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CLINICAL RESEARCH

Accuracy of tooth color determination by dental students using daylight-calibrated dental operatory lighting sources

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ABSTRACT

Statement of problem. Lighting conditions are an essential factor for accurately determining tooth color. However, the ideal lighting conditions for determining tooth shade are rarely met and are difficult to quantify. While the use of a standardized daylight lamp D55 can improve accuracy, its high cost limits its use in dental offices. The use of modern operatory treatment units for tooth color determination is promising, as they now allow for the adjustment of light source settings such as color temperature and intensity. However, studies are needed to determine whether they provide accurate color determination.

Purpose. The purpose of this study was to assess the accuracy of visual tooth shade determinations under the adjusted light sources of 2 different dental treatment units in comparison with a standardized daylight lamp D55.

Material and methods. Dental treatment units from 2 manufacturers KaVoLUX 540 LED (LK) and LEDview Plus (LDS) were tested. The light sources of these units were adjusted to match daylight conditions. A daylight lamp (Dialite Color 7; Eickhorst Co. KG) was used as a control (D55). A total of 49 participants (median age of 25 years, 30 women) underwent the Ishihara screening and received standardized training calibration. A total of 2205 clinical visual tooth shade determinations were performed with the Toothguide Training Box using the Vita 3D-Master shade guide under the 3 different lighting types. Each participant had 15 color determinations made under each of the 3 light settings. Color differences were analyzed by using the Kruskal-Wallis, Wilcoxon rank-sum, and chi-squared tests (α=.05).

Results. The type of lighting used for tooth shade determination had no significant effect on the accuracy of selected shade based on the ΔE_{00} metric (*P*=.133). Perfect matches were achieved in 50.8% of the cases under LK, 49.8% under LDS, and 53.6% under D55 light, with no significant difference among percentages (*P*=.315). Although there was a significant difference in time elapsed for shade determination by light type (*P*=.004), this difference was not clinically relevant (20.8 seconds for LK, 23.9 seconds for LDS, 21.9 seconds for D55).

Conclusions. The accuracy of color determination for both examined dental operatory lamps was found to be comparable with that of the standard D55 daylight lamp when adjusted to specific settings. (J Prosthet Dent 2025;133:238-245)

Achieving excellent esthetics and color matching in prosthodontics remains a significant challenge despite the introduction of different shade determination instruments and methods.[1,2] The tooth color matching process, from color determination in patients to dental laboratory communication and prosthodontic implementation, is sensitive and prone to errors.[3] Visual tooth color matching using a shade guide is the most commonly used method of differentiating color in dentistry.[4] The accuracy of the visual method is influenced by factors that include the shade guide properties, sex of the observer, experience and training in color matching, and quality of the light source.[5–9] For less experienced observers, elements like the shade guide used and lighting conditions become even more influential.[10–12] One

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Clinical Implications

The use of the daylight-calibrated light source of operatory dental units is a promising method for improving tooth color determination that is both convenient and cost-effective. Their use would enhance the accuracy and reliability of tooth color determination, leading to improved clinical outcomes and increased patient satisfaction.

common cause for errors in shade matching is the lack of balance of the spectral composition of light when it deviates from daylight, which can result in different perceptions of color under various lighting conditions, known as metameric effects.[12–14] The ideal lighting conditions for tooth shade determination has been described as a slightly cloudy morning sky at a north-facing window in the northern hemisphere. However, natural lighting can exhibit significant variability, making standardization impractical.[15,16] The use of a daylight lamp (D55) can eliminate weather influences and significantly improve the accuracy of shade selection.[10,11,17] However, its high cost restricts widespread use in dental practices. A study surveying 32 dental practices found that practitioners mainly used visual shade matching under inadequate ambient light.[18] This lack of optimal lighting leads to inconsistent color determinations, potential restoration failure, and significant costs for the dental practice and laboratory.[19]

A potential solution to this problem is to integrate the ideal light conditions for shade determination directly into the dental operatory unit. Modern operatory treatment units offer the possibility of adjusting light source settings such as color temperature and light intensity. Recent developments allow adjustments in light intensity from 5000 to 40 000 lx at 700 mm and in color temperature from 4000 K to 6200 K; these settings suggest their use in color determination. Conventional operatory lights are not ideal for tooth color determination because of their specific color temperature and high light intensity, which are tailored to the clinical requirements of dental treatment. These lights often have a high blue component to enhance tissue differentiation during surgical procedures, which results in teeth appearing bluish, affecting color matching.[20] While color differentiation is challenging at high intensity, studies indicate that illuminance within 807 to 3229 lx does not impact color matching.[21] Further studies have reported that polarization has no effect on color results[22] and that using mobile LED lighting does not enhance shade matching compared with standard illumination.[23]

Luminance intensity can be influenced by factors that include distance to light source, type of lighting, and surface characteristics onto which the light falls. Illuminance is the amount of light energy falling onto a specific surface and is a function of light intensity, which describes the amount of light emitted per second and per solid angle in a particular direction.[24] Understanding the relationship of light intensity, illuminance, and color temperature is essential in determining the suitability of surgical lights for tooth color determination and adjusting lighting settings to improve the accuracy of color determination. Light types with different color temperatures (D65, ambient light A, and fluorescent light F2) have been reported to affect the hue and chroma of restorations and shade guides,[25,26] emphasizing the importance of the balance of the spectral composition of light for accurate color determination.[21–26] While factors affecting shade selection have been explored, the accuracy of tooth color determination under the adjusted light of modern dental units is unclear.

The objective of this study was to analyze the accuracy of tooth color determination by using daylight-calibrated dental operatory lighting sources in clinical practice with reference to a standard D55 lamp. The null hypotheses were that the accuracy of tooth shade selection would not be influenced by light type, that sex would not affect the shade determination, and that the time elapsed for shade matching would not be influenced by light type.

MATERIAL AND METHODS

Forty-nine dental students participated in this study assessing the effect of different lighting conditions on tooth shade matching. As the experience of the observer plays a significant role in determining the accuracy of the visual method, enhancing shade matching skills through education has been recommended.[7,27,28] All participants were calibrated by theoretical and practical instruction to have similar knowledge and skills in color determination. In the experimental setting of a training tool (Toothguide Training Box; Vita Zahnfabrik) (TTB), each participant matched 15 tooth shades randomly selected by the TTB integrated software program out of the 26 3D-Master shades under 3 different lighting conditions (45 matches per student). Color differences were analyzed by using the ΔE_{00} formula. The study evaluated 3 dental operatory light sources: LK (KaVoLUX 540 LED; Kavo Dental GmbH), LDS (LEDview Plus; Dentsply Sirona), and D55 (Dialite Color 7; Eickhorst Co KG). The operatory light sources were adjusted to reproduce daylight in terms of light intensity and color temperature.

Fifty-four senior dental students aged 23 to 33 years with a median age of 25 years were initially recruited for this study. After the Ishihara test,[29] 1 student was excluded for color vision deficiency, and 4 declined to participate because of time constraints. Of the remaining

49 participants, 30 identified as women and 19 as men according to the sex and gender equity in research (SAGER) guidelines. Knowledge calibration consisted of a 45-minute theoretical lecture and practical exercises using the TTB, a standardized training tool that guides users through systematic tooth color determination by using the Vita 3D-Master shade guide.[30] The 3D-Master guide covers the entire 3-dimensional tooth color space and has been considered an ideal scientific instrument in color research.[31,32] The TTB used 3D-Master ceramic specimens which had received standardized quality control procedures carried out by the manufacturer.

The TTB process for shade determination involved 3 steps: choosing brightness groups, determining color intensity, and selecting the hue (L, M, or R). The TTB software program offered a practice and a test mode of use. Before the test mode was activated, participants used the TTB's practice mode until the TTB proficiency level was achieved.

The present study used a daylight D55 lamp set to 8200 lx illuminance at the viewing point, 5500 K color temperature, 15 cm to viewing surface, and a 45-degree angle of incidence of the light as the reference light source. Dental operatory lights LK and LDS (Fig. 1) were adjusted to match the standard D55 light setting. Although manufacturers of the dental lighting sources state their products are suitable for tooth shade determination, they do not specify the required settings. All light parameters were verified by using a Luxmeter (MAVOLUX 5031C BASE; GOSSEN Foto- und Lichtmesstechnik GmbH), ensuring ±3% precision.

The Commission Internationale d'Eclairage (CIE) specifies daylight as having a color temperature between 5500 and 6500 K.[33] While the color temperature of the LK unit adjusts in 5 steps of 500 K from 4000 K to 6000 K, the LDS unit has only 3 levels, 4600 K, 5400 K, and 6200 K. In this study, the LDS was set at 5400 K and the LK at 5500 K. Both were placed at a 45-degree angle of incidence relative to the TTB viewing window, with a 30-cm viewing distance. To achieve 8200 lx illuminance at the viewing point, the distance of the LDS unit was set at 90 cm, and the LK was positioned 110 cm away, using their respective initial intensities at 700 mm of 10 000 lx for LDS and 20 000 lx for LK (Table 1).

Figure 1. Dental operatory lighting sources used, Left: Dentsply Sirona LEDview Plus. Right: KaVoLUX 540 LED.

After calibration, participants were randomized into 6 groups and completed the TTB test mode under the 3 different lighting conditions. The 49 participants each assessed 15 specimens randomly selected by the integrated TTB software program for every light type (2205 total shade matches), and their results were compared with the reference values. To ensure a high reliability of the recorded data, 3 LDS and 3 LK dental treatment units were equipped with TTBs (Fig. 2A), and 3 TTBs were fitted with D55 daylight lamps (Fig. 2B). All settings replicated clinical tooth shade determinations under optimal daylight conditions in the dental office.

The color shades determined by each participant were converted into the CIE L*a*b* coordinates using the CIELab values of the 26 Vita 3D-Master tooth shades supplied by the manufacturer, Vita Zahnfabrik. The CIELab standard describes color across 3 coordinates in a color space L*, a*, and b*.[34] To evaluate color differences between the participants' color selection and the reference color, the CIEDE2000 (ΔE_{00}) formula was used, as it ensures high uniformity of color differences and good agreement with visual tooth color assessment.[35,36] The 50:50% acceptability threshold is set at 1.8 ΔE_{00} units at which 50% of observers will reject the restoration because of unacceptable color differences.[37] The 3D-Master shade guide is structured in 5 brightness groups, where groups 1 and 5 consist of only 2 and 3 shade tabs, respectively, while groups 2, 3, and 4 each have 7 shade tabs. This could lead to increased mismatch rates for groups 2 to 4. To evaluate the accuracy of color matches, the analysis first considered all 5 groups, and then specifically focused on groups 2 through 4.

Statistical analysis was performed using a software program (*R*, v4.3.0; *R* Foundation for Statistical Computing). The Shapiro-Wilk test for normality and nonparametric tests Kruskal-Wallis, Wilcoxon rank-sum, and chi-squared were used. To assess whether light type influenced the accuracy of shade matching, the Kruskal-Wallis test was used to analyze the quantitative data for the 3 light groups (LK, LDS, and D55), and the chi-squared test was used to compare the rates at which perfect matches were attained. The Wilcoxon rank-sum test was used to assess the effect of sex on shade matching. Time elapsed for shade matching by light type was analyzed by using the Kruskal-Wallis test (α=.05 for all tests).

RESULTS

The Shapiro-Wilk test revealed nonnormal ΔE_{00} distributions across all light groups (P<.001 for each of the LK, LDS, and D55 groups). Shade determination results

Table 1. Experimental settings for lighting sources

Light Type	Intensity at 700 mm	Color Temperature	Angle of Incidence	Distance to Source
LK – KaVo	20 000 lx	5500 K	45 degrees	110 cm
LDS – Dentsply Sirona	10 000 lx	5400 K	45 degrees	90 cm

for the 3 light types (LK, LDS, and D55) did not indicate a significant effect of light type on tooth shade determination with *P* values ranging from .094 to .315 (Table 2). The Kruskal-Wallis test showed the differences in mean ΔE_{00} values by light type were not statistically significant (*P*=.133), with values at 1.33 for LK, 1.35 for LDS, and 1.20 for D55 (Fig. 3). To further investigate whether the magnitude of actual errors depends on the type of light, the observations with perfect matches were removed, and the means of the positive ΔE_{00} values were recalculated as 2.69 for LK, 2.68 for LDS, and 2.59 for D55. These differences were not statistically significantly different (*P*=.239). The absolute value differences in the L*, a*, and b* components by light type were also not significantly different (for L*: *P*=.150, for a*: *P*=.155, for b*: *P*=.200; *P*>.05). Figures 4 and 5 show how the mean ΔE_{00} scores and the differences in magnitude for L*, a*, and b* components varied across the 26 shades in the Vita 3D-Master shade guide for each light type.

Table 2 shows the exact match percentages by light type: 50.8% for LK, 49.8% for LDS, and 53.6% for D55. The chi-square test indicated the differences in exact matches by light type were not significantly different (*P*=.315). To assess the frequency of errors with large magnitudes, the percentage of color determinations exceeding the acceptability threshold of 1.8 ΔE_{00} units was calculated at 33.9% for LK, 34.6% for LDS, and 29.7% for D55. These variations were not significantly different (*P*=.094). Table 3 and Figure 6 display the percentage of perfect matches across the 5 Vita 3D-Master brightness shade groups. A Kruskal-Wallis test showed that differences in the mean ΔE_{00} for the more challenging groups 2 to 4 were also not significantly different (*P*=.099).

Overall, sex did not have a significant effect on shade determination (Table 4), with an average ΔE_{00} score of 1.39 for men and 1.23 for women. The difference was not statistically significant based on a Wilcoxon rank-sum test (*P*=.367). When analyzed by light type, a significant difference was found between the mean ΔE_{00} scores by sex for the LK light type (*P*=.003) but not for LDS and D55 (*P*=.959 for LDS and *P*=.231 for D55). The mean ΔE_{00} values are provided in Table 5.

A significant difference was found in the time elapsed for shade determination by light type (*P*=.004); however, the difference was clinically irrelevant as the mean time for matching was 20.82 seconds for LK, 23.90 seconds for LDS, and 21.97 seconds for D55.

DISCUSSION

The null hypothesis that light type would not affect the accuracy of selected shade was not rejected. A comparison of ΔE_{00} color differences and the percentage of perfect matches for shade determination under the adjusted operatory lighting LK and LDS and the D55 daylight lamp did not find a significant effect of light type on tooth shade selection. The null hypothesis that shade determination performance would be independent of sex was also not rejected, but the null hypothesis that the amount of time elapsed for shade

Figure 2. Experimental design. A, KaVoLUX 540 LED (LK) light source with adjusted light on Toothguide Training Box (TTB). B, D55 daylight lamp on Toothguide Training Box with associated laptop for data collection.

Table 2. Summary of shade determination results by light type

Light Type	Overall Mean ΔE_{00}	Mean ΔE_{00} for Mismatches	Number of Exact Matches	Percentage Exact Matches	Number Above Acceptability Threshold	Percentage Above Acceptability Threshold
LK	1.33	2.69	373	50.8%	249	33.9%
LDS	1.35	2.68	366	49.8%	254	34.6%
D55	1.20	2.59	394	53.6%	218	29.7%
P	.133	.239	—	.315	—	.094

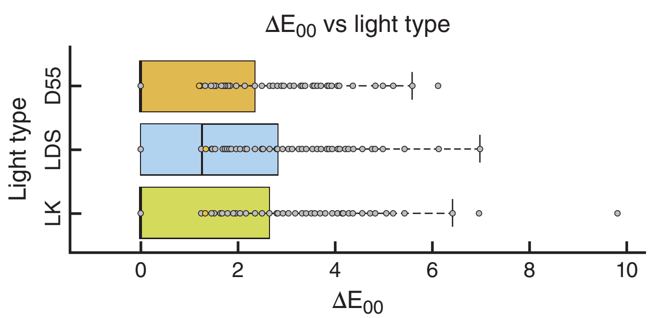

Figure 3. Mean ΔE_{00} color differences by light type (n=2205).

determination would be the same for each light type was rejected.

The type of lighting (D65, A, and F2 with varying color temperatures) has been reported to influence the a* and b* color components; the illuminant influences shade guide color distribution, especially the hue angle.[25,26] However, under daylight-calibrated settings, the present study found no significant differences in these color parameters (P>.05). While ΔE_{00} color differences and the percentage of perfect matches were comparable across the 3 light types, the percentage was relatively low, ranging from 50% to 54%. These low percentages were, however, consistent with another study that reported perfect matches at 54% levels.[32] However, in 30% of cases for D55, 34% for LK, and 35% for LDS, the incorrect matches were above the acceptability threshold and could result in the patient's rejection of the restoration.

The null hypothesis that sex does not affect shade determination was not rejected when comparing ΔE_{00} scores and the percentage of perfect matches across all observations. This finding was consistent with that of Hynková et al,[8] although Haddad et al[9] identified significant differences in color determination. However, when controlling for light type, the difference in shade selection by sex was significant for only 1 light type (LK).

The use of adjusted light settings in dental units may significantly improve shade matching methods. While manufacturers indicate that these dental operatory lights can be used for color determination, the precise settings for such shade matching have not been specified. Identifying optimal light settings with a luxmeter, as done in this study, proved laborious and would be time-consuming for dental practitioners. Therefore, advances are needed that allow for straightforward and precise adjustment of the light source for color determination.

The present study was conducted in a standardized setting with a large number of participants (49) and observations (2205). The study used all 26 3D-Master ceramic shade tabs covering the 3-dimensional dental color space with precisely defined metric color components (L*a*b*).[31] As experience and training affect the

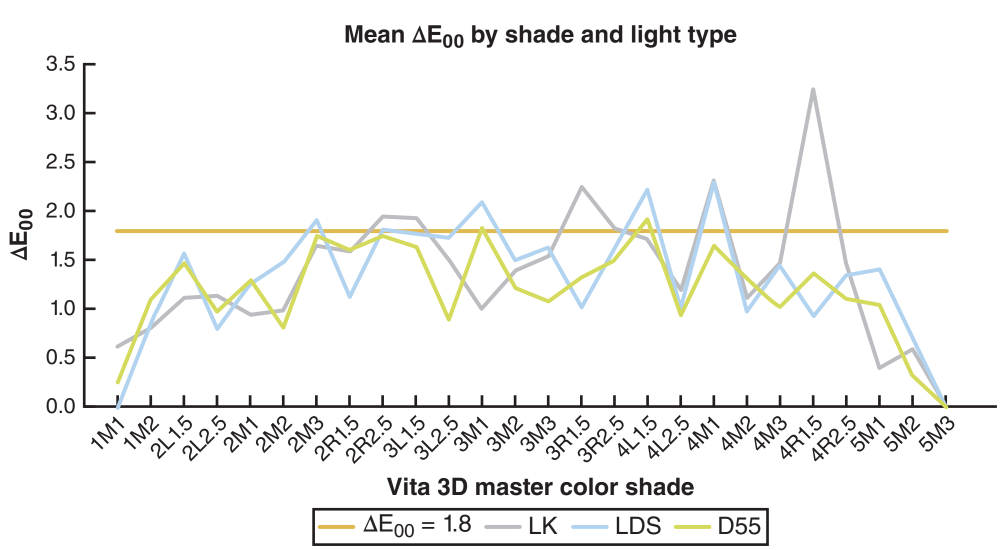

Figure 4. Mean ΔE_{00} by Vita 3D-Master tooth shade and light type.

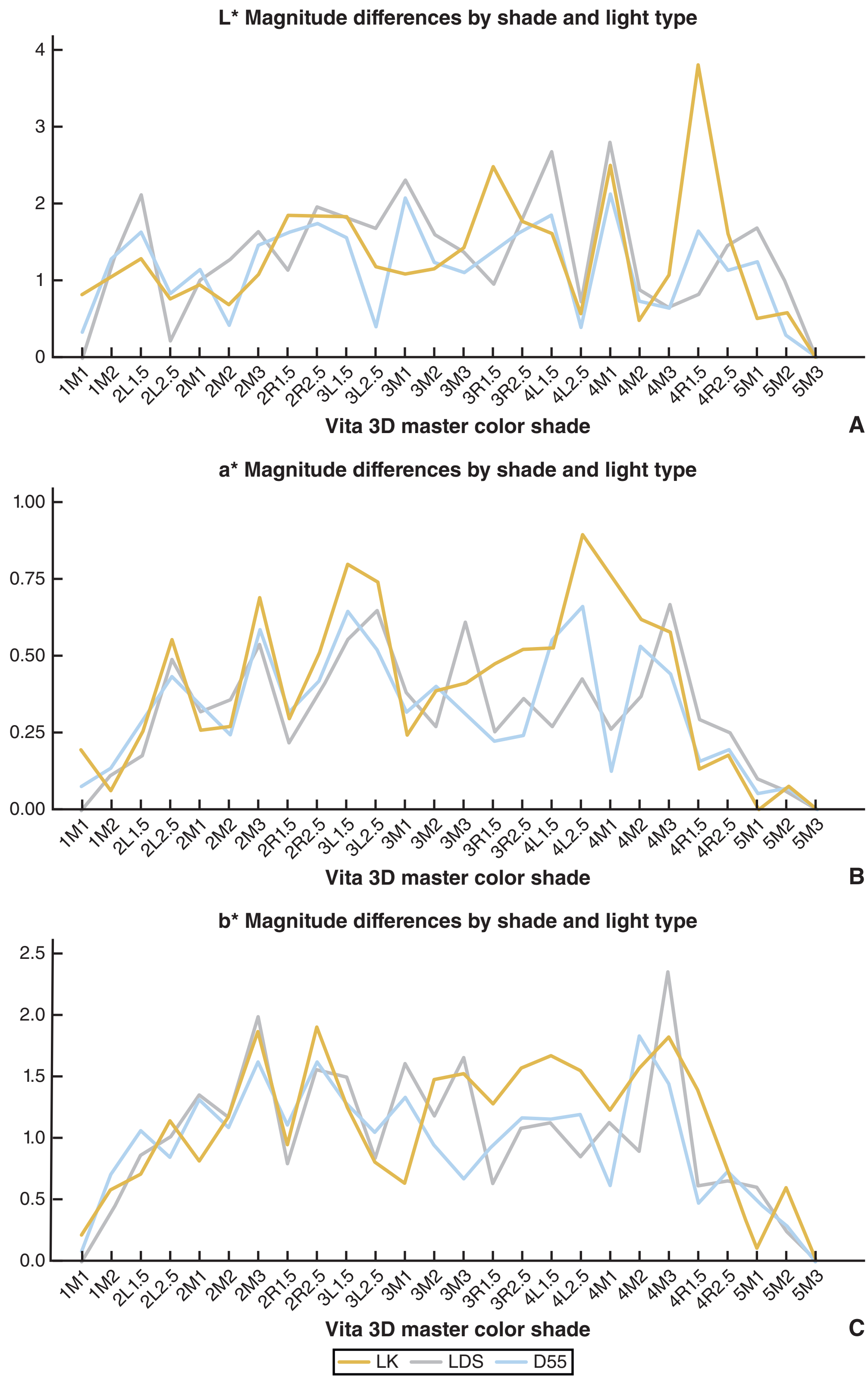

Figure 5. Differences in magnitude for L*, a*, b* components by Vita 3D-Master tooth shade and color type. A, L*. B, a*. C, b*.

Table 3. Percentage of perfect matches by Vita 3D-Master shade group

Light Type	Group 1	Group 2	Group 3	Group 4	Group 5
LK	72.7%	46.3%	42.3%	40.3%	89.4%
LDS	86.3%	42.5%	41.3%	44.0%	78.8%
D55	78.7%	43.3%	50.0%	48.3%	87.0%

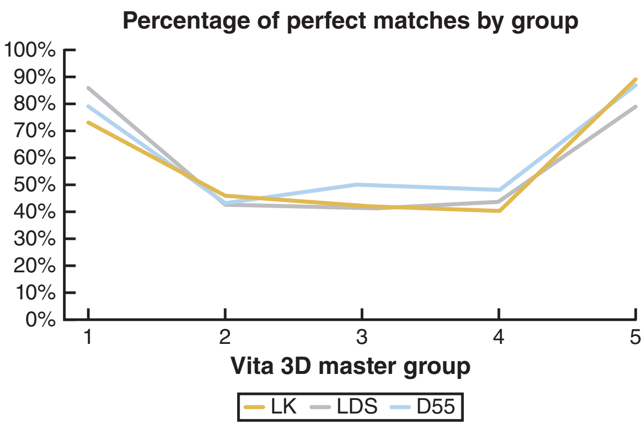

Figure 6. Percentage of perfect matches by Vita 3D-Master shade

Table 4. Overall mean ΔE_{00} scores by sex

Sex	Mean ΔE_{00}	Average Number of Perfect Matches
Men	1.39	21.68
Women	1.23	24.03
P	.367	.262

Table 5. Mean ΔE_{00} scores by sex and light type

Light Type	Men	Women	*P*
LK	1.52	1.21	.003
LDS	1.36	1.34	.959
D55	1.28	1.15	.231

accuracy of color determination,[7,12] the present study used dental students without previous shade matching experience, standardizing their knowledge and training to reduce cofounding variables. Reports on the effects of observer experience are controversial given different samples and test conditions.[12] However, for less experienced observers, shade guide and lighting conditions have been reported to be more influential.[10,11] Thus, it is highly advisable to enhance shade matching skills through education and training.[27] Additionally, the use of controlled lighting is recommended, particularly for less experienced dentists.[27,28]

Limitations of the study include the aging of light sources over time and variations in the quality and electronic controls across manufacturers. As operating time increases, illumination brightness decreases due to tube aging; however, these differences have been reported to be unnoticeable in daily practice.[23] A further limitation was the use of dental operatory units from only 2 manufacturers. Since models across manufacturers differ in the range and number of steps for adjusting light intensity and color temperature, the differences among various types of operatory units should be considered when interpreting the results of this study. Another limitation was due to the TTB shade selection algorithm. While the study included all 26 tabs of the 3D-Master shade guide, the TTB's random shade selection resulted in a nonuniform frequency distribution of the different shades in the experiment. Moreover, during the selection process, the TTB machine did not allow for revisions once the brightness component had been selected, possibly leading to an increase in the number of mismatches. However, since this procedure was the same throughout the experiment, it did not affect the comparison between accuracy of color matching by light type.

The conventional lighting of dental operatory units is well suited for clinical dental treatments because it provides high contrast and edge sharpness. Although the intensity of this operatory light is too strong for color determination, the results of the present study indicate that when using adjusted lighting, the accuracy of color determination was comparable with that under the recommended daylight lamp standard. Therefore, these contemporary adjustable light types can be used for both clinical treatments and color determination by adjusting the light settings.

While the use of the TTB for color determination ensured consistency throughout the experiment, the color samples used were standardized ceramic 3D-Master shade tabs, eliminating the color variations present in natural teeth. Other factors that may influence the accuracy of shade matching include intraoral conditions such as the hydration level of teeth, aging, and variations in the tooth surface and positioning. Further clinical studies are needed to address these limitations by assessing the influence of light types from adjusted dental operatory units on the accuracy of natural tooth color determination in intraoral conditions.

CONCLUSIONS

Based on the findings of this clinical study, the following conclusions were drawn:

1. The accuracy of tooth color determination of the examined dental operatory lamps, when adjusted

to specific settings, was comparable with that of the standard D55 daylight lamp when matching 3D-Master ceramic tab samples. The light type (LK, LDS, D55) had no significant effect on color differences (ΔE_{00}) and perfect matches.

2. Sex did not influence the accuracy of tooth shade selection under the studied light types.
3. The time difference for shade determination by light type was statistically significantly different but not clinically relevant (3 seconds).

DECLARATION OF GENERATIVE ARTIFICIAL INTELLIGENCE (AI) AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the authors used ChatGPT-4 to improve readability and language as the authors are nonnative speakers of English. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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