THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

In vitro comparison of instrumental and visual tooth shade determination under different illuminants

Elke Kröger, Dr med dent,[a] Stefanie Matz, Dr med dent,[b] Markus Dekiff, Dip Phys,[c] Bao Long Tran, Dr med dent,[d] Ludger Figgener, Prof Dr med, Dr med dent,[e] and Dieter Dirksen, PD, Dr rer nat Dipl Phys[f]

ABSTRACT

Statement of problem. While a considerable body of literature deals with the comparison between visual and instrumental tooth color determination, in most of these studies either the number of color specimens or the number of examiners is too small to allow for a general statement about such a subjective method as visual color determination. Furthermore, perceptual aspects like perceptible or acceptable color differences are often not considered.

Purpose. The purpose of this study was to investigate the precision of a spectrophotometer in tooth shade determination compared with visual color matching using a shade guide in vitro. Moreover, the influence of different illuminants as well as of sex and professional experience of the examiners on visual color matching was analyzed.

Material and methods. Fifty examiners (13 men, 37 women; without dyschromatopsia), grouped by professional experience, determined the shades of 10 prosthetic teeth with the Vitapan classical shade guide under 4 illuminants (daylight, halogen, fluorescent [5000 K], fluorescent [nonspecific ceiling light]) and with a spectrophotometer (Shadepilot). Reproducibility (precision) of color determination was characterized by the average of the highest percentages of interexaminer agreement for each specimen. Additionally, color differences (ΔE) were calculated based on CIELab values.

Results. The mean reproducibility of the spectrophotometer was 92.2%, while for visual examination it was 43.7%. The corresponding differences in CIELab color space amounted to ΔE_{instr}=2.6 and ΔE_{vis}=5.2. Illuminants and professional experience showed a significant influence, while sex did not.

Conclusion. While the spectrophotometer provided higher reproducibility, considering the color differences, the results obtained by visual inspection were still satisfactory. The differences due to type of illuminant, degree of experience, and sex of the examiners are of little practical relevance. (J Prosthet Dent 2015;114:848-855)

Prosthetic dentistry will only provide satisfactory results if dental restorations are esthetically pleasing. Thus, an accurate determination of tooth color is crucial for the definitive result. There are 2 different categories of color determination: instrumental and visual. Visual color determination with shade guides is the most frequently applied shade-matching method in clinical practice.[1-3] This procedure is subjective. It is influenced by various factors such as dyschromatopsia, fatigue of the eye, and ambient conditions, for example lighting.[4,5] To eliminate these factors, electronic shade matching devices have become more widespread in dentistry. Most commonly used devices are spectrophotometers and colorimeters; they are subject to research and have been tested in several studies with regard to accuracy and reliability.[6-16] In some studies colorimeters and spectrophotometers have shown better results than visual color determination regarding accuracy and reproducibility.[6-11]

[a]Resident, Department of Prosthetic Dentistry and Biomaterials, University of Münster, Münster, Germany.
[b]Private practice, Unna, Germany.
[c]Doctoral student, Department of Prosthetic Dentistry and Biomaterials, University of Münster, Münster, Germany.
[d]Resident, Department of Prosthetic Dentistry and Biomaterials, University of Münster, Münster, Germany.
[e]Professor and Director, Department of Prosthetic Dentistry and Biomaterials, University of Münster, Münster, Germany.
[f]Head, Division of Technology and Materials, Department of Prosthetic Dentistry and Biomaterials, University of Münster, Münster, Germany.

Clinical Implications

The spectrophotometer proved to be a reliable and precise tool for tooth shade determination with only a limited clinical advantage over visual color matching. However, it may help people with color vision deficiency or those who feel insecure in color determination.

Dagg et al[4] found that light quality was the most critical influencing factor in the visual matching of tooth shades. Imbery et al[5] also concluded that ambient lighting has a statistically significant impact on shade matching. However, Culpepper et al[17] compared different light sources and found no clinically significant differences. Results concerning the influence of sex[11,18,19] and experience [4,11,18,20] on visual color determination are also inconsistent.

In most of these studies the number of examiners was limited to 2 or 3,[6-9,12-14] which might be critical in that perceptual evaluation and judgment of color differences is highly subjective. Furthermore, in some investigations the color of only 1 tooth was assessed.[11,21] In many studies the only criterion for accuracy and precision was the agreement of the shade tab codes determined by different methods or repeated measurements,[11-14] while the fact that there might be more than 1 correct match, considering the threshold of perception,[22-25] was overlooked.

To address these issues, the present study, which compares visual and instrumental examination, involved a larger number of examiners (50) as well as a larger number of specimens (10). Furthermore, not only were color codes evaluated to determine the precision of each method, but also color differences in CIELab color space[26] were calculated. These were related to thresholds for acceptable color mismatch.

To investigate the influence of the light source on visual tooth shade determination 4 light sources were examined: halogen chair light, daylight, nonspecific fluorescent ceiling light, and a fluorescent daylight lamp. In addition, the influence of sex and work experience was evaluated.

The null hypothesis was that there would be no difference between the precision of instrumental and visual color examination. Further null hypotheses included that visual color examination would be influenced by the type of illuminant as well as sex and experience of the examiners. Special emphasis was given to whether observed differences between visual and electro-optical results are of clinical relevance.

MATERIAL AND METHODS

Fifty examiners (37 women and 13 men, aged between 23 and 48 years) were recruited and their informed consent was obtained. They were divided in 2 groups with respect to experience. The first group (17) consisted of 5 dentists, 4 dental technicians, and 8 dental assistants with clinical shade matching experience. Twenty-nine dental students and 4 physicists were part of the second group (33) without experience. All participants were tested with the Ishihara color vision test to rule out dyschromatopsia. The study was approved by the institutional review board.

Both groups were asked to match the colors of 10 different prosthetic teeth made of synthetic resin (SR Vivodent PE prosthetic teeth; Ivoclar Vivadent AG). All prosthetic teeth were maxillary right central incisors. They were fixed on black cardboard to provide better handling and identical backgrounds. These teeth covered the most common tooth colors. Their shades (O1, 1A, 3A, 2B, 4B, 1C, 3C, 6C, 4D, 1E) did not exactly match the colors of the shade guide used in visual examination to better reproduce the clinical situation.

The volunteers were instructed to determine the color only on the basis of the middle third of the tooth. The tooth color was identified within the range of the Vitapan classical shade guide (VITA Zahnfabrik) at 3 different illuminants commonly available in the dental office or dental laboratory (halogen chair light, daylight, nonspecific fluorescent ceiling light) and a fluorescent daylight lamp with a correlated color temperature[27] of about 5000 K (Color Control Daylight 5000; JUST Normlicht GmbH), which is widely used in the graphics industry. Table 1 lists the correlated color temperature, color rendering index,[27] and illuminance of each light source measured with a colorimeter (i1; X-Rite Europe GmbH). The specimens were mixed thoroughly and given to the test persons in random order. After having assessed the tooth color of all specimens, the examination was repeated immediately (once again in random order) to get overall 2 results per specimen and examiner.

No examiners had experience using an electro-optical device for shade measurements. Thus, before use, introductions were given. A spectrophotometer providing complete-tooth measurement (Shadepilot; Degudent GmbH) was used to assess the color of the 10 prosthetic teeth once by each examiner. The spectrophotometer was not used under different illuminants, because it has an integrated standardized illumination and is designed in such a way that ambient light does not influence the data

Table 1. Color temperature, color rendering index (CRI), illuminance of used illuminants

Illuminant	Halogen (chair light)	Daylight	Fluorescent (ceiling light)	Fluorescent (5000 K)
Correlated color temperature	4660 K	Varying	3760 K	5020 K
Color rendering index	93	96	80	95
Illuminance	9770 lux	3550 lux (average)	700 lux	2220 lux

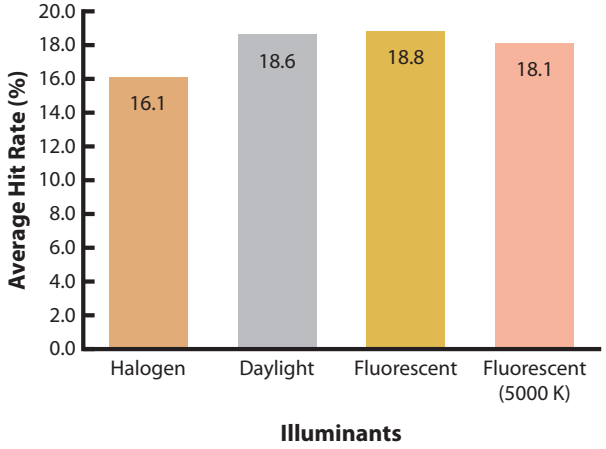

Figure 1. Average hit rate for each illuminant.

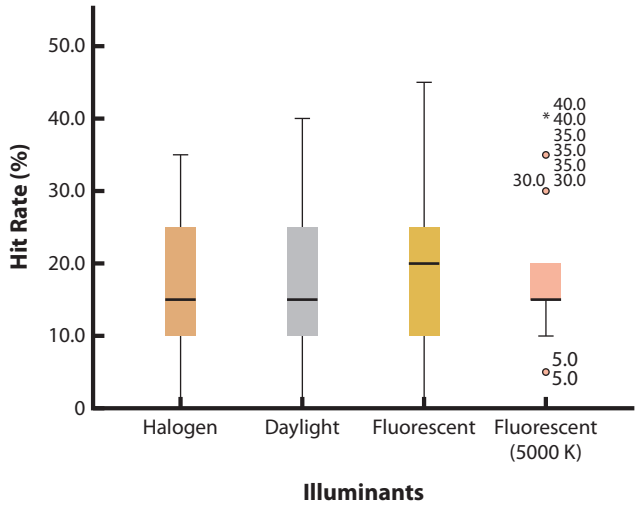

Figure 2. Box plots of hit rate in visual examination under 4 different illuminants.

acquisition. The device was calibrated before use with a target provided by the manufacturer. The cardboard strips with the specimens were placed on a table in a room with dimmed fluorescent ceiling light. To imitate the clinical situation, the measuring angle was not completely fixed but only measurements in a valid angle (as indicated by a green line on the display) were accepted. For the investigations described here, only the result for the middle third of the tooth was used. The spectrophotometer measures CIELab color values, in the following referred to as L*a*b* values. The device then uses factory default L*a*b* values of the Vitapan classical shade guide for a comparison with the measured L*a*b* values. The Vitapan classical shade (A1-D4) closest in CIELab color space is displayed as the result.

In CIELab color space, the difference between 2 colors A and B is commonly determined by calculating the Euclidean distance between them[26]:

$$\Delta E=\sqrt{\left(L_A^*-L_B^*\right)^2+\left(a_A^*-a_B^*\right)^2+\left(b_A^*-b_B^*\right)^2}.$$

The evaluated color differences were calculated on the basis of factory stored L*a*b* values of the Vitapan classical shades and reference L*a*b* values of the specimens, which were obtained by averaging over all 50 measurements (per specimen) performed by the examiners. It has been reported that the colors of shade tabs representing the same shade code differ from one Vitapan shade guide to another.[28] Hence, color differences were also determined based on L*a*b* values of the used shade tabs measured with the spectrophotometer (averaged over 3 measurements per tab performed by one of the authors [S.M.]). In addition, in some cases an improved color difference formula provided by the CIE, the CIEDE2000 formula,[26,29,30] was used for comparison. Color differences that were calculated using this formula are denoted by ΔE_{00}, in all other cases the term color difference refers to the Euclidean distance in CIELab color space.

The hit rate describes how often an examiner selected the same color by visual and instrumental color determination. The selection of a shade that differed no more than ΔE=6.8 from the reference color of the specimen was classified as a success. According to Johnston and Kao,[22] on average a color difference of 6.8 (±2.7) is still assessed as acceptable in the oral environment. The rate of these successful shade matching attempts is named success rate. Furthermore, for each specimen the highest percentage of interexaminer agreement for a shade tab code by visual or instrumental inspection was calculated. Averaged over all specimens, this parameter indicates the reproducibility (precision) of each method.

For the statistical analysis statistics software (IBM SPSS Statistics v22.0; IBM Corp) (α=.05) was used. For the different illuminants data, ANOVA, Kruskal-Wallis test, and Duncan post hoc test were performed. The influence of experience and sex was analyzed with *t* tests. To explore whether the average color differences and success rates for visual examination obtained with measured and factory default color data for the tabs differ significantly, a one-sided Wilcoxon signed rank test was carried out. The Pearson correlation coefficient was used to investigate the relationship among ΔE and ΔE_{00} color differences between shade tabs and specimens.

RESULTS

The hit rates of the investigators were evaluated for the 4 illuminants. As seen in Figure 1, the halogen chair light had on average the lowest hit rate with 16.1%. The mean hit rate with daylight was 18.6%, with nonspecific fluorescent ceiling light, 18.8%, and with the fluorescent daylight lamp (5000 K), 18.1%.

Figure 2 shows that the median values of the hit rates differed more than the averages shown in Figure 1. The

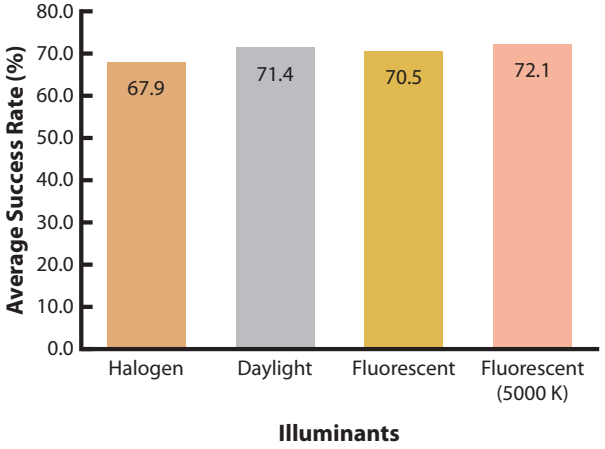

Figure 3. Average success rate in visual shade matching for each illuminant.

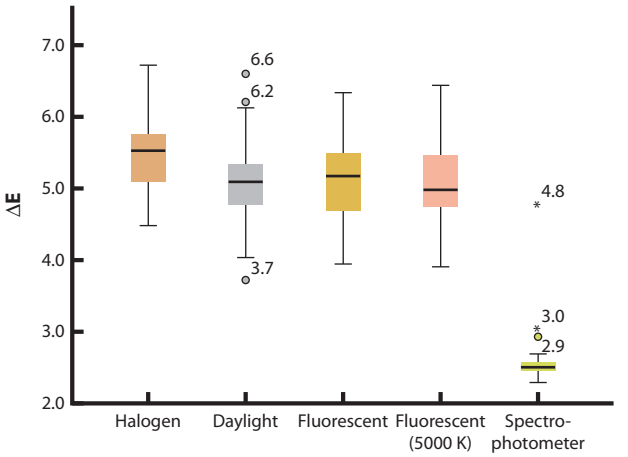

Figure 4. Color differences ΔE calculated from shades chosen by raters under 4 illuminants and by electro-optical device.

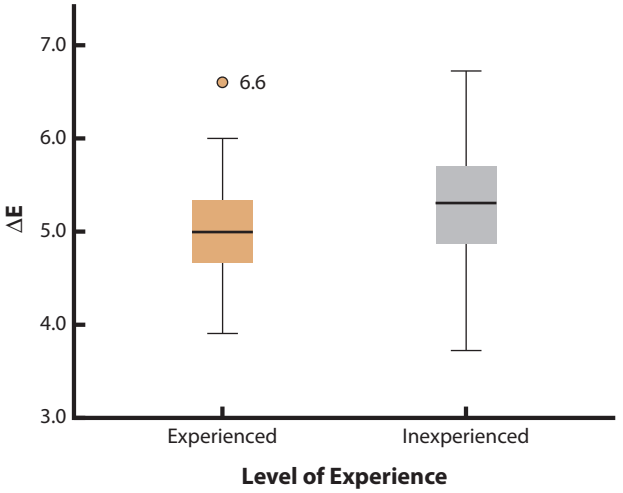

Figure 5. ΔE values at visual examination depending on level of experience of raters.

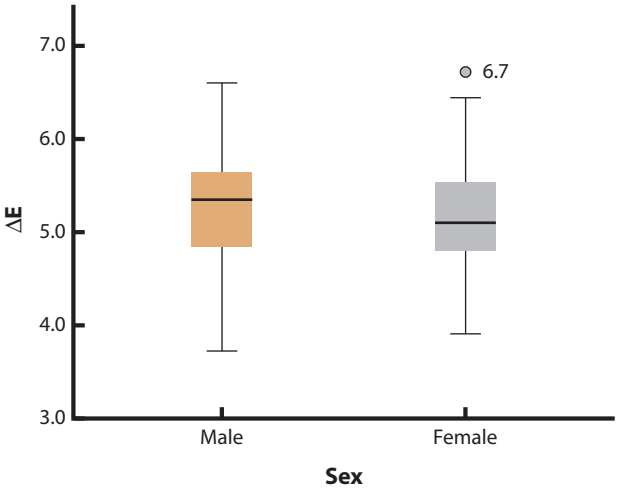

Figure 6. ΔE values achieved in visual examination depending on sex of raters.

nonspecific fluorescent showed the widest spread with 45%. A Kruskal-Wallis test revealed that none of the illuminants produced a significant difference in hit rate (P=.593).

Figure 3 shows that the average success rates achieved by visual examination were quite similar for all 4 illuminants (68% to 72%). In contrast, instrumental examination provided an average success rate of 99% (not shown).

The ideal examiner should determine the best match on the basis of colorimetry, that is, the color with the smallest ΔE. Considering the color differences of visual examination under different illuminants (Fig. 4), mean and median values were in the range from 5 (median value for fluorescent 5000 K) to 5.5 (mean value and median value of the halogen). Figure 4 also shows the ΔE values achieved with the spectrophotometer. The median was 2.3 and the mean was 2.6. The averages of the ΔE values of visual and electro-optical examination differed by 2.6. An ANOVA (dependent variable: mean ΔE value, averaged over all specimens and both visual examinations for each examiner; independent variable: illuminant) revealed a significant effect of the illuminant type on color differences (P=.001). The Duncan post hoc test showed significantly higher color deviations at visual color determination with the halogen lamp compared with the others illuminants.

The color determination by the experienced examiners showed smaller ΔE values compared with the inexperienced examiners in the visual examination (Fig. 5). The t test revealed that there was a significant difference (P<.001) between these 2 groups. The ΔE values achieved by the female raters were slightly smaller than the ΔE values for the male raters (Fig. 6), but the t test indicated no significant difference (P=.162). Figure 7 shows the highest percentage of interexaminer

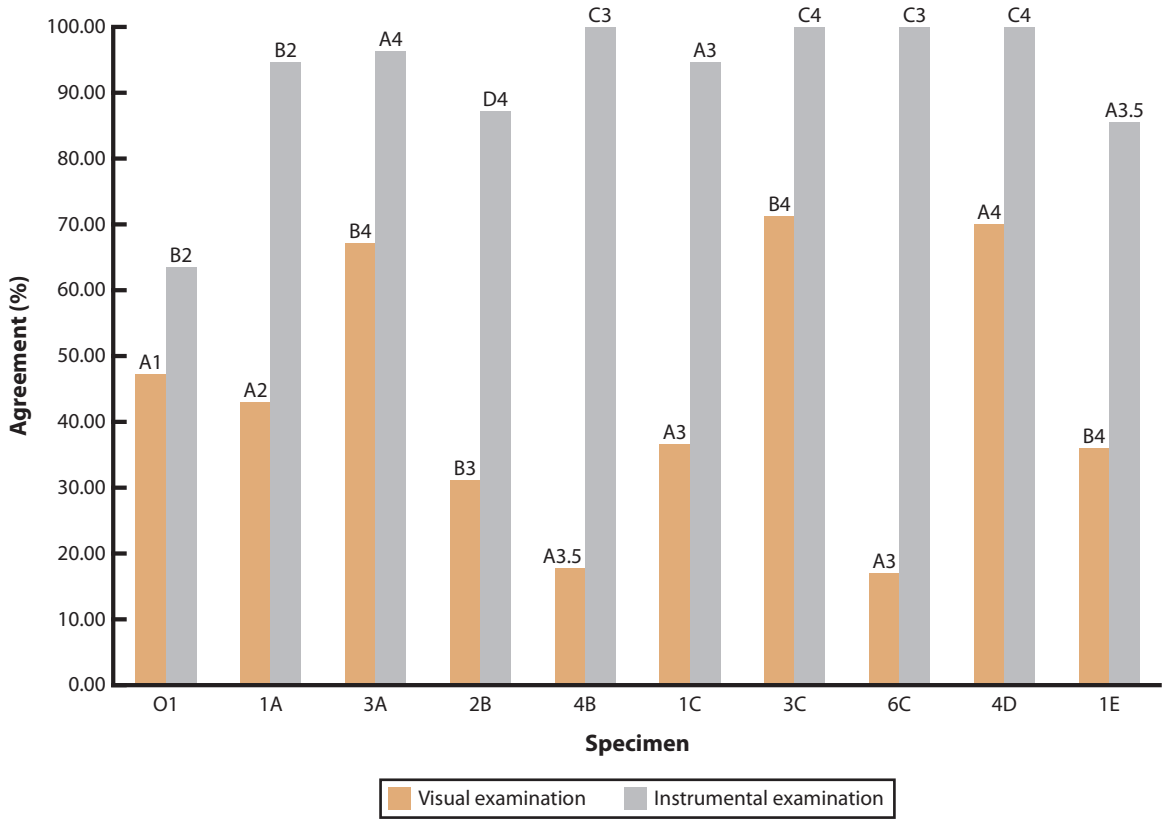

Figure 7. Highest percentage of interexaminer-agreement for shade tab code by visual and instrumental examination.

agreements for a shade tab code by visual and instrumental shade determination for each specimen. The mean value for the spectrophotometer was 92.2%, while for visual examination it was 43.7%. The examiners reported that the shades of some prosthetic teeth were hard to determine with the shade guide. The mean ΔE for visual and instrumental examination and the success rate were calculated for each specimen individually (Table 2). In addition, the ΔE values between each specimen and the closest match from the shade guide based on the average L*a*b* value of the specimen and the factory default L*a*b* values of the shade guide shades are listed. The parameter "ΔE to closest match" thus represents the minimum mean ΔE value that would be achieved by visual or instrumental examination if only the presumably correct shade was selected. Table 2 data demonstrate that the color differences of the closest match as well as the mean ΔE values in visual and instrumental examination were higher for specimens 3C, 6C, and 4D than for the others. Figure 7 appears to indicate that specimens 3A, 3C, and 4D were easier to determine during visual determination, but the success rates for 3C and 4D were rather low.

The measured L*a*b* values of the used shade tabs differed from the factory stored values on average by 2.12 (SD 0.49). Using the measured color values, the average

Table 2. ΔE values and mean success rate for each specimen

Specimen	O1	1A	3A	2B	4B	1C	3C	6C	4D	1E
ΔE to closest match	2.56	1.70	2.89	0.50	1.63	1.55	4.23	4.85	3.66	1.66
Mean ΔE visual	3.20	2.90	3.93	4.23	6.30	3.27	9.37	8.65	7.57	2.61
Mean ΔE instrumental	2.66	1.80	2.92	0.72	1.63	1.66	4.23	4.85	3.66	1.74
Mean success rate visual	97.3	97.3	99.5	98.8	40.3	97.8	18.3	42.3	14.3	99.3

ΔE value between specimen and closest match from shade guide, mean ΔE value between specimen and shade determined by visual examination and instrumental examination as well as mean success rate for each specimen.

success rate in visual examination increased from 70% to 81% (averaged over all 4 illuminants), the mean color difference decreased from 5.2 to 4.5 (halogen: 4.7, daylight: 4.3, fluorescent: 4.4, fluorescent (5000 K): 4.3). The one-sided Wilcoxon signed rank test revealed a significant decrease in the mean color difference (P=.042), while the average success rate increased (not significant, P=.320). Table 3 lists the color differences ΔE and ΔE_{00} between the specimen and the closest match from the shade guide, the mean color differences ΔE and ΔE_{00} between the specimen and the shade determined by visual examination, and the mean success rates for each specimen when measured L*a*b* values of the shade tabs were used instead of the factory default values. A closer look reveals that for 3 of the 4 specimens with the lowest success rates (3C, 6C, 4D), only C and D

Table 3. ΔE and ΔE_{00} values and mean success rate for each specimen when measured color values of shade tabs were used

Specimen	O1	1A	3A	2B	4B	1C	3C	6C	4D	1E
ΔE to closest match (measured shades)	1.71	0.61	2.41	1.51	1.21	2.48	5.22	2.87	3.28	2.16
Mean ΔE visual (measured shades)	2.89	2.51	2.99	3.34	4.62	3.73	8.31	6.51	5.96	3.71
Mean success rate visual (measured shades)	95.0	93.8	98.8	98.8	74.0	97.5	18.5	51.5	83.0	99.3
ΔE_{00} to closest match (measured shades)	1.14	0.62	1.44	0.97	1.01	1.54	2.76	2.03	2.56	1.85
Mean ΔE_{00} visual (measured shades)	2.04	1.88	2.13	2.06	3.21	2.50	6.55	4.93	5.07	2.82

ΔE and ΔE_{00} value between specimen and closest match from shade guide, mean ΔE and ΔE_{00} value between specimen and shade determined by visual examination and mean success rate for each specimen; instead of L*a*b* values stored in spectrophotometer, measured color values of shade tabs were used.

shades of the shade guide (C: shades of gray, D: reddish gray) and the darkest A shade were below a color difference of 6.8. A linear regression analysis indicated a significant correlation among the ΔE and ΔE_{00} color differences between the 16 shade tabs and 10 specimens (Pearson correlation coefficient r=.971, $P<.001$).

DISCUSSION

In this study, 50 raters participated. The groups (inexperienced/experienced, men/women) were not of the same size. While the number of examiners corresponded to that in some other studies,[10,21] often there were only 2 or 3 examiners.[6-9,12-14] The large spreads of hit rates and of ΔE values in visual examination (Fig. 2, Figs. 4-6) indicate that judgments of color differences tend toward individual fluctuations. Thus, small numbers of examiners might be critical.

To ensure standardized conditions, prosthetic teeth were used. The sample size (10) and range of tooth shades were reasonable, in that the reproducibility and mean ΔE values varied considerably among specimens. In some studies the color of only 1 tooth was assessed.[11,21] The results of the present study indicate that such a sample size is insufficient for a quantitative evaluation of visual shade matching.

There are various color matching devices on the market. The Vitapan 3D-Master shade guide, for instance, offers smaller distances in the color space and the arrangement of the tabs allows for separately matching value, chroma, and hue. While Paravina[3] found color matching of natural teeth to be easier with the 3D-Master shade guide than with the Vitapan classical shade guide, these results could not be confirmed by Della Bona et al.[20] Given these inconsistent findings, we chose to use the Vitapan classical shade guide, which is frequently used in clinical settings and familiar to most of the participants.

This particular spectrophotometer was chosen because it is a typical device of its class and clinical experience already existed. Because it provides a complete-tooth measurement, the influence of edge-loss effects[16] on the color measurement is assumed to be negligible. According to the manufacturer, the inter-instrument accuracy is better than ΔE=1. However, other studies showed that ΔE values determined by similar devices can differ by around ΔE=4 from ΔE values obtained with spectroradiometers, which are assumed to provide a higher accuracy.[15] So, although the L*a*b* values from the spectrophotometer were considered as the reference for the comparison with visual examination, there is no guarantee that the instrumentally acquired results are always more accurate.

The L*a*b*-values of the shade guide tabs measured with the spectrophotometer differed on average by 2.12 from the factory default ones. It is reasonable to assume that these differences were partly due to the inaccuracy of the device and partly due to the manufacturing tolerance of the shade tabs, which seems to be rather high, as demonstrated by King et al.[28]

In this study, color differences were quantified by ΔE values. Some studies indicate that the use of ΔE values for tooth colors might not be the best method.[2] However, here the color differences calculated using the presumably more accurate CIEDE2000 formula (ΔE_{00}) showed a significant correlation with corresponding ΔE values. This agrees with findings of Kim et al,[30] who found a strong correlation among ΔE and ΔE_{00} values between shade tab pairs from 2 shade guides.

For the definition of the success rate and as the general acceptability tolerance for shade mismatch, a maximum ΔE of 6.8 has been chosen. This value has been described by Johnston and Kao[22] as the average ΔE for which a mismatch is still in the normal range of tooth shades. They also reported that the tolerance strongly depends on the individual case. If the shades of adjacent teeth are very homogenous, the tolerance will be smaller. Otherwise, it might be even higher. Although the study of Johnston and Kao has been criticized for methodical shortcomings[23] and possibly outdated esthetic demands,[24] the investigated scenario appears to be more realistic than that of other studies, in that the shade assessment was carried out in vivo considering also adjacent and contralateral opposing teeth and restorations. In a more recent in vivo study, Douglas et al[23] came to the conclusion that a color difference of 4 was still acceptable for 95% of the observers, while for a color difference of 5.5, this percentage decreased to 50%. However, they also stated that their study setup would generate the lowest tolerances for shade mismatch and that in other cases the tolerances are likely to be higher.

Further studies concerning acceptability thresholds seem to be necessary.

The presented results show that different illuminants can have a statistically significant effect on visual color determination. The best illuminants with respect to tooth shade determination turned out to be the fluorescent light sources and daylight. For color determination, the color rendering index (CRI) of the illuminating light source should be above 0.9.[27] Surprisingly, the halogen lamp led to slightly worse results, even though it had a CRI of 0.93, while the nonspecific fluorescent ceiling light had a CRI of only 0.8. A possible explanation could be an insufficient adaption of the examiners to the high intensity of the halogen lamp. However, assuming a tolerance of $\Delta E \leq 6.8$, the observed differences are of little practical relevance. This leads to the conclusion that visual color examination can be carried out in the dental office under all 4 types of illuminants investigated here.

The average ΔE values of visual and electro-optical examination were $\Delta E_{vis}=5.2$ and $\Delta E_{instr}=2.6$. So, while instrumental shade determination is considerably more accurate, the results of visual shade determination were on average still tolerable.

According to the *t* test, experienced examiners performed better in shade matching than inexperienced examiners ($P<.001$). However, considering the average ΔE values, the influence of experience is of little clinical relevance. Differences between male and female examiners turned out to be not statistically significant ($P=.162$).

The hit rates of visual inspection appeared to be quite low. However, the relevance of this parameter is small, in that it does not account for the possibility that there might be more than one matching shade. For this reason, the success rate has been introduced. While instrumental examination provided an average success rate of nearly 100%, an average success rate of only approximately 70% was achieved in visual inspection. A closer look reveals that for 6 of the 10 specimens, the success rates were higher than 97%.

The average highest percentage of interexaminer agreement in visual examination was 43.7%; in instrumental inspection, it was 92.2%. However, a high degree of agreement in visual examination is not an indicator for accuracy, as can be seen from the low success rates for the 2 specimens with the highest percentages of agreement.

All in all, the results for the mean ΔE values, the average success rates, and the average highest percentages of interexaminer agreement confirm the findings of other studies[6-11]; that is, instrumental shade determination provides higher reproducibility and (presumably) accuracy than visual shade matching. Inconsistencies between visual and instrumental examination as well as between the examiners can be attributed, in part, to generally known issues in visual color determination, for example the eye's susceptibility to fatigue or previous eye exposure. An additional difficulty in this particular study most likely arose from the inhomogeneous coloring of the specimens due to their translucency, which increased considerably toward the edges.

Because shade code selections in visual examination depend on the true colors of the shade tabs, various parameters were also calculated with measured color data for the tabs instead of the factory default data set. This led to a significantly lower average ΔE of 4.5 ($P=.042$) and a higher average success rate of 81% (not significant, $P=.320$) for visual inspection. Hence, with a more accurate shade guide better results would have been possible theoretically. The low success rates/high average ΔE values for visual examination of specimens 4B and 4D listed in Table 2 can be attributed to discrepancies between the actual and factory default L*a*b* values of the shade tabs (see Table 3 for comparison). The difficulties in the visual assessment of specimen 3C could be explained by the large color difference to the closest match. It remains unclear why specimen 6C had a low success rate/high average ΔE value, regardless of whether measured or factory default L*a*b* values were used for the calculations.

CONCLUSIONS

Color determination with the spectrophotometer investigated here generally led to better results compared with visual examination. One of the advantages of electro-optical examination is that it is not influenced by individual misjudgment. It provided a high reproducibility (92.2%) and can assist the visual examination, as well as replace it. While the comparatively low mean reproducibility of 43.7% and the low average hit rate of approximately 18% seem to indicate a significant disadvantage of visual tooth shade determination, the investigation of color differences in CIELab space revealed that the results of the visual inspection were still satisfactory considering factors like the natural color variation of adjacent teeth. Taking into account a clinically acceptable color difference threshold of $\Delta E \leq 6.8$, the differences attributable to illuminant, degree of experience and sex of the investigator are of little clinical relevance. The variations of the results regarding examiners and specimens suggest that the small numbers of color specimens or examiners involved in most other comparable studies do not allow for a general statement about such a subjective method as visual color determination.

REFERENCES

1. Van der Burgt TP, ten Bosch JJ, Borsboom PC, Kortsmit WJ. A comparison of new and conventional methods for quantification of tooth color. J Prosthet Dent 1990;63:155-62.
2. Chu SJ, Trushkowsky RD, Paravina RD. Dental color matching instruments and systems. Review of clinical and research aspects. J Dent 2010;38(Suppl 2):e2-16.
3. Paravina RD. Performance assessment of dental shade guides. J Dent 2009;37 (Suppl 1):e15-20.

4. Dagg H, O'Connell B, Claffey N, Byrne D, Gorman C. The influence of some different factors on the accuracy of shade selection. J Oral Rehabil 2004;31:900-4.
5. Imbery TA, Geissberger M, Hakim F, Al-Anezi S, Uram-Tuculescu S, Gottlieb R, et al. Evaluation of four dental clinical spectrophotometers relative to human shade observation. J Am Dent Assoc 2013;144:1183-6.
6. Paul S, Peter A, Pietrobon N, Hämmerle CHF. Visual and spectrophotometric shade analysis of human teeth. J Dent Res 2002;81:578-82.
7. Paul SJ, Peter A, Rodoni L, Pietrobon N. Conventional visual vs spectrophotometric shade taking for porcelain-fused-to-metal crowns: a clinical comparison. Int J Periodontics Restorative Dent 2004;24:222-31.
8. Da Silva JD, Park SE, Weber H-P, Ishikawa-Nagai S. Clinical performance of a newly developed spectrophotometric system on tooth color reproduction. J Prosthet Dent 2008;99:361-8.
9. Browning WD, Chan DC, Blalock JS, Brackett MG. A comparison of human raters and an intra-oral spectrophotometer. Oper Dent 2009;34:337-43.
10. Alsaleh S, Labban M, AlHariri M, Tashkandi E. Evaluation of self shade matching ability of dental students using visual and instrumental means. J Dent 2012;40(Suppl 1):e82-7.
11. Bahannan SA. Shade matching quality among dental students using visual and instrumental methods. J Dent 2014;42:48-52.
12. Gehrke P, Riekeberg U, Fackler O, Dhom G. Comparison of in vivo visual, spectrophotometric and colorimetric shade determination of teeth and implant-supported crowns. Int J Comput Dent 2009;12:247-63.
13. Hugo B, Witzel T, Klaiber B. Comparison of in vivo visual and computer-aided tooth shade determination. Clin Oral Investig 2005;9:244-50.
14. Fani G, Vichi A, Davidson CL. Spectrophotometric and visual shade measurements of human teeth using three shade guides. Am J Dent 2007;20:142-6.
15. Zenthöfer A, Cabrera T, Corcodel N, Rammelsberg P, Hassel AJ. Comparison of the Easyshade Compact and Advance in vitro and in vivo. Clin Oral Investig 2014;18:1473-9.
16. Bolt RA, Bosch JJ, Coops JC. Influence of window size in small-window colour measurement, particularly of teeth. Phys Med Biol 1994;39:1133-42.
17. Culpepper WD. A comparative study of shade-matching procedures. J Prosthet Dent 1970;24:166-73.
18. Haddad HJ, Jakstat HA, Arnetzl G, Borbely J, Vichi A, Dumfahrt H, et al. Does gender and experience influence shade matching quality? J Dent 2009;37(Suppl 1):e40-4.
19. Corcodel N, Rammelsberg P, Moldovan O, Dreyhaupt J, Hassel AJ. Effect of external light conditions during matching of tooth color: an intraindividual comparison. Int J Prosthodont 2009;22:75-7.
20. Della Bona A, Barrett AA, Rosa V, Pinzetta C. Visual and instrumental agreement in dental shade selection: three distinct observer populations and shade matching protocols. Dent Mater Off Publ Acad Dent Mater 2009;25:276-81.
21. Özat PB, Tuncel İ, Eroğlu E. Repeatability and reliability of human eye in visual shade selection. J Oral Rehabil 2013;40:958-64.
22. Johnston WM, Kao EC. Assessment of appearance match by visual observation and clinical colorimetry. J Dent Res 1989;68:819-22.
23. Douglas RD, Steinhauer TJ, Wee AG. Intraoral determination of the tolerance of dentists for perceptibility and acceptability of shade mismatch. J Prosthet Dent 2007;97:200-8.
24. Khashayar G, Bain PA, Salari S, Dozic A, Kleverlaan CJ, Feilzer AJ. Perceptibility and acceptability thresholds for colour differences in dentistry. J Dent 2014;42:637-44.
25. Ghinea R, Pérez MM, Herrera LJ, Rivas MJ, Yebra A, Paravina RD. Color difference thresholds in dental ceramics. J Dent 2010;38(Suppl 2):e57-64.
26. Colorimetry. Commission internationale de l'Eclairage, CIE Central Bureau; 2004. p. 16-21.
27. Hunt RWG, Pointer MR. Measuring Colour. John Wiley & Sons; 2011. p. 95-7.
28. King KA, deRijk WG. Variations of L*a*b* values among Vitapan Classical Shade Guides. J Prosthodont Off J Am Coll Prosthodont 2007;16:352-6.
29. Sharma G, Wu W, Dalal EN. The CIEDE2000 color-difference formula: Implementation notes, supplementary test data, and mathematical observations. Color Res Appl 2005;30:21-30.
30. Kim JG, Yu B, Lee YK. Correlations between color differences based on three color-difference formulas using dental shade guide tabs. J Prosthodont 2009;18:135-40.

Corresponding author:
Dr Elke Kröger
University of Münster
Albert-Schweitzer-Campus 1, Bldg W30
48149 Münster
GERMANY
Email: elke.kroeger@ukmuenster.de

Copyright © 2015 by the Editorial Council for *The Journal of Prosthetic Dentistry.*