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## Title page

# Analysis of Colour Differences Obtained by Acceptability and Perceptibility Threshold (Visual Method):-Review

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## Abstract

**Backgrounds:** Various information about acceptability (AT) and perceptibility thresholds (PT) for colour differences ( $\Delta E$ ) was reviewed in dental literatures. There is consensus that determining ( $\Delta E$ ) is ideal for identifying AT and PT. However, there is confusion about which values should be used. The aim of this review was to determine the discrepancies in research results and the critical value of  $\Delta E$ .

**Materials and methods:** MEDLINE/PubMed and Google Scholar were screened for studies that investigated colour acceptability, perceptibility,  $\Delta E$ , but were not sensitive to whether only AT or PT were used. 20 studies matched the study criteria and had been included in this review and clinical measurements were made using spectrophotometers.

**Result:** Most studies evaluated PT using approximately  $\Delta E = 0.8-1.7$ . In terms of AT which ranged between 1.8 and 3.7 as a maximum. Many recent studies evaluate  $AT_{00}=1.8$  according to the CIE2000 colour difference formula.

**Conclusion:** Different formulas as  $\Delta E_{00}$  (2000) or  $\Delta E_{ab}(\text{lab})$  in colour expression may produce different results. The CIEIAB formula ( $\Delta E_{ab}$ ) has greater evidence; however, current research recommends the CIE2000 formula  $\Delta E$ . The absence of colourimetric control has a negative effect on overall product quality.

**Keywords:** Acceptability, Perceptibility,  $\Delta E$ , Thresholds.

## Introduction

Colour sciences is a field of dental study that has received much attention in the past thirty years.<sup>1</sup> A startling search on MEDLINE/PubMed using the keywords "colour" and "dentistry" resulted in about 200 articles annually in the 2000s and up to 500 articles annually from 2010 to 2017,<sup>2</sup> and more than 680 articles between 2018 and 2020, and up to 820 articles each year by 2022. Colour has become a more relevant topic, mainly because colour measurement is used in many scientific fields, such as aesthetics, dental materials and prosthodontics science. The clinical importance of these kinds of investigations depending on how noticeable or acceptable colour changes are considered. Since colour perception or acceptance is subjective and can vary from person to person, reaching a consensus on perceptibility PT and acceptability AT threshold values that can be employed in dental colour research is essential.<sup>1</sup> These are two major thresholds for assessing colour differences. A 50:50% PT indicates that 50% of individuals perceive a difference in colour between two objects, but the other 50% don't see any change.<sup>3</sup> A nearly perfect colour match in dentistry is a colour difference at or below the 50:50 perceptibility threshold.<sup>4</sup> Without comparing the acceptability and perceptibility tolerances the research and study findings cannot be properly assessed regarding their application to clinical circumstances<sup>2</sup>. The following are typical questions about perceptibility and acceptability: [PT] Do you see any differences between these two colours specimens (transparency, whiteness)? [AT]

Would you consider this difference acceptable in a clinical setting? The AT question is not necessary if the response to the PT question is no.<sup>2</sup>

The most popular method for evaluating colour in dentistry is the visual method, clinical and research dentistry both depend on an understanding of the visual limits of color in the color space. The colour difference formula ( $\Delta E$ ) in colour science was created to provide a quantitative representation of the perceived colour difference between two coloured specimens under a specified set of experimental conditions.<sup>5,6</sup>

The Commission Internationale de l'Eclairage CIE-L\*a\*b\* system is the most common colour difference formula used in research. It demonstrates typical colour coordinate variations and refers to the entire visual color space:<sup>7</sup>

$$\Delta E = \{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\}^{1/2} \quad 1,8$$

$\Delta L^*$ ,  $\Delta a^*$ ,  $\Delta b^*$  refer to the variations in lightness to darkness, green to red coordinates, and blue to yellow coordinates respectively.  $\Delta E$  represents the difference in colour between two objects; the bigger the value, the greater the colour difference and, thus, the more noticeable the difference to the eye.<sup>8</sup>  $\Delta E$  represents the measurement of colour differences. However, it is unable to demonstrate the direction of the colour difference.

The objective of this review is to identify the current colour difference  $\Delta E$  values and formula as well as establish the principles for developing a reliable and repeatable

approach for identifying colour in practical situations. There is currently little consensus regarding the measurements of the minimum colour difference that is perceptible (Perceptibility threshold) and the minimum colour difference that is acceptable (Acceptability threshold) in clinical dentistry.<sup>9</sup> In this respect, the related evidence would assist researchers in improving the reliability of clinical evaluations of colour discrepancies, as well as improving the colour conception process in dental practice. The aim of this review was to find the cause of discrepancies in research findings and to determine the critical  $\Delta E$  value for an acceptable and perceptible colour difference obtained by a 50:50% acceptability perceptibility threshold.

### Materials and Methods

Three electronic databases were used (PubMed/MEDLINE (National Library of Medicine), Google Scholar ).The search involved dental publications and specified journals of operative and esthetic dentistry. Only articles in the English language were selected. Inclusion criteria included studies that investigating colour acceptability and perceptibility or  $\Delta E$  are unaffected by whether AT, PT, or both are recorded and whether for prostheses, teeth or restorations.<sup>10</sup> The recommended colour-measuring device is a spectrophotometer. This device is considered a golden standard for clinical and industrial applications due to its great predictability and repeatability. As a result, investigations using spectroradiometer, color-meter, and digital cameras were discarded. From 101 articles in all branches of dentistry, when searching the

keywords of acceptability perceptibility threshold and colour difference in dentistry , 44 articles for restorative dentistry were selected (excluding other branch). Twenty two articles meet the inclusion criteria. Twenty of these studies were included in this review. The AT and PT of each article were collected, as well as the main source from which they were obtained.

### Result

Colour perception changes greatly between and within people throughout time. Moreover, because people can detect a colour difference between two things, there are likely to be disagreements about the acceptability of such a difference.<sup>11,12</sup> Aspects like the observer, object, and illumination affect how people see colour. The characteristics of light, the surrounding environment, emotions, weariness, the perception angle, and individual variances in colour detection are all factors that might lead to a change in the colour difference value in previous research .<sup>13</sup>

Johnson and Kao observed in clinical studies that  $\Delta E=3.7$  for the Acceptability threshold to match the desired colour and  $\Delta E=6.8$  for colour mismatch among comparable teeth and composite veneer<sup>14</sup> as in table (1) , where several of the following literatures use the same source and stated that the acceptable value for  $\Delta E$  is 3.7.<sup>14</sup> Furthermore, Dougglas in 2007 was the pioneer that identified realistic acceptability and perceptibility thresholds for shade mismatch in a clinical scenario utilizing a spectrophotometric device on metal-ceramic crown specimens and showed that a 50%

acceptability threshold for crowns was between  $\Delta E=1.7$  and  $2.7$ ,<sup>12</sup> and for perceptibility was  $\Delta E=2.6$ . Regarding the colour mismatch, the mean acceptability tolerance for 50% of observers was  $\Delta E=5.6$ <sup>10</sup> (Table-1-). In another study Hassel and others (2009), measured the basic dental colour in clinic using a spectrophotometer to assess intraexaminer reliability. The authors found that mean  $\Delta E$  for the intraexaminer reliability was usually acceptable at  $2.7$  in clinical routine even in some changes of surrounding area<sup>15</sup>. Another study using the CIEDE2000 (Published in 2000 by the CIE) formula, established the visual 50:50% acceptability threshold for brightness, chroma, and hue for 3 groups of ceramic specimens were  $L = 2.92$ ,  $C = 2.52$ , and  $H = 1.90$  respectively, and then the 50% acceptability threshold for colour difference  $\Delta E= 1.87$  according to CIEDE2000. Alghazali et al in 2012, analyzed the colour values that represent the denture teeth perceptibility and acceptability criteria. The authors determine the acceptability value between  $\Delta E=3.9$  to  $4.7$ , while the determined colour difference value at which 50% of all observers preferred to replace the tooth due to an undesirable colour difference was  $\Delta E = 4.2$  as mentioned in table (1)

Khashayar and others (2014) reviewed *in-vivo* studies to determine the perceptibility and acceptability thresholds in dentistry. In the above study, spectrophotometers were used to get all of the  $\Delta E$  threshold values.<sup>1</sup> The authors found a trend in the source references of the 48 research that were examined: 44% of the PT studies referenced

to the same paper  $\Delta E = 1$ , and 35% of the AT studies referred to the same article<sup>14</sup>  $\Delta E = 3.7$ . The most comprehensive analysis was conducted by Paravina et al. using monochromatic ceramic specimens in a controlled environment. The 50:50 PTs and ATs differed greatly from one another. In dentistry, the 50:50% PT was found to have  $\Delta E_{ab}$  (colour difference according to CIELAB formula) =  $1.2$  and the 50:50% AT to have  $\Delta E_{ab} = 2$  according to CIELAB formula.<sup>2</sup> Moreover Dalmolin in 2021 assessed the masking performance of bleach shade resin composite applied using multiple layers procedures over coloured substrate by using spectrophotometer. This author found that all combinations supplied by  $\Delta E_{oo}$  (colour difference according to CIE2000 formula) were higher than the acceptable limit  $\Delta E > 1.8$ , varying from  $2.4$  to  $7.4$ , the value  $1.8 < \Delta E \leq 3.6$  moderately acceptable and  $3.6 < \Delta E \leq 5.4$  unacceptable. In the same year Yan et al examined the colour differences between natural teeth and milled veneers made with various CAD-CAM ceramic materials, the colour discrepancies between the natural tooth and A2 shade tab  $\Delta E$  with milled veneer and natural tooth ( $\Delta E_2$ ) were calculated. The  $\Delta E$  values were between  $2.41$  to  $5.36$ , less than the clinically acceptable  $5.5$  colour threshold.<sup>16</sup>

Recently Laura et al. evaluated the influence of nano coating material on the colour acceptability and perceptibility of Polymethylmethacrylate: in *vitro* and clinical studies using spectrophotometer. The authors base on a 50:50% perceptibility threshold was  $\Delta E= 1.7$ , which demonstrates that there is a perceptible colour difference. However,

the  $\Delta E$  values of all acceptability threshold was  $\Delta E_{00} = 4.00$ .<sup>17</sup>

## Discussion

The use of different colour difference formulas will cause different results. The dental literature does not agree on the number of colour differences that represent an acceptable shade mismatch or the value of colour differences that the observers can see. Around 80% of the scientific literature identified an  $\Delta E$  value between 0.7 and 1.9 as visually noticeable (PT). Many of these studies reported the PT value at 0.8.<sup>2,16-18</sup>

Regarding the acceptable threshold, its value varies from 1.8-3.7 with the majority 20 research referencing to 2.7<sup>2,19-21</sup> and just three of 20 studies was consider the acceptability value above 5. It is important to note that each reference (Table 1) got a special research methodology, whether *in vitro* or *in vivo*, as well as a different formula, which could have affected the calculated values for PT and AT.<sup>2</sup>

Johnston and Kao in 1989 conducted the first study on the mean colour difference in the oral environment between examined teeth that were classified as matching was 3.7, according to an evaluation of visual matching by eye observation and clinical calorimetry (*in vivo* study).<sup>14</sup> Despite the fact that the study was carried out in a clinical setting, the colour evaluation tool has not been validated for intraoral use and is known to be susceptible to edge loss mistakes,<sup>22</sup> which could explain their significant standard deviations.<sup>14</sup> In the Web of Science, the article by Johnston and Kao (1989) has received around 295 citations. Years later,

with increased patients demands for aesthetics,<sup>23</sup> one might expect that dental colour thresholds will mimic those clinical developments. Da Silva et al decreased the acceptability limits to a value of 2.6 in 2008, which was followed by around 9% of the literature that could be because the procedures and resources used in the Da Silva research varied significantly.<sup>24</sup> Also Comparatively fewer assessors were used in the current study than in the work by Douglas and others employed 28 evaluators from a general community of prosthodontists and general practitioners with varied levels of colour knowledge.<sup>12</sup> Considerably, despite the high expectations for aesthetics, the  $\Delta E$  values for PT and AT do not decline as much as would be predicted with time. This may be due to the fact that the majority of studies are carried out by qualified dental technicians rather than by people in general (patients), who may have lower expectations for color matching.

Additionally, Ishikwa et al. identified the importance of the standardization of perceptibility acceptability thresholds was conducted, and a gold standard for colour difference was requested. because the optical properties of a tooth, such as surface character and translucency, play a significant role in how observers perceive a colour match. In addition, viewing geometry, ambient light, and the number of examiners may provide varying outcomes.<sup>9</sup> This is in agreement with Ghinea study considering a wide range of colour differences and various experimental setting conditions (such as the use of a shutter, the surrounding environment, etc.), that might explain the

discrepancy in the acquired thresholds and ultimately the difference in AT and PT threshold values.<sup>18</sup>

Alghazali et al. tried to imitate the clinical situation, because the acceptability thresholds ( $\Delta E=4.1$ ) were greater than those reported in past studies. It was likely that the differences between the perceptibility and acceptability thresholds obtained from various studies are due to other factors, such as the selected colour-measuring device, the experimental settings, the type of specimens being looked at (as crown or denture teeth, discs, etc.), complex colour mixing, or diffraction. Thus, it would be difficult to make a direct comparison between these different studies.<sup>11</sup> The variations in these studies might be due to (a) the number of viewers and sampling procedure, (b) sample size and number, (c) the setup and colour formulas that were used in measuring devices, (d) the psychophysiological experiment, (e) data analysis (appropriate method), and (f) the percentage of perceptibility or acceptability values.<sup>2,3</sup> Similar to Douglas's study, which thought that there were big differences between different groups about whether they could easily see as well as accept colour differences, The dentists and technicians had the lowest thresholds for what they could see and what they could accept<sup>12</sup>.

The using of different formulas as  $\Delta E_{00}/\Delta E_{ab}$  in expression of colour might cause different result as in Paravina et al<sup>25</sup> who found that the 50:50 PT CIELAB value was determined to be  $\Delta E_{ab} = 1.2$ , while the 50:50 AT value was found to be  $\Delta E_{ab} = 2.7$ . The corresponding CIEDE2000 ( $\Delta E$ ) values were

0.8 and 1.8. Additionally The complete absence of colourimetric control (monitoring) has a negative implication on the overall product quality. This was in accordance with several studies<sup>18,26</sup> demonstrated that the acceptability and perceptibility thresholds (AT and PT, respectively) values were considerably different by both CIELAB and CIEDE2000 colour difference formulas.<sup>26</sup> Currently, the CIEDE2000 total colour difference formula ( $\Delta E_{00}$ ) is frequently used in dental research and clinical dentistry because of its greater interaction with visual perception.<sup>27</sup> The author suggests further evaluation of the AT/PT threshold with different devices such as colourimeters or digital cameras and to consider the evaluation of differences in colour measurement obtained by the CIELAB and CIE2000 formulas and determine which one is preferred.

To analyze all aspects of colour research in dentistry and create an agreement for dental researchers, an additional prospective controlled (clinical) study is required.

Additionally, there is new grading system in recent studies.<sup>2,7,28,29</sup> This described five intervals based upon which grades 5 and 4 correlate with the  $PT_{00}$  and  $AT_{00}$ , respectively, When  $\Delta E_{00}$  was less than 1.8 it was acceptable match while  $\Delta E_{00}$  between 1.8 and 3.6 it was somewhat unacceptable (MU) or clearly unacceptable (CU), and if it was between 3.6 and 5.4 it was extremely unacceptable (EU).<sup>29</sup> These articles was based on CIEDE2000 formula compared to the CIE Lab colour change formula in dentistry, it's a more modern and acceptable formula to approximate how colour change is

perceived by the human eye<sup>26</sup> and it has also been demonstrated to more closely match human vision.<sup>30,31</sup> The parametric proportion was developed to manage variations in the intensity of acceptance judgments and to make adjustments for the scale of acceptability rather than perceptibility.<sup>2,26</sup> However, still the latter is frequently used in studies.<sup>32</sup> Recently the CIE (Commission Internationale de l'Eclairage)<sup>6</sup> recommended the use of CIEDE2000 colour difference formula ( $\Delta E$ ) because this formula was 100% efficient.<sup>27</sup>

### Conclusion

The using of different formulas as  $\Delta E_{00}$  (2000)  $\Delta E_{ab}$  (lab) in an expression of colour might cause a different results. There is more evidence toward the CIEIAB formula ( $\Delta E_{ab}$ ) However the recent studies recommend the CIE2000 formula  $\Delta E_{00}$ , because the colour difference in CIE2000 is a more acceptable formula to approximate how colour change is perceived by the human eye. The absence of colorimetric control (monitoring) has a negative implication on the overall product quality. Moreover, research on visual thresholds must be carefully organized, even if clinical shade-matching conditions and methodology are rarely controlled.

### Conflict of Interest:

The authors declare that there was no conflict of interest.

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**Table (1)** Overview of threshold research in dentistry and main findings (Paravina et al., 2019)

Author Name	Journal/years	Main finding	Research Area
Johnston and Kao	J Dent Res., 1989	Match/Mismatch: $\Delta E_{ab} = 3.7/6.8$	visual vs. digital
Ragain and Johnston	Colour Res Appl., 2000	50:50% AT: $\Delta E_{ab} = 2.7$	Tooth colour
Douglas et al.	J Prosthet Dent., 2007	50:50% PT/AT: $\Delta E_{ab} = 2.6/5.6$	Tooth vs. shade guide
Da Silva et al.	J Prosthet Dent., 2008	100% AT: $\Delta E_{ab} = 2.7$	Visual vs. digital
Ishikawa-Nagai et al.	J Dent., 2009	100% PT: $\Delta E_{ab} = 2.6$ AT=5.6	Natural teeth and ceramic crowns
Ghinea et al.	J Dent., 2010	50:50% PT/AT: $\Delta E_{ab} = 1.7/3.5$	Ceramic crown
Pérez et al.	J Dent., 2011	50:50% AT: $\Delta E = 1.9$	Dental ceramic
Alghazali et al.	J Dent., 2012	50:50% PT/AT: $\Delta E_{ab} = 1.9/4.2$	Denture teeth
Khashayar et al	J Dent,2014	50:50% PT: $\Delta E_{ab}=1$ AT $\Delta E=3.7$	Colour measuring Device
Paravina et al.	J Esthet Restor Dent., 2015	50:50% PT/AT: $\Delta E = 0.8/1.8$ ; $\Delta E_{ab} = 1.2/2.7$	Dental ceramic
Salas et al.	Dent Mater., 2018	50:50% PT/AT: $\Delta E = 0.6/2.6$ ; $\Delta E_{ab} = 1.3/4.4$	Dental resin composites
Paravina et al.	J Esthet Restor Dent.,2019	50:50% PT $\Delta E_{ab} = 1.2$ , AT $\Delta E_{ab} = 2.7$	Visual thresholds
Aydın et al.	J Clin Exp Dent 2021	50:50 PT $\Delta E: 1.2$ and 50:50 AT $\Delta E:2.7$	Resin composite
Yan et al .	International J of Interdisciplinary Dent.2021	50:50 PT $\Delta E=2.6$ AT $\Delta E=5.5$	CAD-CAM ceramic Materials
Valizadeh et al	International J of Dent.2021	50 : 50% PT $\Delta E= 0.8$ and AT $\Delta E_{00} =1.8$	Bleach shade composite resins
Dalmolin et al.	J Esthet Restor Dent.2021	50:50 PT $\Delta E=0.8$ AT $\Delta E=1.8$	Bleach shade composite resins
Laura et al.	J of Material 2022	50:50% PT $\Delta E = 1.71$ and $\Delta E= 4.00$	Polymethylmethacrylate
Cristina et al.	J of Materials 2022	50:50% PT $\Delta E=0.8$ and AT $\Delta E = 1.8$	Zirconia crowns
Niveen et al.	J Prosthet Dent. 2023	50:50% PT $\Delta E=0.8$ and AT $\Delta E=1.8$	Dental resin composite
Casado et al.	J of Materials. 2023	50:50% PT=0.8 and AT=1.8	Dental resin composite