available at www.sciencedirect.com

ScienceDirect

journal homepage: www.intl.elsevierhealth.com/journals/jden

Perceptibility and acceptability of CIELAB color differences in computer-simulated teeth

Delwin T. Lindsey [a,*], *Alvin G. Wee* [b,1]

[a] *Department of Psychology, The Ohio State University, Columbus and Mansfield, OH, USA*
[b] *Division of Oral Facial Prosthetics, Dental Oncology, Department of Otolaryngology, University of Nebraska, Omaha, NE, USA*

ARTICLE INFO

Article history:
Received 12 February 2007
Accepted 29 March 2007

Keywords:
Tooth color
Perceptibility
Acceptability
Signal detection
Color difference
Computer simulation

ABSTRACT

Objectives: To determine the perceptibility and acceptability of tooth color differences using computer-generated pairs of teeth with simulated gingival displayed on a calibrated color monitor using appropriate signal detection theory methodology (SDT).

Methods: Twelve dental professionals (four from each of the following groups: dentists, dental auxiliaries, and fixed prosthodontic technicians) and four dental patients served as subjects. Responses to tooth color differences (ΔE) were measured on each of the three principal axes of CIELAB color space (L^*, a^*, and b^*). As a control, responses to $\Delta E = 0$ (the false alarm rate) were also measured in the same experimental session.

Results: No group differences among subjects were found. All gave 50% match or acceptance points that averaged about 1.0 ΔE units in the L^* and a^* directions, and 2.6 units in the b^* direction. False alarm rates across all subjects averaged 27% (4–55%) and 28% (0.4–61%), respectively, for perceptibility and acceptability. A reanalysis of the data based on SDT, which takes subjects' false alarm rates into account, gave somewhat larger color difference thresholds.

Conclusions: Color difference thresholds for our simulated teeth are generally in line with and extend results obtained with studies using "real" dental materials. No differences between thresholds for acceptability versus perceptibility were found.

Furthermore, subjects often reported color differences when none existed, and this behavior needs to be factored into any determination of quality control standards for the fabrication of dental prostheses.

1. Introduction

The human eye is very adept at detecting small color differences between natural and prosthetic teeth. Instrumental color analysis, coupled with advanced fabrication techniques, provides a potentially useful way of minimizing the occurrence of these differences during the fabrication process. However, in order to take full advantage of this technology it is important to establish standards for maximum color differences that are acceptable to dental patients. At present, the magnitude of perceptible and/or acceptable color differences for human observers is still not well defined in dental color research.

A study by Kuehni and Marcus[1] is cited frequently as a standard for the perceptibility and acceptability of small color differences. A majority of their 63 subjects were experienced, industrial color matchers. They found that the average CIELAB color difference (ΔE CIELAB) for 50% of the observers to

* *Corresponding author at*: Department of Psychology, 300 Lazenby Hall, Columbus, OH 43210, USA. Tel.: +1 614 292 9535/419 755 4359.
E-mail address: lindsey.43@osu.edu (D.T. Lindsey).

[1] The work was done while he was affiliated with Section of Restorative and Prosthetic Dentistry, College of Dentistry, The Ohio State University, Columbus, OH, USA.

0300-5712/$ – see front matter
doi:10.1016/j.jdent.2007.03.006

perceive a color difference was one unit (ΔE CIELAB = 1). No significant difference between perceptibility and acceptability judgments was found. However, perceptibility and acceptability were assessed using two very different visual tasks, so comparisons may not be valid. Furthermore, Kuehni and Marcus's study tested non-dental materials and spanned a wide color spectrum outside the range of observed tooth colors.

Another study by Seghi et al.[2] evaluated color perceptibility in a group of dental professionals (23 dentists and 4 dental technicians) using translucent color porcelain disks. A visual sorting task, in conjunction with a specialized statistical analysis, was used to estimate perceptibility. Their results suggested that color differences in porcelain disks of about 2 ΔE CIELAB units or greater would be detected 100% of the time and would decline with ΔE. The ΔE CIELAB for 80% probability of observers reporting a color difference was about 0.5–1.0, while ΔE for 50% probability was near zero. Ragain and Johnston[3] also examined color difference acceptability in translucent porcelain disks and reported average acceptability thresholds of 2.72 CIELAB ΔE units. Ruyter et al.[4] who also studied color difference acceptability, found that 50% of their observers (six dentists and six chemists) considered sample pairs of dental composite resin to be unacceptable when ΔE was approximately 3.3 units.

Perceptibility and acceptability were directly compared in a study by Douglas and Brewer.[5] They studied how a group of prosthodontists perceived shade differences in porcelain fused to metal crowns. Acceptability thresholds were measured in the a^* and b^* directions of CIELAB color space, and were found to be dependent on the direction of color change. Thresholds in the L^* direction were not measured. Acceptability of color differences was 1.1 ΔE units in the a^* direction and 2.1 ΔE units in the b^* direction. Furthermore, they found that while acceptability thresholds (50% point) averaged 2.1 ΔE units, perceptibility thresholds averaged only 0.7 units. However, Douglas and Brewer measured color differences of their translucent samples using instrumentation that exhibited edge loss,[6] so the accuracy of the color difference measurements for perceptibility or acceptability may be significantly in error. Moreover, while Douglas and Brewer[5] attempted to examine the effects of color direction in CIELAB on ΔE, the materials employed in their study did not have color differences precisely confined to any one direction in CIELAB color space.

Finally, Sim et al.[7] had subjects select a Vita Lumin shade tab that best matched each of a series of shade tabs. Selection was made from Vita tabs with a preset color, randomly ordered with respect to color. They then calculated the mean ΔEs between test and matching tabs in the L^*, a^*, and b^* directions of CIELAB space. The mean perceptible ΔEs estimated in this way were 4.5, 0.69, and 2.4, respectively. Note, however, that these estimates of threshold were not based on independent tests along each color axis, but represented the outcome of subjects attempting to select a match among preset color shade tabs that varied in all three dimensions of color space.

In summary, while there exists a sizeable literature on the perceptibility and/or acceptability of dental color differences, this literature is diverse both with regard to the methodologies employed as well as results obtained in the study of tooth color differences. All the studies that measured the color of actual specimens of dental materials also used non-ideal color measuring instrumentation, which exhibited edge loss.[6]

The present study attempts to address a number of issues raised by these previous studies; specifically, the degrees to which color perceptibility and acceptability (1) differ from one another, (2) vary with direction of change in CIELAB color space, and (3) depend upon the experience of the observer with dental materials. In addition the present study introduces two new methodologies in dental color research: (1) all stimuli are computer-generated and presented under carefully calibrated and reproducible colorimetric conditions and (2) signal detection theory (SDT)[8] is used to evaluate subjects' color difference decisions. SDT has long been used in the field of diagnostic medicine, where there exist important cost/benefit tradeoffs related to the diagnostician's criterion for making diagnostic decisions.[9] In SDT, estimates of perceptibility and acceptability will take into account both the hit and false alarm rates, which to our knowledge have not been used in dentistry to estimate performance on a color visual task.

The objective of this study was to evaluate the perceptibility and acceptability thresholds of dental professionals and patients for tooth color differences along each of the three principal directions in CIELAB color space: L^*, a^*, and b^*. In addition we reanalyzed the date using STD.[8] The following hypotheses were tested in this study:

- *H1*: perceptibility and acceptability thresholds will differ.
- *H2*: perceptibility and acceptability will differ across groups of subjects in the dental profession.
- *H3*: perceptibility and acceptability will differ across different axes in CIELAB color space.

2. Materials and methods

2.1. Subjects

Sixteen subjects participated in this study, four each drawn from the following categories in dentistry: (1) dentists, whose clinical practice was primarily restorative dentistry, (2) individuals of varying dental experience, primarily dental auxiliaries, (3) dental fixed prosthodontic technicians, and (4) dental patients. Subjects were recruited from faculty and staff from the University Medical Center and surrounding city. All had normal color vision as assessed by the American Optical Hardy–Rand–Rittler (AO-HRR)[10] pseudoisochromatic plate test, and all had normal visual acuity with corrective lenses. The study protocol was approved by the University's Institutional Review Board approval (IRB #2003H0019, dated 2 October 2003), and all subjects gave informed consent prior to their participation in the study.

2.2. Apparatus

Measurements of subjects' tooth color difference discrimination and crown acceptance/rejection were based on computer-generated stimuli presented on a high-resolution ($1600h \times 1200v \times 80$ frames/s $\times$ 8 bit per color channel) 21″ RGB