thresholds) were calculated. The 50:50% point was defined as the difference at which an observer would have a 50% probability of making dichotomous judgment, and represents the level of perceptibility and acceptability for both types of judgments. Finally, the paired *t*-test ($\alpha = 0.05$) was used to evaluate the statistical significance of differences from the evaluated parameters.

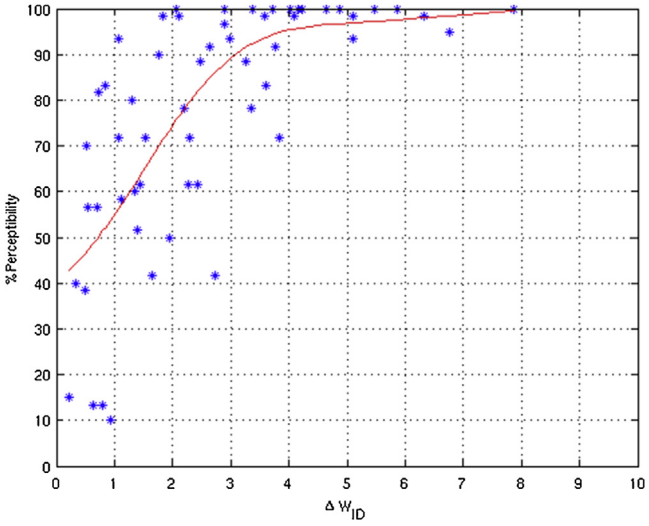

Fig. 3 – Perceptibility percentages versus whiteness differences (ΔWI_D) for all observers.

3. Results

Fig. 3 shows the values of percentage for perceptibility by all observers against ΔWI_D. WPT value corresponding to 50% perceptibility was $0.72WI_D$ units (CI: 0.0–2.69) with $r^2 = 0.52$.TSK Fuzzy Approximation with 4 equally distributed rules along the x-axis was used. Values of percentage for acceptability by all observers and all groups against ΔWI_D are plotted in Fig. 4. WAT value for 50% of acceptance was $2.60WI_D$ units (CI:

Table 1 – WI_D 50:50% perceptibility threshold (WPT) and acceptability threshold (WAT) values with corresponding 95% confidence intervals (95% LCI–95% UCI) by observer group.

Observer group	WPT (95% LCI–95% UCI)	WAT (95% LCI–95% UCI)
Dentist	0.46 (0.0–2.32) $r^2 = 0.52$ TSK rules = 4	2.20 (0.15–7+) $r^2 = 0.59$ TSK rules = 3
Layperson	0.94 (0.0–3.27) $r^2 = 0.50$ TSK rules = 4	2.95 (0.26–7+) $r^2 = 0.53$ TSK rules = 3

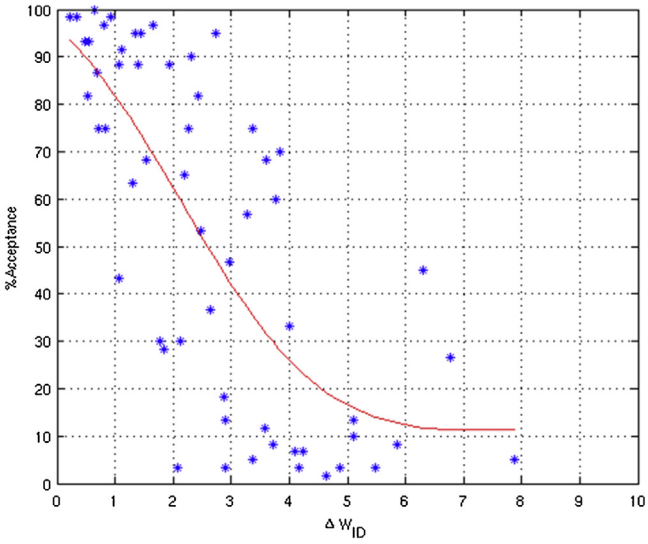

Fig. 4 – Acceptance percentages versus whiteness differences (ΔWI_D) for all observers.

Table 2 – Whiteness thresholds values for all observers based on visual discrimination of the whiteness difference on a scale from 0 to 3.

Visual grading	WI_D
0: No difference	0.70 (0–2.81) $r^2 = 0.52$ TSK rules = 4
1: Small difference	1.57(0.2–5.27) $r^2 = 0.59$ TSK rules = 3
2: Fairly acceptable	2.96 (0.47–7+) $r^2 = 0.54$ TSK rules = 4
3: Hardly acceptable	5.69(1.71–7+) $r^2 = 0.42$ TSK rules = 2

0.2–7 +) with $r^2 = 0.57$.TSK Fuzzy Approximation with 3 equally distributed rules along the x-axis was used.

Whiteness thresholds by observers groups (dentist and laypersons) are presented in Table 1. Significant differences were found between the WPT and WAT values ($p < 0.0001$) and between these values for dentists and laypersons ($p < 0.05$). The 50:50% whiteness thresholds values based on visual discrimination of the whiteness difference on a scale from 0 to 3, are presented in Table 2.

4. Discussion

Several studies have investigated the thresholds for perceptibility (PT) and acceptability (AT) of color difference for dentistry and dental applications [18,21–23,32–36]. It is noteworthy a recent multicenter study [23], which determined the 50:50% PT and the 50:50% AT for CIELAB and CIEDE2000 specifically for dentistry. Results from the study were included as reference values in the ISO/TR 28642:2016 [19] and can be applied as a quality control tool to guide the selection of esthetic dental materials, evaluate clinical performance, and interpret visual and instrumental findings in clinical dentistry or dental research.

Complementary to color assessment, proper measurement of whiteness is important for research and manufacturing of dental materials and for clinical situations such as assessing the effectiveness of different bleaching agents or determining the extent of a successful dental whitening treatment. This trend has been driving the development of new whiteness indices for dentistry [16,17] and triggered the need to carry out experiments based on visual judgments to establish perceptual limits of whiteness perceptibility and whiteness acceptability thresholds. Considering this type of experiment and the chance of observers confusing whiteness with color, observers should be trained to evaluate whiteness only. In the present study, the observers were previously trained in this respect.

A recent study [26] conducted a psychophysical experiment based on visual assessments to determine thresholds for tooth whiteness perception using the WIO index [16]. Thresholds estimates for four conditions (ΔL^*, Δa^*, Δb^* and a blue covarine optical tooth whitening direction) were 2.77, 6.52, 3.09 and 1.99, respectively. Even though these values may be of some interest, WIO maintains the functional form of the CIE WIC [16] and therefore it is based on the CIE1931 color space, which is not commonly used in dentistry. In addition, acceptability thresholds were not determined.

WI_D is a direct measure of whiteness in dentistry and it is based on CIELAB color space [17]. The present study introduced the use of WI_D to evaluate whiteness visual thresholds. The use of a suitable whiteness index is very important since it enables a better correlation of visual judgments to instrumental whiteness differences values. In this sense, WI_D has been validated under experimental laboratory and clinical conditions and outperformed previous indices, being the only CIELAB-based index specifically developed to evaluate whiteness in dentistry [17]. The present study found that 50:50% WPT and 50:50% WAT values for WI_D are 0.72 and 2.60, respectively. Thus, whiteness variation changes lower than 0.72 WI_D

units would not be perceptible to an average observer. The visual whiteness difference thresholds determined with WI_D index can serve as reference values for a series of clinical practice situations, including the effective assessment of bleaching agents and color research in dentistry.

The present study showed significant differences between WPT and WAT and that these values differ between dentists and laypersons, accepting both experimental hypotheses. As expected, dentists showed better discrimination ability, represented by lower values for both WAT and WPT. Similar to studies about chromatic discrimination using CIEDE2000 and CIELAB color difference formulas, [23,28] it was found that laypersons were less discriminating as compared with dentists.

The results of the present study were obtained using computer simulations of human dentition employing CIE L*a*b* color coordinates within color range of pre- and post-bleaching maxillary central incisors [27]. Previous studies used digital images on a calibrated display [26,34] or simulated computer teeth or human dental tissue [28,33] for assessing whiteness or color differences in dentistry. The ability to realistically simulate human dentition, coupled with the computer's inherent capacity to automate data collection in an efficient and highly repeatable manner, offers a method that promises rapid progress in establishing reliable standards to the study of whiteness differences in more realistic computer-generated scenarios.

Using WPT and WAT values to assess whiteness mismatch between teeth, or between teeth and restorations, or even between different restorations is simple: higher values correspond to increasing whiteness mismatch and therefore poor esthetics and, consequently, lower patient satisfaction. The present study used an additional discrimination for the 50:50% WAT, presenting three levels of acceptable whiteness differences (Table 2). Such discrimination provides an in-depth perspective of whiteness mismatch, which can set clinical guidelines to assist the dental professional to estimate and understand the extent of the whiteness variations to deal with. Thus, the level of discrimination may determine the treatment need, e.g. on judging the need to replace an esthetic restoration.

At present, the color match of adjacent teeth/restorations is evaluated by using color difference formulas and corresponding perceptibility and acceptability thresholds. In practice, very often patients are referring to the "level of white" when judging the optical similarity of the restorations with the adjacent teeth. Thus, including thresholds for whiteness difference in the clinical practice, in conjunction with thresholds for color difference, can be highly valuable to understand the optical properties, which are an important component of esthetic dentistry.

Tooth bleaching also offers clinical and research challenge on reporting efficiency evaluation of bleaching agents. The most popular assessment of a bleaching treatment consists of comparing the target tooth/teeth to a dedicated shade guide tab (e.g. Vita Bleachguide 3D Master) before and after the treatment and registering the number of consecutive tabs were encompassed in the process. The bleaching treatment result is expressed in shade guide unit SGU, with values of 3–5 being considered the lower limit for an acceptable result in terms of efficiency, depending on the used protocol [37]. Yet, this judgment is highly subjective. Comparing the values of WI_D differences with WPT and WAT offer a more objective and standardized method to evaluate the efficiency of a bleaching treatment, which might be of great importance to manufactures of bleaching products and research reports.

In this sense, we can assume that a bleaching agent is efficient if it produces a whiteness variation above the threshold of perceptibility whereas if the variation is above the threshold of acceptability, the efficiency of the whitening agent will be both optimal and satisfactory for the patient. Similarly, if what we pursue is to evaluate the optimal application time of a bleaching agent, or when is the most adequate moment to cease the treatment (without leaving aside other criteria that may be involved in such decision), we can assume that such a moment corresponds to whiteness variations (between consecutive evaluations) lower than the WPT. The number of sessions and the total duration of the bleaching treatment could be related to the thresholds values. However, the final outcome should also take into account the perception and desire of the patient, which depend on patient esthetic standards. For this specific purpose, the discrimination of WAT proposed in this study can be also particularly useful, when used in conjunction with the patient's expectations.

5. Conclusion

The present study determined reliable whiteness thresholds with the 50:50% WPT being 0.72 WI_D units and the 50:50% WAT being 2.60 WI_D units, which were significantly different. Both, WPT and WAT values, were different for dentists and laypersons.

Acknowledgements

The authors acknowledge funding support from research projects JA TEP-1136 from "Junta de Andalucía", Spain, MAT2013-43946R from the Spanish Ministry of Economy and Competitiveness.

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