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Original article

Influence of Lighting Variability on the Accuracy and Consistency of Visual Shade Matching: An In Vitro Study

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Abstract
Accurate tooth shade selection is essential for achieving optimal esthetic outcomes in restorations, yet visual shade matching is subjective and may be influenced by lighting conditions. This in vitro study evaluated the effect of different lighting conditions on the accuracy and consistency of visual shade selection. Visual shade matching of 16 blinded tooth samples was performed using the VITA Classical Shade Guide under warm (3000 K), neutral (4000 K), and daylight (5500 K) illumination. A repeated-measures design was used, in which the same examiner conducted shade selection twice at a 1-week interval to assess intra-examiner repeatability. Color differences (ΔE) were calculated using the CIELAB color system, and data were analyzed using two-way repeated-measures analysis of variance (ANOVA), Holm-adjusted pairwise comparisons, and Cohen's kappa. The results demonstrated that lighting condition significantly affected ΔE values ($p = 0.012$), with the lowest mean ΔE under daylight illumination (0.663), indicating improved shade-matching accuracy. A significant difference was observed between warm and daylight illumination (mean difference = 1.496 ΔE, adjusted $p = 0.009$), whereas the other pairwise comparisons were not significant. Neither measurement session ($p = 0.707$) nor the lighting-session interaction ($p = 0.913$) was significant. Intra-examiner repeatability was highest under daylight ($\kappa = 0.865$), followed by neutral ($\kappa = 0.661$) and warm illumination ($\kappa = 0.525$). Within the limitations of this study, daylight illumination was associated with lower color differences and greater repeatability than warm illumination. Standardized, color-corrected, daylight-like illumination is recommended for visual shade selection to minimize lighting-related variability and improve clinical consistency.
Keywords. *Color Perception, Lighting, Dental Esthetics, Color Matching, Reproducibility of Results.*

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Introduction

Dental restoration is a fundamental aspect of modern dentistry that focuses on restoring damaged or missing teeth to restore their function, integrity, and natural appearance. Common procedures, such as fillings, crowns, bridges, and dentures, aim not only to improve oral health but also to enhance aesthetics, thereby improving patient confidence as well as masticatory and speech functions [1]. This means dental technicians must do more than shape a piece of material to fit in the mouth; they must also capture the subtle and unique color of a patient's natural teeth.

Shade matching is a critical step in restorative and prosthetic dentistry [1,2]. A mismatch between the restoration and adjacent teeth is easily perceptible and may compromise the overall aesthetic outcome, regardless of the technical quality of the restoration [2]. For many years, the standard method for choosing a tooth's color has been visual assessment. While this method is simple and cost-effective, it is also highly subjective. The human eye, though remarkable, can be an inconsistent measuring tool. A person's perception of color can be influenced by many factors, including age, experience, and visual fatigue [1,2].

Consequently, reliance on visual assessment alone may result in variability and inconsistency, where two different people might choose different shades for the same tooth, or the same person might make a different choice under slightly changed conditions [2]. This inherent variability has driven the development of more objective, technology-based tools, such as digital spectrophotometers and intra-oral scanners, which aim to improve accuracy and reduce subjectivity in shade matching [1,3]. However, regardless of whether a dental technician uses their eyes or a sophisticated digital device, light remains the fundamental element essential to the process, as shade selection is not seeing objects by themselves, but seeing the light that bounces off them.

Therefore, the quality, intensity, and type of light incident on a tooth surface can significantly alter its perceived appearance. The color of a tooth is not a single, fixed value but a complex result of how light interacts with the layers of enamel and dentin [2]. Suboptimal lighting conditions may lead to inaccurate color perception by both visual and instrumental methods [1]. For instance, the bright, focused light from a dental operatory chair may cause desaturation of color, making it appear lighter, while the warm, yellowish glow of standard room lighting can shift its hue [4,5]. Even natural sunlight, often considered the gold standard, is not constant and changes with the time of day and weather [4]. Understanding the quantitative impact of lighting variability is key to improving outcomes. Previous studies recently showed that the accuracy of visual shade matching may decrease significantly under standard operatory light compared to color-corrected light [4]. Similarly, the precision of advanced intra-oral scanners has been shown to decrease dramatically when ambient room light or dental chair light is added to their built-in light sources [1,5].

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Although many international studies have examined whether lighting conditions have an influence on the accuracy of shade selection, there is still limited evidence within the Libyan dental context. Therefore, this study aimed to comparatively evaluate the effect of different lighting conditions on the accuracy and consistency of visual shade selection.

Methods

Study design and setting

A controlled in vitro experimental study using a within-subject (repeated-measures) design was conducted under standardized laboratory conditions at the Modern Orthodontic Center, Tripoli, Libya.

Materials

The materials used in this study included a VITA Classical Shade Guide (VITA Zahnfabrik H. Rauter GmbH & Co. KG, Bad Säckingen, Germany) consisting of 16 standardized shade tabs (A1 to D4), 16 blinded maxillary central incisor samples, a neutral gray background, and controlled artificial light sources with different color temperatures (3000 K, 4000 K, and 5500 K).

Experimental setup

The experiment was standardized to minimize bias and external influences. The examiner underwent the Ishihara color vision test to confirm normal color perception. All lighting conditions were standardized in terms of intensity, distance, and angle to ensure comparability. As illustrated in (Figure 1), each tooth sample was presented individually against a neutral gray background to eliminate color interference. The light source was positioned at a distance of 50 cm from the sample at an angle of 45 degrees. The examiner was positioned approximately 50 cm away from the sample, with the line of sight perpendicular to the tooth surface. The selected shade was recorded immediately after each observation, and a rest interval of 1–2 minutes was provided between observations. The order of the lighting conditions was randomized for each evaluation session to reduce potential order effects. The entire procedure was repeated after one week to evaluate consistency and intra-examiner repeatability.

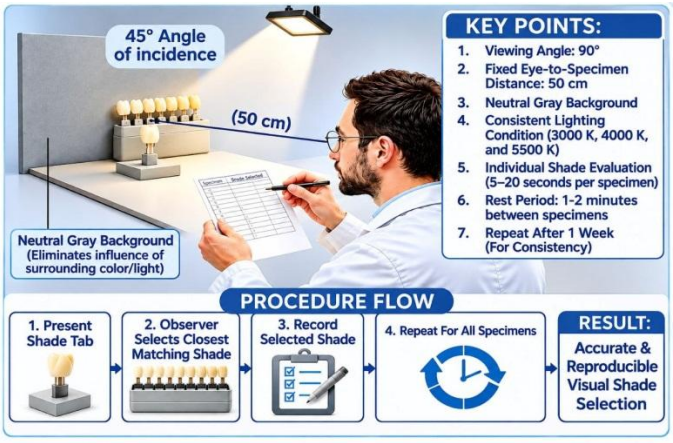


Figure 1. Experimental setup diagram

Data collection

Color differences (ΔE) were calculated using the Commission Internationale de l'Éclairage L*a*b* (CIELAB) color system according to the following equation [6]:

$$\Delta E = \sqrt{(L_2 - L_1)^2 + (a_2 - a_1)^2 + (b_2 - b_1)^2}$$

Where L* represents lightness, ranging from black (0) to white (100), a* represents the red–green axis, where positive values indicate redness and negative values indicate greenness, and b* represents the yellow–blue axis, where positive values indicate yellowness and negative values indicate blueness.

The values of L*, a*, and b* used in this study were obtained from a standardized reference table provided by the VITA Classical Shade Guide corresponding to the manufacturer of the shade tabs used in this study. This ensured consistency in color comparison. L1, a1, and b1 represent the reference values, while L2, a2, and b2 represent the selected color values.

The ΔE value provides a numerical indication of the difference between two matched colors; a smaller ΔE value indicates a closer match, whereas a larger value indicates a more noticeable difference.

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Data analysis

The collected data were analyzed using IBM SPSS Statistics for Windows, Version 27.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were calculated for ΔE values for each lighting condition and measurement session and are presented as means, standard deviations, and 95% confidence intervals. Inferential analysis was performed using a two-way repeated-measures Analysis of Variance (ANOVA) to evaluate the effects of lighting condition and measurement session as within-specimen factors on mean ΔE values. The analysis evaluated the main effects of lighting condition and measurement session and the lighting condition-measurement session interaction, with the level of significance set at $p \leq 0.05$. Mauchly's test was used to assess the sphericity assumption for the lighting factor. When appropriate, pairwise comparisons between lighting conditions were performed using paired comparisons with Holm adjustment for multiple comparisons. Effect sizes were reported as partial eta squared (ηp^2) for ANOVA effects and Cohen's dz for paired comparisons. In addition, intra-examiner repeatability of the categorical VITA shade selections between the two measurement sessions was assessed separately for each lighting condition using Cohen's kappa (κ), with 95% confidence intervals.

Results

A total of 96 complete ΔE observations were obtained from 16 specimens evaluated under three lighting conditions during two measurement sessions. Descriptive statistics for ΔE according to lighting condition and measurement session are presented in (Table 1). In both measurement sessions, mean ΔE values showed a consistent trend, with the highest values observed under warm illumination and the lowest values under daylight illumination.

Table 1. Descriptive statistics of ΔE values by lighting condition and measurement session.

Lighting condition	Session	Mean ΔE	SD	95% CI
Warm	Week 1	2.175	2.135	1.138–3.212
Neutral	Week 1	1.546	2.126	0.415–2.678
Daylight	Week 1	0.826	1.849	-0.159–1.811
Warm	Week 2	2.143	2.384	0.873–3.417
Neutral	Week 2	1.224	2.051	0.131–2.317
Daylight	Week 2	0.500	1.437	-0.266–1.266

Effect of lighting condition and measurement session

A two-way repeated-measures ANOVA was performed with lighting condition (warm, neutral, and daylight) and measurement session (Week 1 and Week 2) as within-subject factors. Mauchly's test indicated that the assumption of sphericity was satisfied for the lighting condition factor ($W = 0.986$, $\chi^2 = 0.210$, $p = 0.900$).

As presented in (Table 2), there was a statistically significant main effect of lighting condition on ΔE values, $F(2,30) = 5.200$, $p = 0.012$, partial $\eta^2 = 0.257$. In contrast, the main effect of measurement session was not statistically significant, $F(1,15) = 0.147$, $p = 0.707$, partial $\eta^2 = 0.010$. The lighting condition-measurement session interaction was also not significant, $F(2,30) = 0.092$, $p = 0.913$, partial $\eta^2 = 0.006$.

Table 2. Two-way repeated-measures ANOVA for the effects of lighting condition and measurement session on ΔE

Effect	F	Df	p value	Partial η^2
Lighting condition	5.200	2, 30	0.012*	0.257
Measurement session	0.147	1, 15	0.707	0.010
Lighting – session	0.092	2, 30	0.913	0.006

The mean ΔE values according to lighting condition are illustrated in (Figure 2), showing progressively lower ΔE values from warm to neutral and daylight illumination.

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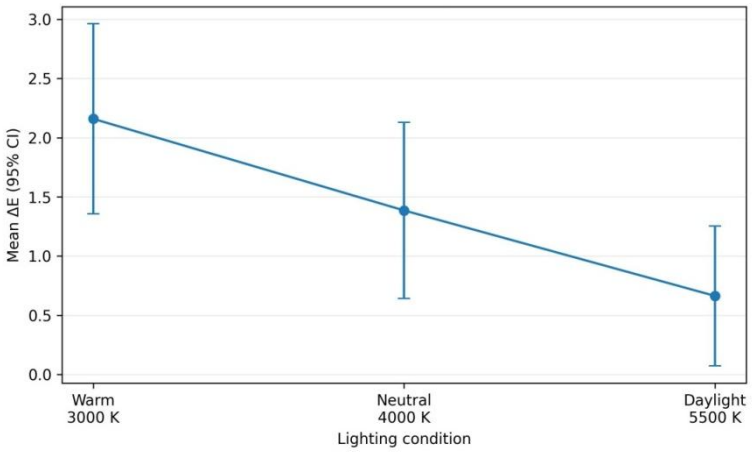


Figure 2. Mean ΔE across lighting conditions, combining both measurement sessions.

Pairwise comparisons between lighting conditions

Holm-adjusted pairwise comparisons demonstrated a statistically significant difference between warm and daylight illumination (mean difference = 1.496 ΔE, t = 3.217, adjusted p = 0.009, Cohen's dz = 0.569). The difference between warm and neutral illumination was not statistically significant (mean difference = 0.774 ΔE, t = 2.081, adjusted p = 0.092, Cohen's dz = 0.368), nor was the difference between neutral and daylight illumination (mean difference = 0.722 ΔE, t = 1.680, adjusted p = 0.103, Cohen's dz = 0.297) (Table 3).

Table 3. Holm-adjusted pairwise comparisons between lighting conditions (both sessions combined).

Comparison	Mean difference (ΔE)	t	df	Holm-adjusted p	Cohen's dz
Warm vs neutral	0.774	2.081	31	0.092	0.368
Warm vs daylight	1.496	3.217	31	0.009*	0.569
Neutral vs daylight	0.722	1.680	31	0.103	0.297

Pairwise comparisons between measurement sessions

Mean ΔE values were slightly lower in Week 2 than in Week 1 under all three lighting conditions; however, none of the within-lighting-session comparisons reached statistical significance. The Week 1 versus Week 2 differences were 0.032 ΔE for warm illumination (p = 0.969), 0.323 ΔE for neutral illumination (p = 0.692), and 0.326 ΔE for daylight illumination (p = 0.613). The similarity of the results across the two sessions is also illustrated in (Figure 3).

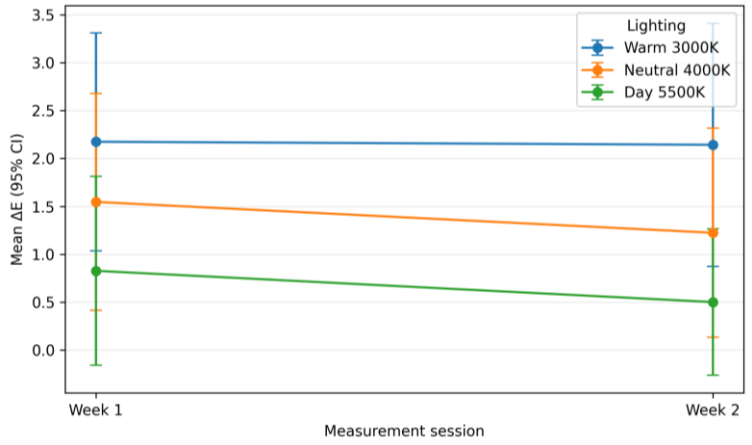


Figure 3. Mean ΔE by lighting condition and measurement session.

Intra-examiner repeatability of shade selection

(Table 4) summarizes the categorical repeatability of visual shade selection using Cohen's kappa. Exact agreement between the two measurement sessions was observed in 9 of 16 specimens (56.300%) under warm illumination, 11 of 16 (68.800%) under neutral illumination, and 14 of 16 (87.500%) under daylight illumination. Cohen's κ values were 0.525 (95% CI: 0.274–0.776), 0.661 (95% CI: 0.425–0.897), and 0.865 (95% CI: 0.691–1.000), respectively. These findings indicate that categorical shade-selection repeatability was highest under daylight illumination and lowest under warm illumination.

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Table 4. Intra-examiner repeatability of categorical VITA shade selection between** standardized **sessions.

Lighting condition	Exact agreement, n (%)	Cohen's κ	95% CI
Warm	9/16 (56.300%)	0.525	0.274–0.776
Neutral	11/16 (68.800%)	0.661	0.425–0.897
Daylight	14/16 (87.500%)	0.865	0.691–1.000

Discussion

This study evaluated whether different lighting conditions affect the accuracy of visual tooth shade selection and whether repeated assessment by the same examiner produces consistent shade-selection outcomes.

The principal finding was that lighting condition had a statistically significant effect on ΔE values, indicating that illumination influenced the accuracy of visual shade matching under the experimental conditions ($F(2,30) = 5.200$, $p = 0.012$, partial $\eta^2 = 0.257$). Mean ΔE values were highest under warm illumination and lowest under daylight illumination in both measurement sessions. Holm-adjusted pairwise comparisons demonstrated that the significant overall effect was primarily attributable to the difference between warm and daylight illumination (mean difference = 1.496 ΔE, adjusted $p = 0.009$). In contrast, the differences between warm and neutral illumination and between neutral and daylight illumination were not statistically significant after adjustment. These findings suggest that the effect of illumination was not uniform across all pairwise comparisons, with the statistically significant difference occurring between the lowest and highest color-temperature conditions.

The observed pattern is consistent with previous evidence by Śmielecka and Dorocka-Bobkowska [7], who reported significant differences in shade selection under different light sources, with color-corrected illumination improving shade-selection performance. More recent investigations have likewise highlighted the importance of illumination when assessing tooth color. Perou et al. [1] demonstrated that lighting conditions can affect shade-matching accuracy among dental students, while Saeed et al. [4] specifically evaluated three lighting conditions using the Vitapan Classical shade guide. Together with these findings, the present results support the view that illumination should be considered an important component of the clinical shade-matching environment. The lower ΔE observed under daylight illumination may be associated with its spectral characteristics and higher correlated color temperature, potentially providing more favorable conditions for distinguishing subtle differences between the tooth specimens and the shade guide. However, the present study does not establish that daylight illumination is universally superior to all other clinical lighting conditions. Rather, within the controlled experimental conditions used here, daylight produced the lowest color difference and differed significantly from warm illumination. This distinction is important because visual shade selection is influenced not only by correlated color temperature but also by the spectral composition, intensity, surrounding colors, observer characteristics, and viewing conditions [1,7].

The absence of a significant difference between warm and neutral illumination and between neutral and daylight illumination after Holm adjustment is also relevant. It indicates that the observed ordering of mean ΔE values should not be interpreted as evidence that every incremental increase in color temperature produces a statistically detectable improvement. Instead, the results suggest that sufficiently different illumination conditions may produce measurable differences in shade-matching performance, whereas intermediate differences may be smaller than the variability observed within specimens and measurements. This may partly explain why studies using different illumination ranges or experimental protocols have reported differing levels of statistical significance [1,4,7].

Measurement session did not have a significant main effect on ΔE values ($F(1,15) = 0.147$, $p = 0.707$), and the lighting-session interaction was also not significant ($F(2,30) = 0.092$, $p = 0.913$). Although mean ΔE values were descriptively lower during Week 2 under all three lighting conditions, these changes were small and did not reach statistical significance. Therefore, the present data do not provide evidence that repeated exposure to the shade-matching task systematically improved performance or that the effect of lighting changed between the two sessions. Therefore, the observed descriptive reduction in ΔE should not be interpreted as evidence of a learning or adaptation effect, as the measurement-session effect did not reach statistical significance.

In addition to the continuous ΔE analysis, categorical shade-selection repeatability was highest under daylight illumination ($\kappa = 0.865$). This finding provides complementary evidence to the ΔE analysis, suggesting that the lighting condition associated with the lowest mean color difference also produced the greatest consistency in repeated categorical shade selection. The relatively high repeatability observed under daylight illumination is clinically relevant because visual shade selection remains dependent on human color perception. Özat et al. [8] reported limited repeatability of visual shade selection when the same dentists repeated their assessments, demonstrating the inherent variability of visual shade matching. The higher intra-examiner repeatability observed under daylight illumination in the present study may reflect more favorable conditions for visual color discrimination. Nevertheless, the present study involved a single examiner and a controlled in vitro environment; therefore, the κ values should not be generalized directly to clinical populations or to inter-examiner agreement.

On the other hand, previous research has demonstrated that instrumental and visual shade-selection methods may differ in accuracy and repeatability [9]. Knezović et al. [10] reported high repeatability for the VITA Easyshade system in both in

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vivo and in vitro settings, while Witkowski et al. [11] investigated the reliability of an intraoral spectrophotometer. Kutkut et al. [12] similarly compared instrumental devices with visual shade selection in vitro. These studies support the value of instrumental approaches when high measurement reproducibility is required. However, visual shade selection remains clinically important because it is widely used in routine restorative dentistry and does not require specialized instrumentation. The present findings therefore support improving the conditions under which visual shade selection is performed rather than suggesting that visual methods should necessarily be replaced by instrumental techniques.

The study has several limitations. First, the relatively small sample size of 16 specimens may have limited statistical power and restricts the generalizability of the findings. Nevertheless, the repeated-measures design allowed each specimen to be evaluated under all lighting conditions and in both sessions, thereby reducing between-specimen variability. Second, the experiment was conducted under controlled in vitro conditions, which do not fully reproduce the complexity of the clinical oral environment. Third, shade selection was performed by a single examiner, so the kappa analysis reflects intra-examiner repeatability and cannot be interpreted as evidence of inter-examiner reliability. Finally, the findings should be interpreted in relation to the specific illumination characteristics and viewing conditions used in the experiment.

Conclusion

Within the limitations of this in vitro study, daylight illumination demonstrated greater shade-matching accuracy, as indicated by lower ΔE values compared with warm illumination. The statistically significant difference was observed specifically between warm and daylight conditions. Furthermore, daylight illumination demonstrated the highest intra-examiner repeatability, as reflected by Cohen's kappa values. The absence of a significant measurement-session effect or lighting-by-session interaction suggests that the observed influence of illumination was consistent across sessions. These findings underscore the importance of standardized daylight-like illumination in clinical shade selection to enhance color-matching accuracy and minimize discrepancies.

Conflict of Interest

There are no financial, personal, or professional conflicts of interest to declare.

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