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Color determination with no-match-templates using two different tooth color scales—An in vitro evaluation

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Abstract

Objectives: Visual shade selection is the most commonly used method in dentistry and a challenge for every dentist. However, differences to natural tooth color and the differences of each shade guide are well known. The aim of this paper is to investigate the suitability of two different color scales for determining the color of no-match templates.

Materials and methods: Volunteers (N = 76) selected a shade color of a no-match template with two shade guides (VITA Classical shade guide (VC) and VITA Linearguide 3D-Master (V3D LG), both Vita Zahnfabrik). The neutral grey background was laterally illuminated with a color differentiation lamp (Dialite, Eickhorst GmbH). For the volunteers' accuracy, the triangle's area was used which are emerge by the color coordinates of a template ($L_T a_T b_T$) and the color coordinates of the two decisions ($L_1 a_1 b_1$ and $L_2 a_2 b_2$). Statistical software was used to evaluate the differences in ΔE_{00} with α = .01.

Results: A deviation in the median of ΔE_{00} of 7.6 (V3D LG, first choice) to 6.6 (VC, second choice) was detected, while *U* test showed no significant differences in the median for both color scales. But the triangle's area generated by both shade decisions and tooth color with V3D LG was significant smaller (14.2) then VC (19.2) ($P \leq .001$).

Conclusions: When comparing both results no significant difference in the subject's shade selection and the shade guides was detected. The new evaluation strategy using the size of the triangle's areas proves the superiority of the V3D LG due to a better distribution of the tooth color shades within the color space.

KEYWORDS
color space differences, no-matched templates, shade taking, tooth color

1 | INTRODUCTION

Esthetics and color play an increasingly more important role in dentistry nowadays compared to some years ago. Beautiful, natural and color-accurate teeth in a denture (eg, fixed partial or removable dentures) do not only emphasize the oral health and social status of the patient, but reflect on the skills of the dental technician who is able to create perfect and color accurate prosthesis.

Today, color differences can be exactly measured, metrically recorded and evaluated.[1-6] With the coordinates in the spherical

CIELab color space, all colors are easily captured and described within the Cartesian coordinates as *L*, *a**, and *b** (Figure 1).[7] *L* is the lightness coordinate (brightness or value), which connects an imaginary south pole (black) with an imaginary north pole (white), all grey values are represented in this vertical line. On the sphere's equator all other saturated colors shown. The right angles in the equator plane, the *a**- and *b**-axis, that represent the directions of the color valences red-green and blue-yellow, respectively. For more clearness, the Cartesian coordinates (*L*, *a**, *b**) can be converted into cylinder coordinates *L*, *C*, *h*° according to the following formulas:

$$C = \sqrt{a^2 + b^2} \quad (1)$$

$$h^\circ = \arctan(b/a) \quad (2)$$

L remains unchanged, C (Chroma) represents the distance from the polar axis and represents the color intensity; h° is the hue angle in the equatorial plane.

Tooth colors can be determined visually by comparison with tooth color examples (ceramic templates) or by electronic measuring devices (spectrophotometers). The most commonly used method of tooth color determination is, however, the visual shade taking with VITA Classical shade guide and the VITA Toothguide 3D-Master System (VITA Zahnfabrik, Bad Säckingen, Germany). The majority of dentists in private offices in the United States use visual shade taking with VITA Classical shade guides (59.8%) and VITA Toothguide 3D-Master (34.4%).[8,9] Only one dentist in this research used dental images and only one dentist used electronic devices for color determination.[9] In European dental schools, however, visual color determination by VITA Classical shade guide (17%-67%) and VITA Toothguide 3D-Master (0%-47%) represent the most popular teaching method for shade selection. Dozic et al confirmed these results in their study and showed that only a minority of the students (2%-47%) were familiar with the methods of digital color determination and handling of electronic devices.[10]

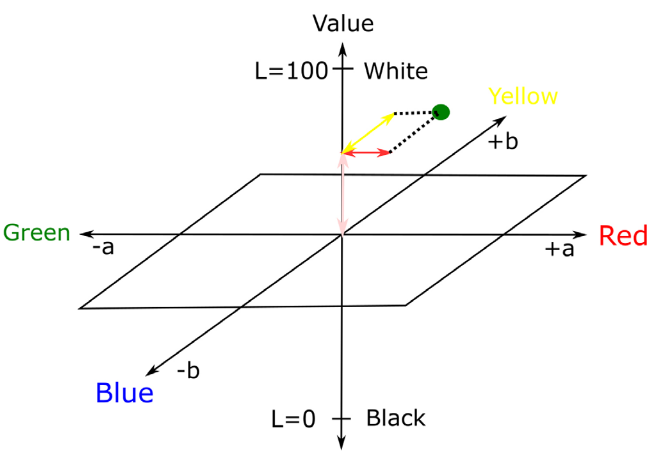

FIGURE 1 Color space in Reference 7. The color (green spot) can be defined by the Cartesian coordinates (*L*, *a**, *b**)

The space of tooth colors in the CIELab color space is located in a small area in the upper, brighter (*L*) reddish-yellow range (*a**, *b**). It can be conclude that brightness is the most important parameter for tooth color determination.

Based on the *L a*b** values of each color, color determination differences can be measured and evaluated. The *L a*b**- or CIELab color space (CIE of 1976) is most commonly used in publications and color differences (ΔE_{ab}) are calculated according to the Euclidean difference formula:

$$\Delta E_{ab} = \sqrt{(L1 - L2)^2 + (a1 - a2)^2 + (b1 - b2)^2} \quad (3)$$

$$\Delta E_{ab} = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad (4)$$

However, the CIELab color space is not ideally equidistant either. Douglas and Brewer found that a ΔE_{ab} of 2.1 was accepted for porcelain fused to metal crowns (pfm) if the crowns varied in yellow tones.[11] For a variation in shades of red, only a ΔE_{ab} of 1.1 was accepted.

There are numerous literature references that demonstrated that under certain circumstances other difference formulas can reflect the individual subjective impression of a color difference even better. Wee et al found that small color differences like in the range of tooth colors shade determination are better reproduced with the more developed CIEDE2000 and CMC (2:3) color spacing formulas.[12] For the color correction of textile fabrics and thread structures in textile industry, the CMC (2:3) formula is very common, due to the suitable correction factors.[13] Sharma et al described in detail how color differences in the *L a*b** color space can be calculated according to the CIEDE2000 color distance.[14] Lee compares in a study the color changes in composites after polymerization and after thermocycling with the conventional ΔE_{ab} formula and the CIEDE2000 color difference formula.[15] He pointed out, that there was a close correlation between the color differences and the used formula and concluded that the new formula CIEDE2000 was used for the calculation. Furthermore, he demands further investigations in color differentiation calculated with the new formula.[15]

However, for dental practitioners it is very important to know, which tooth color differences are recognizable, which are tolerable? There are different statements in the literature that make it difficult to give an unambiguous, generally valid answer. The perception of "color" varies significantly between individuals and depends on age, gender, education and profession. Lindsey et al demonstrated in their research, that the results of color difference thresholds for simulated teeth are comparable with studies using practitioners' dental materials.[16] Not any differences between thresholds for acceptability vs perceptibility were found in their studies. Their study subjects reported color differences even when none existed, and this human behavior needs to be factored into any determination of quality control standards for the fabrication of dental prostheses.[16] In a review, Wee et al cite studies which were focused on the perceptibility of a shade difference ΔE_{ab} between a tooth and an adjacent restoration.[17] They showed that shade differences (ΔE_{ab}) between ΔE_{ab} = 1[18] to 2,[19] respectively ΔE_{ab} = 2.72[20] and ΔE_{ab} = 3.8[21] in vitro and ΔE_{ab} = 3.7,[22] respectively ΔE_{ab} = 6.8[22] in vivo were found. According to Baltzer et al who showed that ΔE_{ab} values of 1 to 3 are demanded today, earlier reconstructions with ΔE_{ab} values of 3 to 6 are now considered as suboptimal.[7] The most important factor probably in this context is however, the "perceptibility threshold" and "acceptability threshold." Paravina et al investigated very early the relationship between "50:50% perceptibility thresholds" and "50:50% acceptability thresholds." They defined the terms "50:50% perceptibility threshold" or "50:50% acceptability threshold" and referred to values where 50% of the observers perceive or still accept a color difference. Paravina et al showed in a multicenter study (with seven additional research locations) a high level of statistical differences in all thresholds, the observer groups (according to their profession: dentists, dental students, dental auxiliaries, dental technicians, and lay persons) and the research centers. They found differences in shade selection of 50:50% perceptibility (ΔE_{ab} = 1.2, resp. ΔE_{00} = 0.8) and 50:50% acceptability (ΔE_{ab} = 2.7, resp. ΔE_{00} = 1.8) were significantly different.[23] These results were later implemented in ISO 28642:2016.[24]

The aim of this paper is to investigate the suitability of two different, commonly used shade guides for determining no-match templates, which do not fit to any shade tabs of both color scales. The null hypothesis was that neither of the two tooth color scales showed a significantly better result.

2 | MATERIAL AND METHODS

2.1 | Participants

Dental students (N = 76; 48 women and 28 men, mean age: 22.7 years ± 3.8 SD) in the preclinical phase at the Universities of Berlin, Dresden, Leipzig, and Greifswald (Germany) participated in this prospective multicenter study. The students were volunteer participants who were attending the preclinical course "Learning tooth color differentiation" and this was their first contact of shade matching.[25] The Ethical Board of the University of Leipzig (Ref. 454/17-ek) approved the study protocol. The students assumed pseudonyms for the purpose of data generation once they had agreed to participate in the research project. Information of color theory, color differentiation and shade taking were given in an additional lecture. All subjects underwent a color discrimination competence test (using the Ishihara test as beamer projection) as a screening for visual impairment (color control) and color competence on acceptability or perceptibility before participation according to ISO/TR 28642:2016.[24] The suitability of this method was described in the literature before by Bratner et al,[26] Awad et al,[27] Kuchenbecker et al,[28] and Samra et al.[29] No further inclusion criteria (such as subjects with average or high color competency discrimination as required by ISO 28641:2016) were applied.

2.2 | Shade guides

VITA Classical shade guide (VC) contains in total 16 shade tabs samples separated into four groups (A-D). The groups differ in color and are divided in group A: for slightly reddish-brownish, group B: contains the reddish-yellowish colors, group C: the grey colors and D: the reddish-grey colors. Within each group the tooth patterns are arranged and numbered according to increasing saturation and decreasing brightness.

The VITA Linearguide 3D-Master (V3D LG) changes the systematic order of shade selection. The V3D LG contains 6 shade tabs of the brightness group L from 0 to 5 with medium intensity and shade, is used first to preselect the brightness. Five Chroma/hue guides were then available, one each for the preselected brightness group. Within the corresponding Chroma/hue guides, the shade tabs patterns that differ in intensity C and shade h° were selected.[30-32] In total, VITA Linearguide 3D-Master contains 29 shade tabs compared to the 16 VITA Classical shade guide tabs. This selection procedure appears more intuitive and is more reminiscent of the VC's selection procedure. For this reason, the V3D LG was used in addition to the VC for the second shade selection.

2.3 | Templates

Four template sets (10 shade tabs each) were produced of colors in the used two scales: For the fabrication of the no-match shade tabs light-curing, micro particle composite (VITA VM LC) in the amount ratio 1:1 out of the indicated colors of the respective shade guide was used. For group 1 (template 1-5) VC's color (VITA VM LC VITA classical A1-D4, Dentin) was used (Table 1). For group 2: (template 6-10) the corresponding color used of the VITA System 3D-Master (VITA VM LC VITA SYSTEM 3D-MASTER, Dentin) was used and light cured polymerized (Table 1). A handgrip and a barcode tag were attached to the teeth for better handling and better identification (Figure 2).

The color coordinates according to L, C, and h° of each no-match shade tab were measured 10 times by two special trained persons using a spectrophotometer (VITA Easyshade Advance, VITA Zahnfabrik, Bad Säckingen, Germany). The tip of the measurements was placed in the middle third of the labial dental surface of the

TABLE 1 The no-match templates were made out of composite material (VITA VM LC) in the ratio 1:1 out of the indicated colors (group 1 (template 1-5): VC shade guide (VITA classical A1-D4), group 2 (template 6-10): V3D LG (VITA SYSTEM 3D-MASTER)) and polymerized

Group 1: VC		Group 2: V3D LG	
Template 1	A1/B1	Template 6	1M2/2M2
Template 2	A2/B2	Template 7	2M2/3M2
Template 3	A4/C4	Template 8	2R2.5/3L2.5
Template 4	D2/B3	Template 9	3M2/4M2
Template 5	D4/A3.5	Template 10	4M2/5M2

central incisor.[8] Thus, for each tooth pattern, 20 measurements were taken, which were averaged. A total of 800 measurements of color coordinates or 2400 measurements of individual color coordinates were performed. The measuring instrument was calibrated after every fifth measurement.

2.4 | Matching box

The matching box consisted of a ground plate (30 × 30 cm) and a wooden distance frame (observation distance 35 cm). The ground plate was colored in a neutral grey color (light grey: RGB: 197/199/196 resp. CMYB: 20/10/15/5) and the field of view (FoV) was lighted laterally non-glare in an 45° angle with a color differentiation lamp (Dialite, Eickhorst GmbH, Hamburg, Germany, color temperature of 5500 K at 1500 lx, Figure 3). The matching box was covered with a lightproof dark fabric to reduce any influencing factors (Figure 4). The used dimensions of the color matching box provides a realistic practical observation distance, whereby the sample template appears with an angle of view (α) of approx. 2° on the retina which corresponds to the 2°-normal observer. This angle α is calculated from the used height of a tooth pattern template (prox. 12 mm) using the formula:

$$\alpha = 2 * \arctan\left(\frac{12}{2 * 350}\right) \tag{5}$$

The 10°-normal observer then corresponds analogously to a field of view of approx. 6 cm in diameter. Through the opening on top of the box, the view of the FoV could be perceived; laterally the subject's hands with the templates could be inserted into the matching box.

FIGURE 2 Template with handgrip and bar-code tag

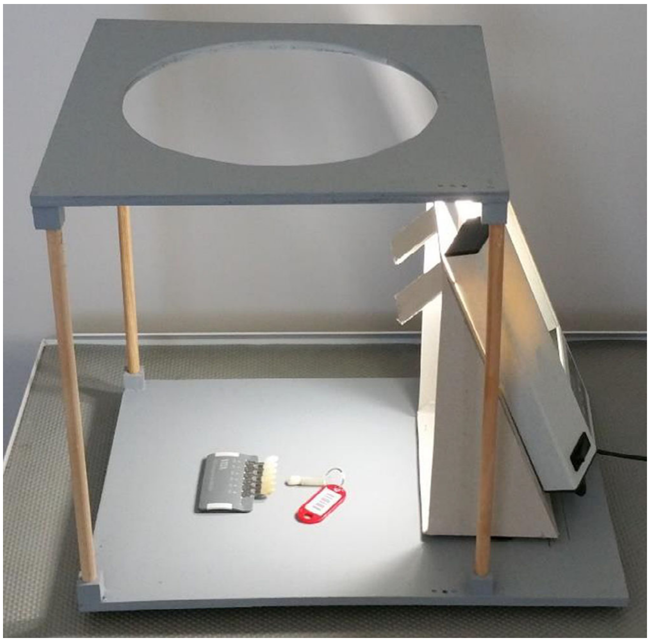

FIGURE 3 Matching box used in the experiment with an observation distance of 35 cm and illuminating and observation geometry according to Reference 23

2.5 | Color matching procedure

The subject's task was to determine 10 templates (5 each from the VITA Classical shade group and the VITA Linearguide 3D-Master group (Table 1)) in the color matching box in a random order. Before the experiment the subject's adaptation time was 1 to 2 minutes to get used to the set and to adapt the eyes to the situation. The template's barcode was scanned into the PC using a hand-held scanner and stored there in an encrypted form. The barcode tag was

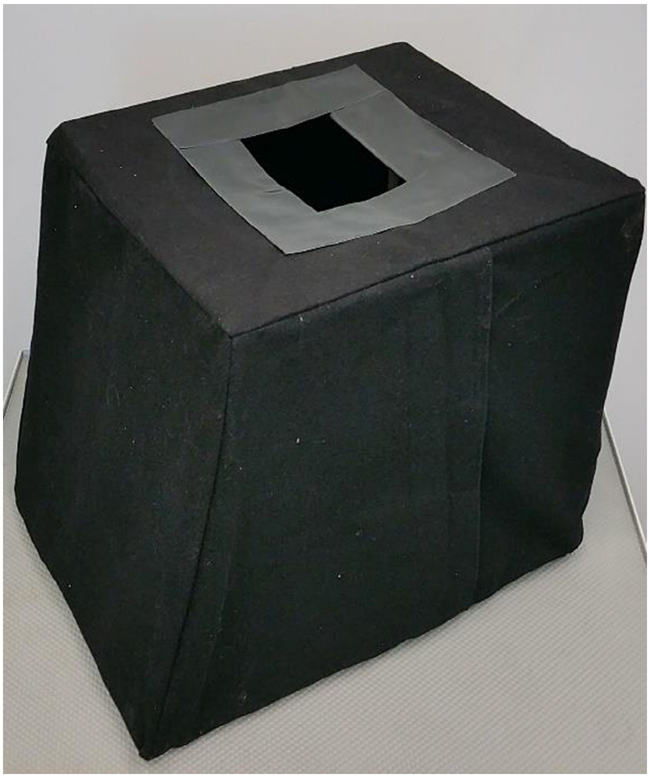

FIGURE 4 To reduce the influencing factors, the matching box was covered with a optically opaque dark fabric

covered by subject's hand to reduce the influence of the template tag's high chromatic color while color discrimination. Due to the fact, that the templates did not fit with the color scales, the test persons were asked to determine the two closest shade tabs and to inform the study manager about their results. Two shades of each shade guide (VC and V3D LG) were determined for each no-match template. The evaluation time was not limited. To meet the requirements of a double-blind study, neither the subject nor the study manager were informed of the currently used color of the template or results.

2.6 | Statistical evaluation

The *L a**b** values of the subject's decision were used to investigate the suitability of the two different color scales for the determination of a series of no-match templates in vitro.

In this study, the deviation in shade determination used by the shade information of the following three points in the *L a**b** color space: 1. actual shade of the no-match template, 2. selected color of the first closest shade tab, and 3. selected color shade of the second closest shade tab (Figure 5). From these three points, the triangle were calculated which are numbers without units of measurement on the axes in the Cartesian L a*b* color space. For this reason, the calculated areas do not have any unit of measurement either. As a parameter, the sizes of the triangular's surface was used to evaluate the observer's accuracy in color determination, which are emerge by the color coordinates of a template (T) as well as the color coordinates of the two decisions (D_1, D_2 in Figure 5). The smaller the size of the triangle's area, the better are the observer's two color decisions, that is, the more conformal and closer are the selected color to the no-matched template.

Statistical software (SPSS v19.0; IBM Corp.) was used to evaluate the differences in ΔE_{00} and the size of the triangle's area. The mean and SD and the 95% confidence interval (95% CI), median were calculated using Mann-Whitney-Test *U* test and students *t* test for each selection (α = .01).

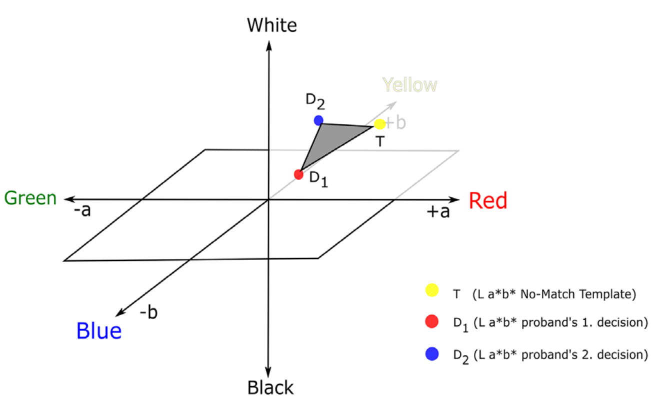

FIGURE 5 The triangle's surface is created by the *L a**b** values of the no-match template, the subject's first and second choice

3 | RESULTS

None of the participants had a color vision deficiency (Ishihara-Test). For each subject's color selection, ΔE_{00}, (ie, the distance between the template and the scales' selected color shade) was determined and statistically evaluated. The distribution of the ΔE_{00} values for the first and second subject's choice for each shade guide (VITA Linearguide 3D-Master and VITA Classical shade guide) is shown in box plots (Figure 6). No superiority of the VC in the no-match template group 1 to 5 and no advantage in the use of the V3D LG in group 1 to 6 were found in the results. The volunteers achieved a deviation in ΔE_{00} of 7.7 (V3D LG, 1st selection) to 6.7 (VC, 2nd selection) (Table 2). The median for the color selection with the V3D LG tends to be worse than for the volunteers' selection with the VC, but SD is lower proximately ± 5.7 (V3D LG) (Figure 6, Table 2). Mann-Whitney (*U* test) showed no significant differences in the median of ΔE_{00} according to the both color scales.

In a second evaluation, the areas of the triangles were used to show the measurement's deviation within the color determination, which are defined by the color coordinates of the following three points in the *L a**b** color space: (a) no-match template's shade, (b) selected shade tab color of the first choice and (c) selected shade tab color of the second selection (Table 3). The triangle's areas which were generated by tooth color differentiation with the V3D LG are smaller (median 14.2) than the triangles formed with the VC (median 19.2). The mean and SD is comparable and reached a value of 21.2 ± 19.5 (V3D LG) and 25.7 ± 20.6 (VC) (Figure 7, Table 3). The difference in the median values between both groups using Mann-Whitney *U* test is greater than would be expected; there is a statistically significant difference ($P < .001$).

4 | DISCUSSION

The results of this study supported the assumption of the null hypothesis that neither of the used shade guides (V3D LG vs VC) showed better results in the color definition of no-match templates.

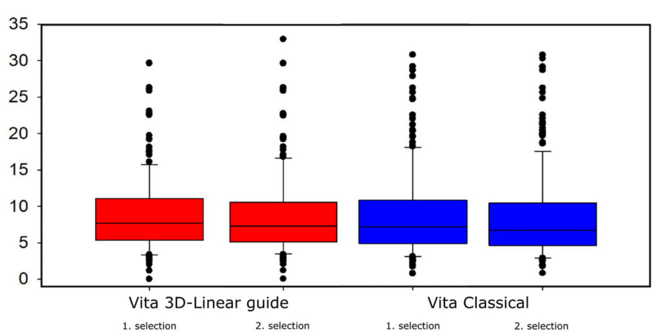

FIGURE 6 Distribution of ΔE_{00} values for both subjects' selection. No significant differences were found between the volunteers' first and second selection

TABLE 2 Results of the shade selection of V3D LG and VC in ΔE_{00} values of the subject's first and second color selection (Figure 6)

	VITA 3D LG 1. selection	VITA 3D LG 2. selection	VC 1. selection	VC 2. selection
Mean ± SD	9.10 ± 5.72	8.90 ± 5.77	9.17 ± 6.26	8.58 ± 6.04
Confidence interval (95% CI)	8.68-9.52	8.48-9.32	8.72-9.62	8.14-9.02
Median	7.67	7.31	7.19	6.66
SE	0.21	0.21	0.45	0.22

TABLE 3 Results of the area size in comparison of shade selection using two different color scales (VC vs V3D LG, Figure 7). The results show significant differences ($P < .001$)

	Area V3D LG	Area VC
Mean ± SD	21.17 ± 19.50	25.66 ± 20.61
Confidence interval (95% CI)	19.75-22.59	24.16-27.16
Median	14.17	19.25
SE	0.72	0.76

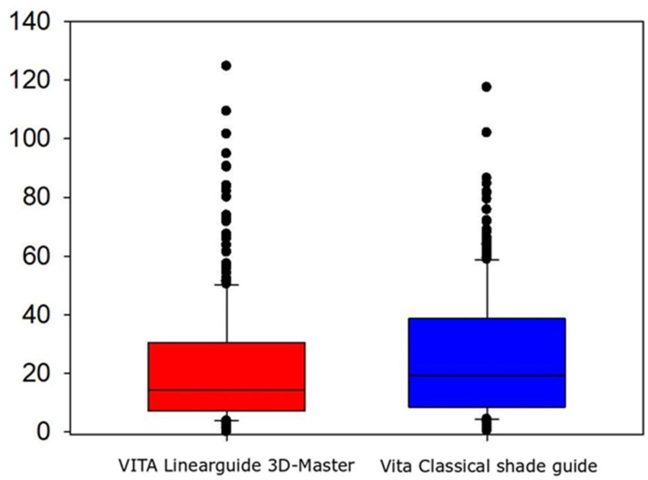

FIGURE 7 Area comparison for the shade selection with VITA Linearguide 3D-Master and VITA Classical shade guide: The smaller the triangle's areas, the better the color match ($P < .001$)

The determination of the tooth color is an important treatment step in the daily dentist's routine, which is not always easy to achieve. Various earlier pretreatments, such as single-, multi-surface fillings or ceramic veneered restorations in the vicinity of the tooth that need to get treated, complicates the color differentiation of the tooth to be supplied. The challenge is to determine the most suitable and closest color shade of the natural tooth with its existing individual deviations and the new restoration in order to avoid new fabrications due to an incorrect shade.[33] Many articles in the literature have already shown that professionals (dentists, dental technicians, dental assistances) can determine color shades even better than patients; color deviation of $\Delta E < 2$ were visually perceive and recognize here.[11,23] Dependencies in regards to the shade guide used and color deviations in shade determination can also be seen here in this context. In this study, the shade was determined using two different color shade guides, the deviation of the results in color differentiation performed with the VITA Linearguide 3D-Master tends to lead to slightly better but comparable results with lower standard deviations in this study (Table 1), the differences, however, were not significant. In this context it has to be discussed, that the reason for this result on the one hand could be the better shade tabs' coverage of the color space due to the higher number shade tabs (N = 29) by VITA Linearguide 3D-Master. On the other hand, the smaller number of only 16 shade tabs and random distribution of the colors in the VITA Classical shade guide makes the differentiation decision for each participant much more intuitive and difficult. Which one of these effects predominates in the concrete case depends not only on the subject's ability of shade differentiation but also on the position of the shades of the handmade no-matched-templates in the color space. Paravina already recognized in 2009 that the color differentiation of the 29 shade tabs of the VITA 3D-Master system provided significantly better results than with the VITA Classical shade guide with only 16 shade tabs.[31] For a better method comparison he propagated the linear application of shade tabs and showed that the better selection method is used intuitively by dental technicians and dentists. Although VC color matching leads to worse results, a combination of the linear arrangement of 29 shade tabs could lead to better accuracy.

The CIEDE2000 represents the current and best possible approximation of visual sensation for small color differences. In contrast, the CIEDE2000 formula retains, however, the CIELab color space, so only the calculation of the color distance's way is different.[25] An evaluation of the color deviations ΔE showed no significant differences between the two shade guides V3D LG and VC. This applies both to the Euclidean color deviation in the CIELab color space and to the determination of the color deviation according to the current CIEDE2000 formula, which better reflects the subjective differences in the perception of small color differences.

To calculate the color distance of the selected no-match templates, a new evaluation method was used: The surface of the triangles in the color space were used, which were calculated from the color coordinates of the no-match template and respective of the two closest color shades. The color distance ΔE_{00} was calculated from the coordinates $L_1a_1b_1$ and $L_2a_2b_2$ of two color formulas in the $L\ a^*b^*$ color space. It is impossible, for a general case, to convert color distance ΔE_{00} to color distance ΔE_{ab} to the CIELab according to the CIEDE2000 and reverse. Sharma et al provide an online software for the calculation of color distances according to the CIEDE2000 formula from $L\ a^*b^*$ values,[14] so that the values of the color distances were also calculated and displayed as ΔE_{00}. In order to calculate the color based on the $L\ a^*b^*$ color space to different other color systems, Lindbloom published the color difference calculator in 2017, where it enables the conversion to different color systems such as CIE 1976, CIE 1994, and CIE 2000.[34]

To the best of our knowledge, this paper is the first that evaluates the triangle's surface calculated by using the $L\ a^*b^*$ values of a handmade no-match template, the $L\ a^*b^*$ values of the first subject's decision and the $L\ a^*b^*$ values of second participant's decision with two shade guides. With the new, here used evaluation method was proved a significant superiority of the VITA Linearguide 3D-Master ($P \le .001$), so that the null hypothesis must be rejected.

As a limitation of the surfaces determination of the triangles it should be noted that in certain hypothetical cases the surfaces of two triangles could be mathematically identical. In this case it should be noted that the distances T-D_1 and T-D_2 cannot be arbitrarily large, however, otherwise the match of the no-match template's color from the subject's decision (ΔE VC or ΔE V3D LG) would be classified as "poor" to "clinically unacceptable" (Figure 5). The same limitation applies to the distance D_1-D_2, which cannot be arbitrarily small, since this vector (line) is formed by two points (or two subject decisions D_1 and D_2) in the Cartesian coordinate system (Figure 5). This vector cannot be smaller than the smallest distance between two shade tabs and corresponds within the range of standard deviations for visual tooth color determination.

In this context it has to be discussed, that the reason for the smaller triangle's surface of VITA Linearguide 3D-Master are based on the better tooth shade selection, that is, the closer selected tooth shades to the no-match template are, the smaller are the color deviations of the selected tooth shade. Another reason could be the fact, that compared to VITA Classical shade guide the color shades of the VITA Linearguide 3D-Master have a better distribution within the color space. Due to both color decisions of the subjects are used for creating the triangular surface area, randomly influences are better averaged than with the first evaluation of ΔE_{00} and wrong subject's color decisions in this case are more minimized.

The evaluation used in this study is based on the triangle's surfaces that are spanned in the color space by the color coordinates of the no-match templates and the two shades selected. The evaluation method used in this study was focused on the size of a triangle whose vertices are formed by the $L\ a^*b^*$ value of the template and the $L\ a^*b^*$ shade tab values of the first and second subject's choices. If the two $L\ a^*b^*$ values were far apart, the result was a large triangle's surface, if both definitions are close together, a small triangle was formed within the CIELab color space. This shows on the one hand the sufficiency of the subject's shade selection and the respective used shade guides. A comparable result is displayed too, that the used shade guide is capable of reproducible and adequately displaying the no-matching template color. In the context of this investigation, an advantage of the V3D LG was found ($P \le .001$), both in the deviations and in the coverage of the triangles. Within the limits of this study, we can state that the deviations in shade differentiation of no-match templates with the VITA Linearguide 3D-Master were smaller, compared to color differences when the Vita Classical shade guide was used. The reason for this is the closer and more even better coverage of the tooth color space by the V3D LG. Due to two shade tabs are used simultaneously in this study to determine the triangular surfaces, random influences are likely to be better determined than in the first evaluation. The superiority of the V3D LG especially in the surface of medium-bright tooth shades, that is, the most common shade by far and this represents a significantly better reproducibility of tooth shades for the dentist, the dental technician and thus an added value for the patient.

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