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Intraoral determination of the tolerance of dentists for perceptibility and acceptability of shade mismatch

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Statement of problem. There is little agreement in the dental literature as to how much color difference constitutes an acceptable shade mismatch or how much color difference is considered perceivable to observers. Most studies attempting to determine perceptibility and acceptability of tolerances for shade mismatches have been conducted under in vitro conditions that are not applicable to clinical scenarios.

Purpose. The goal of this study was to determine valid acceptability and perceptibility tolerances for shade mismatch in an actual clinical scenario using spectroradiometric instrumentation.

Material and methods. A test denture was fabricated that allowed 10 maxillary left central incisors of varying shade mismatch with the right central incisor to be interchanged within the denture base. A spectroradiometer was used to determine the CIELAB coordinates and color differences (ΔE) between the right central incisor and the interchangeable left central incisor denture teeth. The interchangeable denture teeth ranged uniformly from 1 ΔE unit (visually undetectable) to greater than 10 ΔE units (an obvious shade mismatch). The test denture with each of the interchangeable teeth was modeled by a subject to 28 dentists in a clinical setting. For each of the interchangeable teeth, dentist observers were asked if they could see a difference between the central incisors and, if so, whether the difference was acceptable. A Probit regression analysis was used to predict acceptability and perceptibility tolerances with 95% confidence limits.

Results. The predicted color difference at which 50% of the dentist observers could perceive a color difference (50/50 perceptibility) was 2.6 ΔE units. The predicted color difference at which 50% of the subjects would remake the restoration due to color mismatch (clinically unacceptable color match) was 5.5 ΔE . Acceptability and perceptibility color tolerances at the 50/50 level were significantly different ($P < .05$), as their 95% confidence limits did not overlap.

Conclusions. Tolerances for perceptibility were significantly lower than tolerances for acceptability for shade mismatch between 2 denture teeth. (J Prosthet Dent 2007;97:200-8.)

CLINICAL IMPLICATIONS

Acceptability and perceptibility tolerances of shade mismatch determined in a clinical setting were considerably higher than those previously determined under nonclinical, in vitro conditions. Future dental investigators evaluating color (color stability, shade duplication, and bleaching efficacy) should compare the results to perceptibility and/or acceptability tolerance levels that have been determined under clinical conditions.

The ability of a restoration to match the color of the surrounding dentition is an integral part of the success of a restoration. In a 1984 survey, Goldstein and Lancaster found that of subjects who were dissatisfied with their smiles, the predominant complaint was tooth color.¹ The ability to match a ceramic crown with the surrounding dentition is a consistent problem in clinical dentistry. Prospective and retrospective clinical studies have

documented between 44% and 63% color mismatch of cemented ceramic crowns.²⁻⁵ Presently, shade selection by visual comparison of a target color (typically an adjacent tooth) to a shade guide is the most common method for color determination in dentistry.⁶ However, visual assessment of color is subject to numerous sources of variability and is considered to be unreliable.^{4,7-8} Paul et al⁹ found the shade assessment of 3 dentist observers to be 33% less accurate than a reference spectrophotometer.

Instrumental color measurement has the advantages of eliminating the subjective aspects of color measurement and expediting the determination of color. Current photometric and colorimetric instruments have been used extensively in dental research.⁸⁻¹⁴ However, most devices are currently unsuitable for clinical dental use (intraoral color measurement) due to their

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complexity and cost. More importantly, when measuring translucent specimens such as teeth, their accuracy is subject to edge loss errors.⁶ Edge loss errors occur in devices where illumination and color measurement are made through the same small window. In translucent specimens, such as human teeth, denture teeth, and porcelains, a considerable portion of the light entering the specimen is lost through translucency and scattering, never returning to the sensor for measurement. The resultant color measurement will therefore be affected. To determine the true colors of translucent specimens and avoid the inaccuracies of edge loss, it is recommended that a spectroradiometer be used with a 45-degree illumination and 0-degree observation configuration, so as to measure the reflection with a sensor located at a distance to avoid interfering with the illumination of the specimen.^{15,16}

The evaluation of color, whether by visual or instrumental means, requires an understanding of the parameters with which color is expressed and measured. The Commission Internationale de l'Eclairage (CIE) $L^*a^*b^*$ color space (CIELAB) and color difference formula¹⁷ defines color in terms of 3 coordinate values (L^* , a^* , b^*), which locate the color of an object within a 3-dimensional color space. The L^* coordinate represents the brightness of an object represented on the y axis, the a^* value represents the red (positive x axis) or green (negative x axis) chroma, and the b^* value represents the yellow (positive z axis) or blue (negative z axis) chroma. The color difference (ΔE) of 2 objects can then be determined by comparing the differences between respective coordinate values for each object. The formula¹⁷ used for calculating color differences in this system is: $\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$, where ΔL^* , Δa^* , and Δb^* are differences in color parameters for the 2 specimens measured for comparison. Numeric description of color permits precise definition of the magnitude of the color difference between objects—for example, the porcelain color of a metal-ceramic crown and the shade tab or tooth to which it is to match.

One of the goals of instrumental color measurement in dentistry is the development of valid intraoral optical electronic determination of color or shade of teeth. Such technology would eliminate the variability in the subjective, visual process of shade selection. It would also allow for verification that the color of an indirectly fabricated restoration would match the tooth from which the shade was determined. Practical application of technology that quantifies color and color difference first requires the establishment of clinical parameters that have some visual significance. The mere determination of a color difference between 2 specimens is of little clinical value without an understanding of the magnitude of color difference that is visually detectable (perceptibility tolerances) and the magnitude that constitutes an unacceptable alteration to dental esthetics (acceptability tolerances).

Several studies have attempted to determine color matching tolerances (Table I). Kuehni and Markus¹⁸ established a perceptibility tolerance of 1 ΔE unit for 50% of observers using textile specimens and matte paints under optimal viewing conditions. Seghi et al,¹⁹ using monochromatic porcelain discs, determined that a color difference of 2 ΔE units was correctly judged by 100% of observers under in vitro conditions. Acceptability tolerances have also been investigated under ideal viewing conditions. Using monochromatic composite resin discs, Ruyter et al²⁰ reported that 50% of observers considered specimens unacceptable when the color difference was approximately 3.3 ΔE units. Similarly, at a color difference of 2.72 ΔE units, Ragain and Johnston²¹ found that observers had an equal probability (50%) of accepting or rejecting the color match of the specimens. Rather than using monochromatic specimens, Douglas and Brewer²² used metal-ceramic crown specimens and determined that the 50% acceptability tolerance for a group of 20 prosthodontists was between 1.7 and 2.7 ΔE units for crowns varying in yellowness and between 0.5 and 1.5 for crowns varying in redness (Table I).

The preceding studies have limited clinical application because they were all performed in nonclinical in vitro conditions, an environment that did not simulate color matching and assessment in an intraoral scenario. Only 1 study²³ to date has attempted to determine perceptibility and acceptability tolerances under in vivo conditions. Using a colorimeter fitted with a metal mouthpiece, intraoral color measurements were made of composite resin veneers and adjacent or contralateral unrestored teeth. Using these data, the authors found a mean color difference of 3.7 ΔE units (range 0.5-12.5) between composite veneers and compared teeth that was rated as a perfect match in the oral environment. They also determined a mean color difference of 6.8 ΔE (range 1.3-13.1) units between compared teeth that was rated as a marginally acceptable mismatch. Although this is the only clinically relevant study identified in the literature to date, it has several limitations. The instrument used for color determination was not validated for intraoral application and is known to be subject to edge loss errors, which could have resulted in inaccuracies. This potential source of error may be manifest in the large standard deviations associated with the perceptibility and acceptability tolerances reported in that study. Furthermore, although a large number of assessments were made, the data were derived from only 2 observers. Nevertheless, the results do suggest that the tolerances for perceptibility and acceptable shade mismatch determined under clinical conditions are higher than those determined in vitro.

To date, no investigators have attempted to determine perceptibility and acceptability of tolerances for shade mismatches under in vivo (intraoral) conditions

Table I. Summary of studies relevant to dental color-matching tolerance

Study	Study design	Color difference	Results
Color perceptibility studies			
Kuehni and Marcus ¹⁸	In vitro	$\Delta E = 1.0$	Fifty percent of observers perceived color difference.
Seghi et al ¹⁹	In vitro	$\Delta E = 2.0$	Porcelain specimens were correctly judged by observers 100% of the time.
Johnston and Kao ²³	In vivo	$\Delta E = 3.7$	Average color difference between compared teeth rated as match in oral environment.
Color acceptability studies			
Douglas and Brewer ²²	In vitro	$\Delta E = 1.7$	Mean color difference at which 50% of prosthodontists rejected shade match for metal-ceramic crowns.
Ragain and Johnston ²¹	In vitro	$\Delta E = 2.72$	Average 50:50 ΔE replacement rate for all subjects was found.
Ruyter et al ²⁰	In vitro	$\Delta E = 3.3$	Fifty percent of observers considered composite resin specimens to be unacceptable.
Johnston and Kao ²³	In vivo	$\Delta E = 6.8$	Average color difference between compared teeth rated as mismatch within normal range of tooth color in oral environment.

using valid colorimetric or spectrophotometric instrumentation. The goal of this study was to determine valid acceptability and perceptibility tolerances for shade mismatch in an actual clinical scenario using spectroradiometric instrumentation. It was hypothesized that clinically determined acceptability and perceptibility tolerances for shade mismatch would be higher than those previously determined using in vitro methodology. It was further hypothesized that acceptability tolerances would be higher than perceptibility tolerances.

MATERIAL AND METHODS

A test denture was fabricated that allowed central incisors of varying shade mismatch to be interchanged within the denture base. The test denture was modeled by a subject to determine the acceptability and perceptibility tolerances of 28 dental practitioners in a clinical scenario. A spectroradiometer (PR 705; Photo Research Inc, Chatsworth, Calif) and fiber optic light cable were fixed on an optical table (Mecom Inc, Risingsun, Ohio). The fiber optic light cable was connected to a xenon arc lamp (300W; Newport Corp-Oriel Instruments, Stratford, Conn). The spectroradiometer and the optic light cable, positioned at a 45-degree angle inferior to the horizontal plane, provided an optical configuration of 0-degree observation and 45-degree illumination to the object. For all color measurements in this study, spectral reflectance was obtained from 380 to 780 nm with a 2-nm interval (SpectraWin 2.0; Photo Research Inc) and subsequently converted to CIELAB values (D65 illumination and 2-degree observer). The spectroradiometer was standardized to 8 cm to the measured object with a measurement aperture size of 1 mm.

The color of 20 artificial teeth (Dentsply Portrait IPN, mold 22E; Dentsply Intl, York, Pa), 20 right central incisor denture teeth and 20 left central incisor denture teeth of different shades was determined using the

previously mentioned color measurement arrangement. Based on an evaluation of the color data of these teeth, shade P65 was selected as the target shade for shade assessments in the study. From the color coordinates of these denture teeth, color differences (ΔE) between the shade P65 right central incisor target denture tooth and each of the 20 left central incisor denture teeth of the same mold but different shades were determined using the following formula¹⁷:

$$\Delta E = [(L^*c_8 - L^*_9)^2 + (a^*c_8 - a^*_9)^2 + (b^*c_8 - b^*_9)^2]^{1/2}, \text{ where}$$

c_8 = maxillary right central incisor, control tooth, shade P65

9 = maxillary left central incisor, test tooth

From the color difference data, 10 left central incisor denture teeth with color differences that ranged uniformly from 1 ΔE unit (visually undetectable) to greater than 10 ΔE units (an obvious shade mismatch) were selected as interchangeable teeth for use in the study (Table II). The interchangeable denture teeth were coded by another investigator to ensure that the primary investigator did not know the shade of each tooth.

Institutional review board approval was obtained to perform this study. A patient who met the following criteria was selected as a model for the study: completely edentulous maxilla, a high smile line that would expose the entire incisogingival length of the incisors during full smile, and moderate to severe residual ridge resorption that allowed for arranging and processing of the anterior denture teeth without hollow grinding. A complete denture was fabricated for the patient using artificial teeth (Dentsply Portrait IPN, mold 22E; Dentsply Intl of shade P65 (target shade). At the wax trial insertion stage, it was confirmed that the anterior teeth were arranged in an esthetic fashion and were fully visible during smiling. Prior to flasking and processing the study

Table II. Color coordinate (SD) values of interchangeable left central incisor denture teeth and color differences from right central incisor [$L^*=70.6$ (0.29), $a^*=4.6$ (0.11), $b^*=21.1$ (0.14)]

Shade	L^*	a^*	b^*	ΔE
P65	70.0 (0.26)	4.3 (0.07)	22.2 (0.04)	1.4
P67	68.5 (0.05)	3.4 (0.01)	21.0 (0.02)	2.5
B3	68.6 (0.08)	1.9 (0.04)	19.3 (0.02)	3.8
A3	67.7 (0.16)	2.5 (0.02)	18.2 (0.10)	4.6
A2	68.9 (0.19)	2.5 (0.01)	16.5 (0.05)	5.3
B4	65.8 (0.18)	3.6 (0.03)	24.9 (0.10)	6.2
P59	74.1 (0.18)	1.1 (0.01)	14.4 (0.02)	8.3
C3	62.1 (0.19)	2.8 (0.01)	18.3 (0.14)	9.1
C4	60.7 (0.26)	3.5 (0.03)	19.1 (0.05)	10.2
B1	73.9 (0.14)	0.6 (0.10)	10.0 (0.05)	12.2

denture, the maxillary left central incisor was coated with a thin film of wax (Baseplate Wax #5 Hard; Kerr Corp, Orange, Calif) to prevent chemical bonding of the denture tooth to the denture base resin. The denture was processed with heat-polymerized acrylic resin (Lucitone 199; Dentsply Intl) according to the manufacturer's recommendations. The denture was deflasked, finished, and polished, yielding a complete maxillary denture with a left central incisor tooth that was removable from the denture base. A clinical trial insertion was performed with the test denture to ensure that the denture could be worn comfortably by the patient model and that the incisor teeth were completely exposed when the model smiled (Fig. 1). Because the denture base could influence the final color of the denture teeth, the color of the maxillary right central incisor and each of the interchangeable left central incisor artificial teeth was reassessed after processing in the denture base using the same methodology as previously described. All spectrophotometric data used for this study was derived from this second instrumental assessment.

Twenty eight dentists (4 women and 24 men) with an average practice experience of 21.3 years were selected to participate as observers in the study. Four of the dentists had postdoctoral training in prosthodontics. Observers were screened for defective color vision using a color discrimination test (Dvorine Pseudochromatic Plates; Harcourt Assessment, San Antonio, Tex). Shade acceptability and perceptibility assessments were performed in a 10-foot-square room illuminated with eight 40-watt color-corrected fluorescent tubes, with a color rendering index (CRI) of 86 (GE, Fairfield, Conn) at a ceiling height of 10 feet. The walls of the room were painted with a neutral off-white color ($L^*=90.3$, $a^*=+0.17$, $b^*=+7.7$). The model was seated in the middle of the room wearing the test denture. Observers were told that the patient was wearing a test denture that allowed interchanging of a variety of left central incisor artificial teeth of identical molds but



Fig. 1. Model wearing test denture without interchangeable tooth.

different shades. Observers were instructed to regard the left central incisor as a fixed, single-tooth complete coverage restoration. For each different artificial left central incisor inserted into the denture, observers were asked, "Do the right and left central incisor teeth match in color?" This question was used to determine if a perceptible color difference existed between the 2 central incisors. If the response was "yes," the interchangeable tooth was removed and replaced with a different artificial left central incisor. If the answer was "no," the observer was asked if he or she would remake or modify the color of the restoration prior to insertion, or insert the restoration as is. This question was asked to determine clinical acceptability of the color mismatch. The response would be either: accept the restoration despite the color mismatch or remake or modify the color of the restoration. The observers were instructed to use whatever methods they would typically employ in their practice to visually assess shade matches, such as magnification and distance of observation. After each assessment, the observer looked away while the investigator removed the artificial left central incisor and replaced it with a different denture tooth. The investigator was blind as to the numerical shade of each artificial tooth and the color difference between each left and right central incisor. The teeth were inserted into the denture in a different order for each observer. Each evaluation was scored as either an imperceptible color difference, or a perceptible color difference but clinically acceptable or clinically unacceptable. Ten evaluations were made by each dentist for a total of 280 evaluations for the 28 observers.

When response data were plotted as a function of color difference, the typical cumulative normalized curve was a sigmoid, or S-shaped, curve. Therefore, a Probit analysis (SPSS 12.0 for Windows; SPSS Inc, Chicago Ill) was used to measure the relationship of the color difference (ΔE) between the right and left central incisors and the proportion of subjects exhibiting

a perceptibility response. The Probit transformation increased the linear region of the S-shaped curve, allowing for more precise regression analysis. A Pearson goodness-of-fit chi-square test was used to determine whether a variance and covariance required adjustment by a heterogeneity factor in the calculation of confidence limits. The same test was applied for acceptability responses. Using this test, regression analyses were performed on each subject's observations. Sigmoid curves plotting the probabilities of a subject perceiving a color difference and accepting a shade mismatch between right and left central incisor teeth as a function of the color difference (ΔE) between the 2 central incisors were determined. From these Probit regression analyses, the 50/50 ΔE tolerance point and the 95% upper and lower confidence limits were determined for both perceptibility and acceptability judgments. The 50/50 ΔE tolerance point for perceptibility judgments is that amount of color difference between right and left central incisors at which the observers had an equal probability of perceiving a color difference between right and left central incisor teeth. The 50/50 ΔE tolerance point for acceptability judgments is that amount of color difference between right and left central incisors at which the observers had an equal probability of either accepting or rejecting the left central incisor if it were a complete coverage restoration in a clinical scenario. Estimation procedures were used, rather than hypothesis testing, to determine the nature and strength of relationships between the variables. Therefore, 95% confidence limits for 50/50 ΔE tolerance points of acceptability and perceptibility were compared for overlap to determine whether a statistically significant difference existed between perceptibility and acceptability tolerances at an alpha level of $<.05$.

RESULTS

None of the dentist observers in this study tested positive for defective color vision. The CIELAB coordinates for each interchangeable left central incisor denture tooth used in the study are listed in Table II. Color differences between the right central incisor denture tooth and the 10 left central incisor teeth are also listed. Figure 2 demonstrate images of the test denture with 3 different interchangeable teeth of varying color difference from the contralateral central incisor denture tooth. Perceptibility and acceptability responses for the subject group are depicted graphically in Figure 3.

The Probit analysis determined a regression coefficient of -1.08 (SD 0.16) for acceptability data and a regression coefficient of -0.73 (0.10 SD) for perceptibility data. The Pearson goodness-of-fit chi-square was not significant for either acceptability or perceptibility analyses, and, therefore, no heterogeneity factor was used in the calculation of confidence limits. The predicted color



Fig. 2. Model wearing test denture with different interchangeable left central incisor denture teeth. A = $1.4 \Delta E$ units; B = $5.3 \Delta E$ units; C = $12.2 \Delta E$ units.

difference at which 50% of the observers could perceive a color difference (50/50 perceptibility) was $2.6 \Delta E$ units, with a 95% confidence limit between $2.2 \Delta E$ units and $3.0 \Delta E$ units (Table III). The predicted color difference at which 50% of the observers would remake the restoration due to color mismatch (clinically unacceptable color match) was $5.5 \Delta E$ units, with a 95% confidence limit between $5.3 \Delta E$ units and $5.8 \Delta E$ units. The 95% and 5% acceptability and perceptibility tolerance levels are also shown in Table IV. Acceptability and perceptibility color tolerances at the 50/50 level were

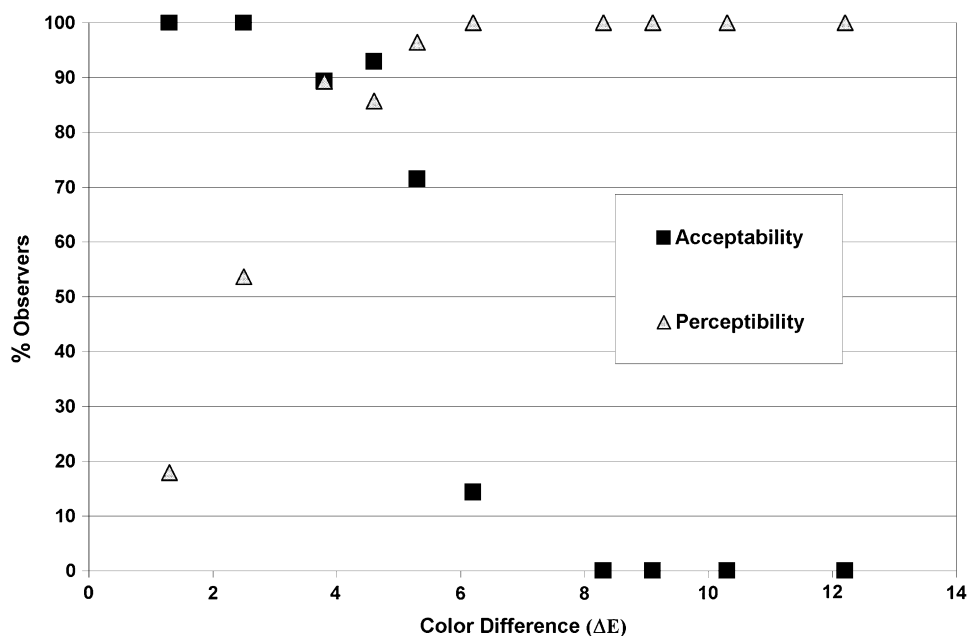


Fig. 3. Perceptibility and acceptability responses as function of color difference.

Table III. Predicted color difference at which different percentages of observers would indicate perceived color difference (shade mismatch)

% Observers	ΔE	95% confidence limit	
		Lower	Upper
5	4.9	4.4	5.7
50/50	2.6	2.2	3.0
95	0.4	0.0	1.04

Table IV. Predicted color difference at which different percentages of observers would consider a shade mismatch to be clinically acceptable

% Observers	ΔE	95% confidence limit	
		Lower	Upper
5	7.0	6.6	7.9
50/50	5.5	5.3	5.8
95	4.0	3.4	4.4

significantly different ($P < .05$) because their 95% confidence limits did not overlap.

DISCUSSION

The null hypothesis, that there is no difference between acceptability and perceptibility tolerances for shade mismatch under in vivo conditions, was rejected. Acceptability tolerances for shade mismatch were significantly higher than those for perceptibility in this study. The difference between color assessment research conducted under in vitro conditions and the in vivo evaluation is evident in this study. This in vivo study predicted 50% of the dentist observers could perceive a color difference of 2.6 ΔE units, as compared to the 50% perceptibility threshold of 1.0 ΔE unit reported by Kuehni and Marcus¹⁸ using in vitro assessments of opaque textile specimens. Acceptability tolerances showed a similar disparity to those of the in vitro studies.²⁰⁻²² The regression model of the present study predicted a 50% acceptability

tolerance of 5.5 ΔE units. Again, this was much higher than the value of 2.7 ΔE units determined by Ragain and Johnston²¹ and 3.3 ΔE units reported by Ruyter et al,²⁰ both of whom used similar observer groups viewing monochromatic composite resin specimens. Douglas and Brewer²² reported even lower acceptability tolerances (mean of 1.7 ΔE units) for prosthodontists viewing metal-ceramic crowns of varying color difference. These results suggest that clinicians are more tolerant of shade mismatch in a clinical scenario than under controlled, in vitro conditions.

Aside from the variability of in vitro versus in vivo conditions, Douglas and Brewer²² used exclusively prosthodontists in their observer group. In the present study, only 4 of the 28 observers had postdoctoral training in prosthodontics. The possibility of a lower tolerance for shade mismatch in the specialty observer group cannot be discounted. Therefore, the differences between observer group training and experience could also account for the large difference between the

50/50 color acceptability tolerance reported by Douglas and Brewer and the color tolerances reported in the current study.

Only 1 study, conducted by Johnston and Kao,²³ attempted to determine perceptibility and acceptability tolerances in a clinical scenario. The authors reported an average color difference of 3.7 ΔE units (range of 0.5-12.5 ΔE units) for a composite resin veneer restoration that was considered a perfect match to the adjacent or contralateral tooth. The authors also determined that there was an average color difference of 6.8 ΔE (range 1.3-13.1) units between veneers and adjacent or contralateral teeth that were considered a mismatch but still within an acceptable range of tooth color. A direct comparison of perceptibility and acceptability tolerances from the current study to those of Johnston and Kao's is difficult, as their values were not subjected to regression analyses but were merely averages with large standard deviations. The variability of their data may, in part, be due to the method of intraoral instrumental color assessment used. A customized colorimeter was used to make direct contact color measurements of teeth and composite resin veneers intraorally. The colorimeter had not been validated for intraoral use and is now known to be subject to edge loss effects that were not considered, thereby resulting in inaccuracies. It was the intent of Johnston and Kao to compare 2 visual assessment systems; the averages reported for acceptability and perceptibility were simply a byproduct of their results. As such, the methodology was not designed to generate perceptibility and acceptability data that lent itself to statistical analysis for the purpose of determining clinical tolerances. Although a large number of visual assessments were made, there were only 2 observers in the study; therefore, it is unlikely that the data could be subject to regression analyses for the purpose of precise determination of clinical visual assessment tolerances. Nevertheless, prior to the present study, Johnston and Kao's work was the only study reported in the dental literature to report clinically derived acceptability and perceptibility data, and it is frequently cited in dental color research as a reference for the size of a clinically acceptable color difference.

The present study predicted that 50% of observers would perceive a shade mismatch between teeth that had a color difference of 2.6 ΔE units. Johnston and Kao²³ reported a mean color difference for an alpha match (perfect color match) of 3.7 ΔE units. Acceptability tolerances predicted in the current study (5.5 ΔE units for 50% acceptability) were also lower than the mean color difference of 6.8 ΔE reported for a bravo match (just barely acceptable) reported in the Johnston and Kao study. As mentioned previously, Johnston and Kao used instrumentation that was not validated for intraoral color measurement and was subject to edge loss effects, evident in the large standard

deviations reported by the authors. Furthermore, the 2 observers of that study based their assessment of shade match not only on the adjacent tooth, but also the contralateral opposing teeth and other existing restorations when present. By matching a single central incisor to the contralateral central incisor, the present study used a clinical scenario that would generate the lowest tolerances for shade mismatch. It is likely that tolerances for perceptibility and acceptability would be higher as matches for more posterior teeth are assessed.

The main hindrance to the determination of valid clinical tolerances for acceptability and perceptibility of shade mismatches is the absence of a colorimetric or spectrophotometric instrument capable of reliable, accurate, intraoral color measurement. The use of a denture with interchangeable teeth circumvented this problem. The artificial teeth were readily amenable to color assessment using the spectroradiometer in an extraoral environment. Therefore, the color of the artificial teeth could be determined accurately without the potential of edge loss (the source of error for intraoral instrumental color measurement). Additionally, the measurement area of the artificial tooth could be precisely controlled with the spectroradiometer. This variable is important to control when measuring artificial and natural teeth that are polychromatic and nonuniform in translucency. It is difficult to ensure repeatable positioning of handheld, contact intraoral colorimeters or spectrophotometers, and minor positional changes will yield large variations in color measurement. While it would be ideal to use the spectroradiometer used to measure the artificial teeth intraorally, this methodology would have been more subject to positioning errors due to subject model movement. Regardless, the measurement of the artificial teeth in an extraoral setting may be considered a limitation of this study.

The test denture allowed for intraoral (in vivo) visual color assessments, even though the color measurements were made in an in vitro setting. Confounding variables were minimized during the visual assessment phase of the study. Assessments were made in a small room with walls of a neutral color. The patient wore no lipstick and was draped with a light blue bib to standardize the surrounding background during assessments, which were made on different days to accommodate the large number of dentist observers in the study. One potential source of error is the lack of standardization between the illumination of the room (8 color-corrected fluorescent tubes, CRI=86) and the D65 lighting of the spectroradiometer. Although the light sources for instrumental and visual assessment were not identical, the authors believed that the color rendering index of the fluorescent tubes was sufficiently high to introduce only minimal error. High regression coefficients of the Probit analysis suggest that the preceding variables did not adversely affect the results of this study. The differing light sources

between instrumental and visual assessment, and inability to perform all assessments on the same day can also be considered study limitations.

This study did not attempt to determine the intrarater reliability for the dentist observers. It would be informative to know the test/retest validity for the respective tooth shades to evaluate preliminary Cohen kappa values for the difference within 1 dentist measured over time. Unfortunately, the experimental design of the study did not incorporate a retesting of the dentists to determine the reliability of the same dentist to make the same judgments at different times. Therefore, reliability within dentists over time is a confounding variable that was not controlled and is a limitation of the study.

This study did not assess the variable of translucency on acceptability and perceptibility tolerances. The translucency of the acrylic resin artificial teeth evaluated in this study is very different from that of a metal-ceramic crown. Because metal-ceramic crowns are fabricated with a metal substructure, they do not possess the varying translucency of natural teeth, certain all-ceramic and composite resin restorations, and denture teeth. The impact on perceptibility and acceptability tolerances of comparing a metal-ceramic crown to a natural tooth that possesses varying degrees of translucency cannot be ascertained from this study and limits the extrapolation of this study's results to metal-ceramic crowns. A previous study has demonstrated that under in vitro conditions, the perceptibility tolerance for opaque, monochromatic textile specimens is low (1 ΔE unit).¹⁸ Perceptibility tolerances for monochromatic, semitranslucent porcelain specimens are also low.¹⁹ However, this does not infer that perceptibility and acceptability tolerances determined in this study using artificial teeth would be applicable for shade mismatches between metal-ceramic crown and natural teeth. It is likely that the perceptibility tolerances for metal-ceramic crowns would be similar to those demonstrated in this study using denture teeth. However, the acceptability tolerances for shade mismatch between metal-ceramic crowns and natural teeth could be higher than those determined in this study if the observers consider the perceived color difference to be due to the optical limitations inherent in a metal-ceramic crown. In this case, the observer would be more tolerant of shade mismatches between metal-ceramic restorations and natural dentition than shade mismatches between plastic denture teeth and restorations whose varying translucencies more closely resemble those of natural teeth.

All dental research that evaluates color (color stability, shade duplication, bleaching efficacy) requires that the author select a perceptibility and/or acceptability tolerance level with which to compare the results. The quantitative determination of a color difference is of little value unless it is known whether that difference is

perceivable to an observer and, perhaps more importantly, whether the color difference is clinically acceptable. Without establishing tolerances for perceptibility and acceptability in terms of color difference (ΔE units), research results can be assessed for statistical significance but cannot be interpreted for clinical significance. This study attempted to establish acceptability and perceptibility tolerances under clinical conditions rather than in vitro conditions reflective of an artificial, nonclinical environment. Future research should be focused on determining the effect of education (pre- and postdoctoral) on perceptibility and acceptability tolerances, determining whether tolerances are dependent on the direction of the color difference, and assessing whether the tolerances of dentists are different from those of nondentists.

CONCLUSIONS

Within the limits of this study, the following conclusions were made:

1. Tolerances for perceptibility were significantly lower than tolerances for acceptability of shade mismatch between 2 artificial acrylic resin teeth ($P < .05$).
2. Mean color perceptibility tolerance for 50% of observers was 2.6 ΔE units.
3. Mean acceptability tolerance for 50% of observers was 5.6 ΔE units and 4.0 ΔE units for 95% of observers.

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