Journal of Dentistry 160 (2025) 105922

Contents lists available at ScienceDirect

Journal of Dentistry

journal homepage: www.elsevier.com/locate/jdent

Influence of zirconia thickness and background color on color matching accuracy of monolithic zirconia restorations

Danya Hashem [a], Lamis A. Al-Taee [b], Samah Ibrahim Mourad [c,d], Nahla Gamaleldin Elhelbawy [e,f], Khaled E. Ahmed [g,*], Samah Mahmoud [h,i]

[a] *Department of Restorative Dental Science, College of Dentistry, Taibah University, Madinah Saudi Arabia*
[b] *Department of Conservative & Aesthetic Dentistry, College of Dentistry, University of Baghdad, Baghdad 1417, Iraq*
[c] *Department of Oral surgery, Faculty of Dentistry, Mansoura University, Mansoura, Egypt*
[d] *Department of Oral and Maxillofacial Diagnostic Sciences, College of Dentistry, Taibah University, Madinah, Saudi Arabia*
[e] *Dental Biomaterials Department, Faculty of Dentistry, Tanta University, Tanta, Egypt*
[f] *Department of Restorative Dental Science, College of Dentistry, Taibah University, Madinah, Saudi Arabia*
[g] *Melbourne Dental School, University of Melbourne, Melbourne, Australia*
[h] *Department of Substitutive Dental Science, College of Dentistry, Taibah University, Madinah, Saudi Arabia*
[i] *Department of Fixed Prosthodontics, Faculty of Dentistry, Mansoura University, Mansoura, Egypt*

ARTICLE INFO

Keywords:
Color
Monolithic zirconia
Shade match
Background color
Restoration thickness

ABSTRACT

Objective: To evaluate the influence of monolithic zirconia brand, thickness, and substrate color on color matching accuracy when optically coupled to abutment substrates.
Methods: A total of 180 samples of two brands of monolithic zirconia [Prettau Anterior (PA), Ceramill Zolid FX Multicolor (CZ)] were prepared in three different thicknesses (0.8 mm, 1.5 mm, and 2 mm) with a standardized 10 mm diameter. Color properties of the samples were assessed using spectrophotometry at baseline and after coupling to three substrate types: standard dentin, discolored dentin, and titanium. Color differences (ΔE) were calculated and statistically analyzed by 3-way ANOVA and pairwise comparison (α=0.05).
Results: The brand and material thickness, at baseline and after coupling to different substrate colors, had significant effect on color variations ($P < 0.001$). CZ consistently exhibited higher color differences than PA across all conditions. Thinner specimens (0.8 mm) demonstrated greater sensitivity to substrate color, and increasing the thickness to 1.5 mm resulted in a reduction in color differences, particularly for CZ formulations. Thinner zirconia restorations (0.8 mm) require careful material selection and substrate matching to mitigate perceptible color shifts.
Conclusion: The accuracy of color matching of monolithic zirconia restorations is significantly influenced by material composition, thickness, and underlying substrate color. CZ demonstrated greater substrate transparency effects compared to PA, emphasizing the critical role of material selection in clinical outcomes.
Clinical significance: Clinicians should carefully consider the potential change of the color properties of monolithic zirconia restorations, especially in thin sections and with dark tooth substrate, when color masking is needed.

1. Introduction

Zirconia is a polycrystalline ceramic material that exists in three crystallographic phases: monoclinic, tetragonal, and cubic, and exhibits transformation toughening behavior [1,2]. The incorporation of yttria (Y_2O_3) at varying concentrations is used to stabilize the cubic phase of zirconia. A concentration of at least 8 mol % Y_2O_3 leads to the formation of fully stabilized zirconia (FSZ), while partially stabilized zirconia (PSZ) is achieved with Y_2O_3 concentrations in the range of 4 to 6 mol %. In yttria-stabilized tetragonal zirconia polycrystals (Y-TZP), improved translucency is attained by reducing the alumina content and increasing the yttria concentration, thereby mitigating the susceptibility to low-temperature degradation [3–7].

Monolithic zirconia restorations have become widely utilized in

* Corresponding author.
E-mail addresses: dhashem@taibahu.edu.sa (D. Hashem), lamis.al-taee@codental.uobaghdad.edu.iq (L.A. Al-Taee), smourad@taibahu.edu.sa (S.I. Mourad), nhelbawy@taibahu.edu.sa (N.G. Elhelbawy), khaled.ahmed@unimelb.edu.au (K.E. Ahmed), ssakr@taibahu.edu.sa (S. Mahmoud).

https://doi.org/10.1016/j.jdent.2025.105922
Received 2 May 2025; Received in revised form 17 June 2025; Accepted 19 June 2025
Available online 20 June 2025

dental clinics due to their excellent mechanical properties, reduced wear on opposing dentition, preservation of tooth structure, and the absence of veneering porcelain, which streamlines both clinical and laboratory workflows [8–12]. The final shade of monolithic zirconia is not solely determined by shade selection but is instead the result of various interacting factors, such as the coloring method [13–16], the color of the abutment substrate [17,18], type of luting cement [17,19–21], sintering parameters [22,23], glazing and polishing techniques [24–26], zirconia brand [27,28], material thickness [18,20,21,28,29], and aging processes [30–32].

The recommended thickness range for translucent zirconia is 0.5 –2.0 mm [18,20,21]. Increasing the thickness of zirconia enhances its ability to mask imperfections but reduces final restoration translucency [28,29]. However, a previous study observed that low-translucency zirconia crowns with a thickness of <1.5 mm, when positioned over non-tooth-colored substrates, do not result in a perceptible color discrepancy with discolored natural teeth [30].

Color assessment for dental materials has traditionally been based on the standards established by the CIE (Commission Internationale de l'Eclairage), which has developed the foundational color systems, concepts of color difference (ΔE), and illumination patterns utilized in color science. In the CIE L*ab** color space –where L* represents the lightness-darkness value axis, a* signifies the red-green axis, and b* represents the yellow-blue axis. ΔE_ab has historically been the standard parameter for quantifying the total color difference between two objects. As a result, a higher ΔE value indicates a larger color difference, rendering the distinction more perceptible to the human eye [31–37].

However, the CIE recommends the use of the CIEDE2000 color-difference formula (ΔE00), which incorporates specific adjustments to account for the non-uniformity inherent in the CIELAB color space. This formula includes weighting functions (S_L, S_C, S_H), a rotation term (RT) that addresses the interactions between chroma and hue differences in the blue region, and modifications to the a* coordinate of CIELAB, which primarily affect colors with low chroma (neutral colors). Furthermore, the formula incorporates parameters that consider the effects of illumination and viewing conditions on the evaluation of color differences (the parametric factors: K_L, K_C, K_H).

Balancing translucency and strength is crucial when selecting zirconia materials. 3Y-TZP and 5Y-PSZ zirconia types exhibit distinctly different optical characteristics and are commonly used in clinical practice. While 3Y-TZP is known for its high strength and relatively low translucency, 5Y-PSZ offers greater translucency but with reduced mechanical strength. By examining both materials, the study provides a thorough evaluation of how zirconia thickness and substrate color influence shade matching, thereby aiding clinicians in choosing the most appropriate material for various restorative situations.

Despite extensive research on the impact of substrate on the appearance of restorations made from various dental materials, a consensus remains lacking regarding the factors involved in this process and their influence on the final optical properties. Dental structures or other restorative materials can represent this substrate. Therefore, the aim of this study was to evaluate the effect of different substrate colors on the appearance of monolithic zirconia, accounting for the variables of zirconia thickness and material brand. The null hypothesis was that changes in zirconia thickness, along with different substrate colors, would not significantly influence the color properties of monolithic zirconia.

2. Materials and methods

2.1. Specimen preparation

Two brands of monolithic zirconia materials, Prettau Anterior (PA, 3Yttria-stabilized Tetragonal Zirconia Polycrystal, 3Y-TZP) and Ceramill Zolid FX Multilayer (CZ, 5Y-TZP), were assessed in this study (Table 1). A total sample size of 180 specimens was calculated based on an alpha level of 0.05 and a beta of 0.20 (power of 80 %), guided by effect sizes reported in previous studies [8,9,15,22,27,30]. The specimens were digitally designed using AutoDesk Inventor software (Autodesk Inc.) with a 25 % increase in dimension to accommodate sintering shrinkage. Three thickness groups were prepared: 0.8 mm, 1.5 mm, and 2 mm, all with a standardized 10 mm diameter (Fig. 1). The final specimen thickness was verified with an accuracy of ±0.02 mm using digital calipers (Mitutoyo Series 209 Caliper; Mitutoyo Corp., Japan).

Table 1
List of materials used in the study.

Material	Brand	Manufacturer	Composition
Uncolored zirconia	Prettau Anterior (FSZ) (PA)	Zirkonzahn	ZrO_2: main component $Y2O_3$: 8–12 % Al_2O_3:, 0–1 % SiO_2: 0.02 % Fe_2O_3: 0.01 % Na_2O: 0.04 %
Shade gradient zirconia	Ceramill Zolid FX Multilayer (CZ)	Amann Girrbach AG	ZrO_2+HfO_2+Y_2O_3: ≥99.0 Y_2O_3: 8.5 − 9.5 HfO_2: ≤5 Al_2O_3: ≤0.5

For PA specimens, surface coloring was achieved through immersion in A2 coloring solution (Prettau® Aquarell; Zirkonzahn GmbH) for 10 s, followed by infrared drying using a Zirkonlamp 250 (Zirkonzahn) for 20 min according to the manufacturer's instructions. CZ specimens were milled with precise nesting in CAM software to align vertical shade gradients (enamel-dentin-cervical), followed by dry milling using diamond-coated burs at optimized speeds (6000–12,000 RPM), sintered at 1450 °C using a standardized furnace program (Ceramill Therm) with a 1–2 hour hold time at peak temperature and a total cycle duration of 8–10 h, including controlled ramp up (8 °C/min). This difference in shade protocols is due to the difference in manufacturers' presentation of the materials. PA is typically supplied in a white, uncolored form and requires external coloring procedures while CZ is supplied as a pre-shaded, multilayered block.

Post-sintering, specimens were categorized by thickness cohort. Surface standardization involved sequential polishing with 320-, 400-, 600-, and 1200-grit silicon carbide papers under water cooling for 60 s per abrasive grade. Final cleaning consisted of ultrasonic treatment in 99 % alcohol for 3 min to remove particulate residues.

2.2. Fabrication of tooth- colored foundation

Within each ceramic thickness, the specimens were then divided into three groups (n = 10) based on the background color. The first group comprised Group ND3: shade ND3 of tooth-colored resin substrates (IPS Natural Die Material; Ivoclar Vivadent, Schaan, Liechtenstein) to imitate standard dentin color. The second group was Group ND9: resin substrates representing severely discolored dentin (IPS Natural Die Material; Ivoclar Vivadent, Schaan, Liechtenstein) prepared to be 10 mm in diameter and 5 mm thick by using putty molds. Finally, Group T: A titanium background disk with a diameter of 10 mm and a height of 5 mm was designed (Fig. 1). The same digital caliper was used to confirm the thickness of background materials (5.0 ± 0.02 mm).

The contact surface of each foundation was sandblasted using aluminum oxide (Al_2O_3) particles (Korox, Bego, Bremen, Germany). Following sandblasting, the foundation blocks were ultrasonically cleaned in distilled water (Healthsonics, Livermore, USA) for 10 min to remove any surface contaminants and subsequently air-dried. To establish optical contact, a saturated sucrose solution (73 % concentration, refractive index n = 1.5) was applied between the zirconia and underlying substrates. This solution served as an intermediary layer, facilitating the optical contact between the zirconia specimens and the underlying substrates [4,6].

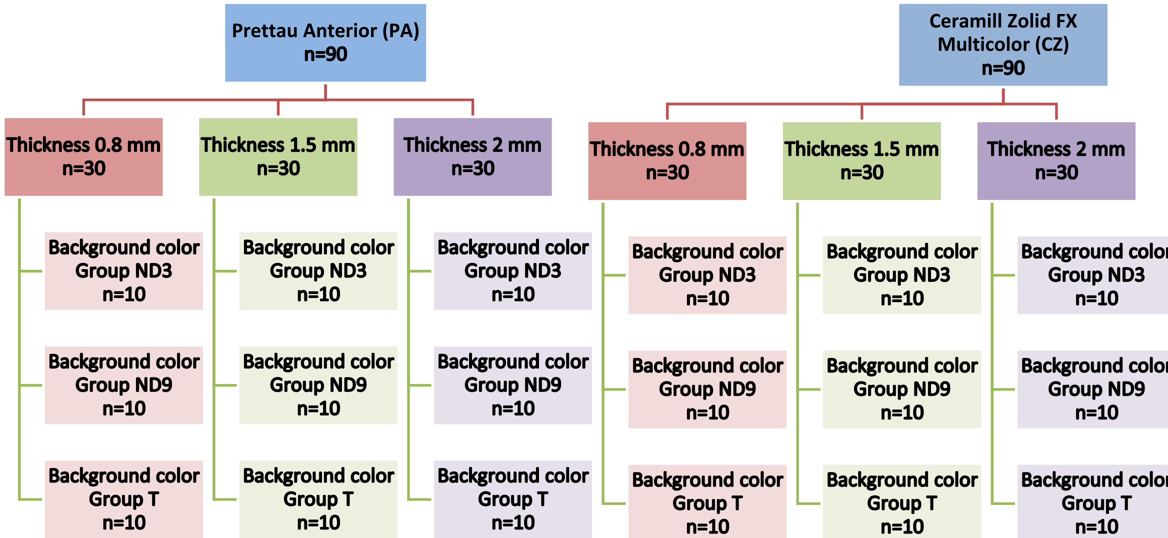

Fig. 1. Flow chart illustrating the distribution of specimens into groups and subgroups.

2.3. Color assessment

For each specimen, color values were measured at the baseline, and after optical coupling of the zirconia specimens to tooth-colored substrates, according to the Commission Internationale de l'Eclairage (CIE) 1976 L*a*b* values and the average of 3 readings for each specimen was calculated. To ensure consistent measurement across all specimens, a custom mount was fabricated using condensation silicone (Zeta+; Zhermack GmbH). Color evaluation was conducted using a double-beam reflectance spectrophotometer (Cary 5000 UV–Vis-NIR Spectrophotometer; Agilent Technologies), which was calibrated prior to measuring each specimen's color, utilizing an integrating sphere attachment. Relative reflectance data were collected at 5-nm intervals across the visible spectrum (380 to 780 nm). The CIE D65 standard illuminant and a 10° standard observer angle were used for the measurements. Each color was characterized by three parameters: L* (lightness), a* (red-green value), and b* (yellow-blue value). The color difference (ΔE) was calculated using the following formula:

$$\Delta E = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right]^{1/2} \text{where :}$$

ΔL=(L1*−L2*), Δa=(a1*−a2*), Δb=(b1*−b2*). Here, L1*, a1*, and b1* represent the baseline color values of the specimens (as sintered), while L2*, a2*, and b2* correspond to the measurements after optical coupling to tooth-colored substrates.

ΔE_{ab} values were compared with an ideal threshold and an acceptable clinical threshold for assessment of the perceptibility and acceptability of the color changes. A ΔE value of 1 was assumed as an ideal (perceptible) threshold; whereas, 3.7 was assumed as an acceptable clinical threshold [39].

And CIEDE2000 (ΔE_{00}) color difference formula, according to following equation:

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{\kappa_L S_L}\right)^2 + \left(\left(\frac{\Delta C'}{\kappa_C S_C}\right)\right)^2 + \left(\frac{\Delta H'}{\kappa_H S_H}\right)^2 + R_T\left(\frac{\Delta C' \cdot \Delta H'}{S_C \cdot S_H}\right)}$$

In the CIEDE2000 color difference formula, ΔL_o, ΔC_o, and ΔH_o denote the differences in lightness, chroma, and hue, respectively, between two color samples. The term R_T represents the rotation function, which adjusts for the interaction between chroma and hue differences, particularly in the blue region of the color space. The weighting functions S_L, S_C, and S_H normalize the total color difference based on the specific position of the color pair within the L_0, a_0, and b_0 coordinates of the CIELAB color space. Furthermore, the parametric factors K_L, K_C, and K_H are applied as correction terms to account for different experimental conditions.

Color differences were assessed by comparison with the 50:50 % perceptibility (PT) and 50:50 % acceptability (AT) thresholds. The PT and AT values used in this study were 1.74 and 3.48 units for ΔE*ab, and 1.25 and 2.23 units for ΔE_{oo}, respectively, as determined for dental ceramics. An A2 shade tab from the VITA Classical shade guide (VITA Compact EasyShade; VITA Zahnfabrik) was used as a reference color and were measured at the center of its middle third using the same spectrophotometer and were considered the reference CIELab values for the final color (control) (L*=74.8, a*=0.7, b*=20.0).

2.4. Statistical analysis

The data were statistically analyzed using SPSS version 26.0 (SPSS, Inc., an IBM Company, Chicago, IL, USA). The normality of data distribution was evaluated with the Kolmogorov-Smirnov test ($P > 0.05$). A three-way analysis of variance (ANOVA) was performed to examine the interaction between the three independent variables (material brand, material thickness, and substrate color) and their individual effects on color properties. For each material, a two-way ANOVA was performed to evaluate the influence of material thickness and substrate color on color properties, assessing both their individual effects and potential interaction on colorimetric outcomes. When significant differences were identified, post-hoc comparisons of mean values were conducted using Bonferroni correction (α=0.05).

3. Results

The study compared three thicknesses (2 mm, 1.5 mm, 0.8 mm) of two different monolithic zirconia materials. Table 2 presents mean values and standard deviations of ΔL*, Δa*, and Δb* for PA and CZ brands coupled to tooth-colored substrates. Negative ΔL* and Δa* values indicate an increase in lightness (L*) and the red component (a*) of the tested zirconia brands, corresponding to changes in material thickness and optical coupling to tooth-colored materials. Conversely, the positive Δb* values suggest an increase in the blue component of the material. Results from 3-way ANOVA demonstrated that the changes in the ΔL* and Δa* values were affected by significant interaction between the tested variables (material brand and thickness) ($P \leq 0.05$). However, the changes in the Δb* value weren't influenced by interaction between the tested variables (Table 3).

The mean values of the color difference ΔE_{ab} and ΔE_{00} after coupling

Table 2
Mean values of ΔL, Δa, and Δb ± standard deviation of tested zirconia brands of different thickness after optical coupling to different abutment substrates.

Zirconia Brand	Color Parameter	Thickness	Background ND3	Background ND5	Background T (Metal)
PA	Δl	2mm	−1.90	−1.49	−2.22
		1.5mm	−1.49	−2.42	−2.97
		0.8mm	−2.42	−2.91	−2.71
	Δa	2mm	0.64	0.64	0.41
		1.5mm	−0.15	−0.16	−0.59
		0.8mm	−0.54	−0.42	−0.59
	Δb	2mm	−2.01	−2.74	−2.54
		1.5mm	−2.31	−2.31	−1.81
		0.8mm	−2.11	−1.78	−2.80
CZ	Δl	2mm	−1.37	−1.77	−2.69
		1.5mm	−1.74	−2.18	−2.21
		0.8mm	−2.05	−2.44	−2.84
	Δa	2mm	0.64	0.64	0.59
		1.5mm	0.62	0.61	0.62
		0.8mm	−0.04	−0.04	−0.03
	Δb	2mm	−2.53	−2.23	−1.93
		1.5mm	−2.17	−2.37	−2.57
		0.8mm	−2.52	−2.62	−2.82

Table 3
Three-way ANOVA test for influence of material brand, material thickness and substrate color on ΔL, Δa, and Δb.

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	Dl	47.550[a]	17	2.797	4.292	0.000
	Da	40.563[b]	17	2.386	10.046	0.000
	Db	17.976[c]	17	1.057	1.605	0.068
Intercept	Dl	869.924	1	869.924	1334.980	0.000
	Da	4.573	1	4.573	19.252	0.000
	Db	986.685	1	986.685	1497.566	0.000
Material	Dl	.563	1	.563	.865	0.354
	Da	10.498	1	10.498	44.198	0.000
	Db	1.008	1	1.008	1.530	0.218
thickness	Dl	13.411	2	6.705	10.290	0.000
	Da	22.777	2	11.388	47.946	0.000
	Db	1.041	2	.521	.790	0.455
substrate	Dl	19.993	2	9.996	15.340	0.000
	Da	.730	2	.365	1.537	0.218
	Db	.554	2	.277	.420	0.658
Material * thickness	Dl	.802	2	.401	.616	0.542
	Da	5.500	2	2.750	11.579	0.000
	Db	2.965	2	1.483	2.250	0.109
Material * substrate	Dl	.074	2	.037	.057	0.945
	Da	.636	2	.318	1.339	0.265
	Db	.324	2	.162	.246	0.782
thickness * substrate	Dl	5.019	4	1.255	1.925	0.109
	Da	.212	4	.053	.223	0.925
	Db	4.612	4	1.153	1.750	0.142
Material * thickness * substrate	Dl	7.688	4	1.922	2.950	0.022
	Da	.210	4	.053	.221	0.926
	Db	7.472	4	1.868	2.835	0.026

to tooth-colored substrates are summarized in Table 4. Between the monolithic zirconia brands, the CZ group recorded the highest ΔE value regardless of the variable tested, and the difference was statistically significant (Table 5).

Two-way ANOVA test (Table 5) revealed a difference in the mean value of ΔE_{ab} and ΔE_{00} that was significantly affected by the material thickness and background color ($P < 0.001$) while no significant difference between the material brands was recorded (Table 6).

4. Discussion

The results of this study reject the null hypothesis, demonstrating that the color of monolithic zirconia is significantly affected by both the material brand and thickness when optically coupled to different tooth-colored substrates.

The study’s findings emphasize the importance of careful material selection and restoration design to achieve the best esthetic results. Differences in zirconia composition and microstructure across brands affect how light is transmitted and reflected, while thickness influences the extent to which the underlying substrate color is masked. A thorough understanding of these factors is crucial for clinicians seeking to reduce visible color mismatches, particularly in cases involving thin restorations or substrates with discoloration. The results of the current investigation indicate a statistically significant inverse relationship between zirconia thickness and L* value, independent of other experimental factors. This phenomenon may be attributed to variations in the structural and optical characteristics among the monolithic zirconia brands tested. A plausible explanation is that reduced thickness promotes decreased light dispersion, resulting in a lower L* value [15]. This finding aligns with the principle that thinner layers of a material may exhibit reduced light scattering and increased translucency, leading to a lower L* value as the underlying substrate influences the overall color perception. The different structural and optical properties inherent to each monolithic zirconia brand likely contributed to this phenomenon [25,28,38,39]. Specifically, the variations in grain size, porosity, and the concentration of stabilizing oxides can influence light transmission and scattering behavior. It can be deduced that reduced light dispersion with reduced thickness, which induces lower L* value, could occur. The significant interaction between material brand and thickness underscores the complexity of color matching with zirconia restorations [27,29,40,41]. The finding indicates that the optimal thickness for achieving a desired shade may vary depending on the specific brand of zirconia used, highlighting the importance of considering material-specific guidelines and conducting thorough shade matching procedures when selecting and fabricating zirconia restorations [15]. Clinicians should be aware that simply increasing or decreasing the thickness of a restoration may not predictably alter the color outcome, and a more nuanced approach –taking into account the material’s inherent optical properties –is necessary.

The effect of cement color and thickness have been studied by many researchers [16–23]. It was not within the scope of this study to investigate the effects of cement, and so to avoid the effect of cement color, a saturated sucrose solution (73 % concentration, refractive index $n = 1.5$) was applied between the zirconia and underlying substrates.

The analysis of color differences using ΔE_{00} provides additional

Table 4
Mean color difference (ΔE_{ab} & ΔE_{00}) ± standard deviation of tested zirconia brands of different thickness after optical coupling to different abutment substrates. (Similar superscript letters indicate no statistically significant difference ($P > 0.05$).

Zirconia Brand	Thickness	Color Difference	Background ND3	Background ND5	Background T (Metal)
PA	2mm	ΔE_{ab}	2.97± 0.64[a]	3.32±0.67 [a,b]	3.51±0.8 [b]
		ΔE_{00}	2.03±0.48[c]	2.132±0.41[c]	2.32±0.53 [c,d]
	1.5mm	ΔE_{ab}	2.89±0.45[a,d]	3.48±0.79[b]	3.61±0.75 [b]
		ΔE_{00}	1.87±0.53[c,e]	2.35±0.84 [c,d]	2.81±0.88 [a,d]
	0.8mm	ΔE_{ab}	3.37±0.58 [a,b]	3.60±0.52 [a,b]	4.14±1 [f]
		ΔE_{00}	2.35±0.9[c,d]	2.75±0.8 [a,d]	2.85±0.84 [a,d]
CZ	2mm	ΔE_{ab}	3.00±0.89 [a,b]	3.16±1 [a,b]	3.46±0.74 [b]
		ΔE_{00}	1.94±0.58 [c,e]	2.15±0.79 [c,e]	2.46±0.5[c,d]
	1.5mm	ΔE_{ab}	2.92±0.86[a]	3.40±0.8 [a,b]	3.54±0.84 [b]
		ΔE_{00}	2.00±0.54[c]	2.34±0.54 [c,d]	2.41±0.55 [c,d]
	0.8mm	ΔE_{ab}	3.33±0.86 [a,b]	3.62±0.7[b,f]	4.06±0.66 [f]
		ΔE_{00}	2.21±0.53 [c,d]	2.45±0.45 [c,d]	2.79±0.57 [a,d]

Table 5
Two-way ANOVA test for the influence of material brand, material thickness and substrate color on color difference (ΔE_{ab} & ΔE_{00}) of tested monolithic zirconia.

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	**Sig.**
Corrected Model	ΔE_{ab}	20.644[a]	17	1.214	1.994	0.014
	ΔE_{00}	15.682[b]	17	.922	2.061	0.011
Intercept	ΔE_{ab}	2098.176	1	2098.176	3444.459	0.000
	ΔE_{00}	993.988	1	993.988	2221.007	0.000
Material	ΔE_{ab}	.089	1	.089	.147	0.702
	ΔE_{00}	.281	1	.281	.628	0.429
thickness	ΔE_{ab}	7.010	2	3.505	5.754	0.004
	ΔE_{00}	4.890	2	2.445	5.463	0.005
substrate	ΔE_{ab}	12.367	2	6.184	10.151	0.000
	ΔE_{00}	8.747	2	4.374	9.773	0.000
Material * thickness	ΔE_{ab}	.006	2	.003	.005	0.995
	ΔE_{00}	.270	2	.135	.301	0.740
Material * substrate	ΔE_{ab}	.062	2	.031	.051	0.950
	ΔE_{00}	.048	2	.024	.053	0.948
thickness * substrate	ΔE_{ab}	1.013	4	.253	.416	0.797
	ΔE_{00}	.493	4	.123	.276	0.893
Material * thickness * substrate	ΔE_{ab}	.097	4	.024	.040	0.997
	ΔE_{00}	.953	4	.238	.532	0.712

Table 6
Mean color difference (ΔE_{ab} & ΔE_{00}) ± standard deviation between shade tab and tested zirconia brands of different thickness after optical coupling to different abutment substrates. NDS: standard dentine; ND5: discolored dentine.

Zirconia Brand	Thickness	Color Difference	Substrate ND3	Substrate ND5	Substrate T (Metal)
PA	2mm	ΔE_{ab}	4.16±0.65	4.55±0.71	4.73±0.85
		ΔE_{00}	2.69±0.53	2.82±0.44	3 ± 0.0.45
	1.5mm	ΔE_{ab}	5.14±0.55	5.88±0.79	5.96±0.88
		ΔE_{00}	3.28±0.33	3.79±0.70	4.24±0.54
	0.8mm	ΔE_{ab}	6.41±0.97	6.61±0.8	7.13±0.93
		ΔE_{00}	4.15+0.80	4.57±0.58	4.73±0.46
CZ	2mm	ΔE_{ab}	5.41±1.3	4.79±0.75	5.32±0.97
		ΔE_{00}	3.00±0.67	3.11±0.39	3.46±0.65
	1.5mm	ΔE_{ab}	5.53±0.8	6.06±0.66	8.18±1
		ΔE_{00}	3.75±0.58	4.10±0.62	4.18±0.74
	0.8 mm	ΔE_{ab}	7.01±1.36	7.06±1.1	7.50±1.2
		ΔE_{00}	4.61±0.82	4.88±0.90	5.23±1

insights into the deviation from ideal color matching in dental restorations. While ΔE_{ab} values were previously discussed, considering ΔE00 is important as it offers a more perceptually uniform color difference formula [33,36].

Many studies have shown that background color significantly influences perceived color differences [16,17,19,23,33–35]. Specifically, studies have found that samples viewed against a white background tend to exhibit more pronounced color differences compared to those viewed against grey or black backgrounds [33–35]. In this study, it was observed that the acceptability threshold values were higher when samples were placed on a white background compared to grey or black backgrounds, aligning with recent findings. Additionally, it has been noted that neutral backgrounds, such as grey, generally result in smaller perceived color differences than white backgrounds, a pattern that was also observed in our analysis of acceptability threshold values. Comparing ΔE_{ab} and ΔE_{00} values, a linear relationship of $\Delta E_{00} = 0.66\Delta E_{ab}$ has been observed. This relationship suggests that ΔE_{00} values are generally smaller than corresponding ΔE_{ab} values, which is important to consider when interpreting color difference data. These results are supported by the findings of a previous study [37], which reported a linear relationship between ΔE_{00} and $\Delta E_{ab.}$

The mean ΔE_{ab} values representing the average color difference between the zirconia restorations and the target shade after optical coupling to various abutment substrates ranged from (4.16±0.65 to 8.18 ±1). These values are substantially higher than the ideal threshold of 1, indicating that, regardless of zirconia brand, thickness, or abutment shade, a perceptible color difference is almost inevitable. This is consistent with a previous study [42] that evaluated color differences of different ceramic systems in comparison with Vita Classic (VC) shades. The study evaluated color differences between CAD-CAM ceramic systems (IPS e.max, IPS Empress, Paradigm C, VITABLOCS Mark II) and Vita Classical (VC) shade guide shades A1-A3, as well as intra-system shade variations. Results showed clinically unacceptable color differences (ΔEab* 6.32–13.42; ΔE004.48–9.30) between ceramic systems and corresponding VC shades, with some intra-system differences below acceptability thresholds (A1-A2, A2-A3) and perceptibility thresholds (A2-A3). The authors suggested that this is due to manufacturers finding bright teeth appealing [34].

In agreement with previous studies [15,17,18,20], the change in chromaticity, b* value, was more sensitive to the change in zirconia thickness than the a* value. Similarly, another study reported that the difference in subjective color assessment between a* and b* values for monolithic zirconia was accompanied by the change in ceramic thickness [39].

CZ's higher ΔE values compared to PA may stem from its multilayer architecture, which introduces additional light-scattering interfaces compared to homogeneous PA. This structural disparity likely explains CZ's heightened sensitivity to substrate color changes, particularly at 0.8 mm thickness, where layer interactions are maximized [5,9].

This study was constrained by its exclusive evaluation of two monolithic zirconia systems (PA and CZ), the absence of translucency quantification, and its *in-vitro* design, which limits extrapolation to clinical scenarios. Additionally, the study did not incorporate resin cements with varying shades, which can influence the final color outcome of zirconia restorations. Future research should include a wider range of zirconia compositions, employ spectrophotometric translucency measurements, and assess the effect of different cement shades.

5. Conclusions

Based on the results of the present study, it can be concluded that:

1. The color of monolithic zirconia can be influenced by the material brand and thickness.
2. Increasing zirconia thickness from 0.8 mm to 1.5 mm notably reduced color differences, especially for the CZ brand, highlighting the importance of adequate material thickness to achieve acceptable esthetic outcomes.
3. The CZ zirconia coupled to different tooth-colored substrates consistently exhibited elevated ΔEab and ΔE00, indicating a higher likelihood of visible color mismatch compared to PA, regardless of thickness. Thinner zirconia restorations require careful material selection and substrate matching to mitigate perceptible color shifts, particularly in CZ formulations.

Disclosure statement

The authors do not have any financial interest in the companies whose materials are included in this article.

CRediT authorship contribution statement

Danya Hashem: Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation, Conceptualization. **Lamis A. Al-Taee:** Writing – review & editing, Writing – original draft, Validation. **Samah Ibrahim Mourad:** Writing – review & editing, Writing – original draft, Validation. **Nahla Gamaleldin Elhelbawy:** Writing – review & editing, Validation. **Khaled E. Ahmed:** Writing – review & editing, Validation. **Samah Mahmoud:** Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors did not have any commercial interest in any of the materials used in this study.

References

[1] S. Ghodsi, Z. Jafarian, A review on translucent Zirconia, Eur. J. Prosthodont. Restor. Dent. 26 (2018) 62–74, https://doi.org/10.1922/ejprd_01759ghodsi13.
[2] N. Juntavee, A. Juntavee, C. Jaralpong, Color characteristics of high yttrium oxide-doped monochrome and multilayer partially stabilized zirconia upon different sintering parameters, Eur. J. Dent. 19 (2025) 227–239, https://doi.org/10.1055/s-0044-1787700.
[3] M.G. Park, Effect of low-temperature degradation treatment on hardness, color, and translucency of single layers of multilayered zirconia, J. Prosthet. Dent. 133 (2025) 258–263. https://doi.10.1016/j.prosdent.2023.01.023.
[4] L.M. de Miranda, S.E.G. da Silva, J.V.D.N. Santos, R.O.A.E. Souza, Multilayer ultratranslucent Monolithic Zirconia crowns treated with Multimode universal adhesive system containing Zirconia primer: a clinical report, J. Esthet. Restor. Dent. 2 (2024), https://doi.org/10.1111/jerd.13347. Dec.
[5] R. Ghanem, A. Adel, W. Al-Zordk, Effect of simulated intraoral adjustment on the color and translucency of gradient multilayered monolithic zirconia, J. Prosthet. Dent. 132 (2024) 1313.e1–1313.e8, https://doi.org/10.1016/j.prosdent.2024.08.025.
[6] S.M. Čokić, M. Li, S. Huang, J. Vleugels, et al., Coloring multilayer zirconia may affect its optical and mechanical properties, J. Dent. Res. 103 (2024) 1091–1099, https://doi.org/10.1177/00220345241271211.
[7] P. Uasuwan, N. Juntavee, A. Juntavee, Effect of glass infiltration and modified cooling rates on color characteristics alteration of monochrome and multilayer high yttrium oxide containing zirconia, J. Clin. Exp. Dent. 16 (2024) e1079–e1091, https://doi.org/10.4317/jced.62066.
[8] M. Shirani, M. Emami, R. Mosharraf, O. Savabi, et al., Comparing the color match of monolithic CAD-CAM dental ceramics with the VITA Classical shade guide, J. Prosthet. Dent. 132 (2024) 605–611, https://doi.org/10.1016/j.prosdent.2022.06.024.
[9] C.M. Kang, T.Y. Peng, Y.A. Wu, C.F. Hsieh, et al., Comparison of optical properties and fracture loads of multilayer monolithic zirconia crowns with different Yttria levels, J. Funct. Biomater. 15 (2024) 228, https://doi.org/10.3390/jfb15080228.
[10] Z. Chen, Y. Zhou, D. Li, M. Zhang, et al., Does the internal surface treatment technique for enhanced bonding affect the color, transparency, and surface roughness of ultra-transparent zirconia? Clin. Oral Investig. 28 (2024) 473, https://doi.org/10.1007/s00784-024-05847-4.
[11] C.M. Kang, W.C. Hsu, M.S. Chen, H.Y. Wu, et al., Fracture characteristics and translucency of multilayer monolithic zirconia crowns of various thicknesses, J. Dent. 145 (2024) 105023, https://doi.org/10.1016/j.jdent.2024.105023.
[12] M.H.A. Abdelhafez, M.R.H. Abu-Eittah, Effect of common staining beverages on color stability of polymer-infiltrated ceramics and extra translucent zirconia: an In vitro study, J. Contemp. Dent. Pract. 25 (2024) 411–416, https://doi.org/10.5005/jp-journals-10024-3679.
[13] F. Yang, L. Zhang, J.Chen M.Yang, et al., The effect of deviations in sintering temperature on the translucency and color of multi-layered zirconia, BMC Oral Health 18 (2024) 471, https://doi.org/10.1186/s12903-024-04243-4.
[14] P. Uasuwan, N. Juntavee, A. Juntavee, Optical characteristics of monochrome and multilayer fully stabilized zirconia upon sintered cooling speed, Eur. J. Dent. 18 (2024) 196–207, https://doi.org/10.1055/s-0043-1764233.
[15] C.M. Kang, Y.W. Huang, S.H. Wu, Y. Mine, et al., Evaluation of shade correspondence between high-translucency pre-colored zirconia and shade tab by considering the influence of cement shade and substrate materials, Heliyon 9 (2023) e23046, https://doi.org/10.1016/j.heliyon.2023.e23046.
[16] G. Alrabeah, N. Alamro, A. Alghamdi, A. Almslam, et al., Influences of luting cement shade on the color of various translucent monolithic zirconia and lithium disilicate ceramics for veneer restorations, J. Adv. Prosthodontics 15 (2023) 238–247, https://doi.org/10.4047/jap.2023.15.5.238.
[17] B.A. Alfahed, A.S. Alayad, Influence of layer and sintering temperature on the optical properties of multilayered Zirconia materials, Eur. J. Prosthodont. Restor. Dent. 31 (2023) 308–320, https://doi.org/10.1922/EJPRD_2508Alfahed12.
[18] S. Miura, A. Shinya, H. Koizumi, M. Fujisawa, Effect of speed sintering of monolithic zirconia with different yttria contents on color and crystal phase, Eur. J. Oral Sci. 130 (2022) e12898, https://doi.org/10.1111/eos.12898.
[19] K. Ueda, J.F. Güth, K. Erdelt, M. Stimmelmayr, et al., Light transmittance by a multi-coloured zirconia material, Dent. Mater. J. 34 (2015) 310–314, https://doi.org/10.4012/dmj.2014-238.
[20] W.C. Hsu, T.Y. Peng, C.M. Kang, F.Y. Chao, et al., Evaluating the effect of different polymer and composite abutments on the color accuracy of multilayer pre-colored Zirconia polycrystal dental prosthesis, Polymers (Basel) 14 (2022) 2325, https://doi.org/10.3390/polym14122325.
[21] S.R. Khosravani, M.A. Kahnamoui, S. Kimyai, E.J. Navimipour, et al., Final colour of ultratranslucent multilayered zirconia veneers, effect of thickness, and resin cement shade, Biomed. Res. Int. 2022 (2022) 2555797, https://doi.org/10.1155/2022/2555797.
[22] M. Kang, T.Y. Peng, H.H. Huang, Effects of thickness of different types of high-translucency monolithic multilayer precolored zirconia on color accuracy: an in vitro study, J. Prosthet. Dent. 126 (2021) 587, https://doi.org/10.1016/j.prosdent.2021.07.011, e1.
[23] Q.N. Sonza, A. Della Bona, O.E. Pecho, M. Borba, Effect of substrate and cement on the final color of zirconia-based all-ceramic crowns, J. Esthet. Restor. Dent. 33 (2021) 891–898, https://doi.org/10.1111/jerd.12632.
[24] M. Shirani, O. Savabi, R. Mosharraf, M. Akhavankhaleghi, et al., Comparison of translucency and opalescence among different dental monolithic ceramics, J. Prosthet. Dent. 126 (2021) 446e1, https://doi.org/10.1016/j.prosdent.2021.04.030. -446.e6.
[25] S. Saker, M. Özcan, Effect of surface finishing and polishing procedures on color properties and translucency of monolithic zirconia restorations at varying thickness, J. Esthet. Restor. Dent. 33 (2021) 953–963, https://doi.org/10.1111/jerd.12681.
[26] X. Li, Q. Wang, X. Qiu, B. Zhao, Effect of different CAD/CAM cutting depths on the post-fatigue load-bearing capacity of novel multilayer zirconia restorations, J. Dent. 111 (2021) 103709, https://doi.org/10.1016/j.jdent.2021.103709.
[27] C.M. Kang, T.Y. Peng, S. Shimoe, Color accuracy of different types of monolithic multilayer precolored zirconia ceramics, J. Prosthet. Dent. 124 (2020) 789.e1–789.e7, https://doi.org/10.1016/j.prosdent.2020.04.026.

[28] W. Al-Zordk, S. Saker, Impact of sintering procedure and clinical adjustment on color stability and translucency of translucent zirconia, J. Prosthet. Dent. 124 (2020) 788.e1–788.e9, https://doi.org/10.1016/j.prosdent.2020.05.024.

[29] M. Michailova, A. Elsayed, G. Fabel, D. Edelhoff, et al., Comparison between novel strength-gradient and color-gradient multilayered zirconia using conventional and high-speed sintering, J. Mech. Behav. Biomed. Mater. 111 (2020) 103977, https://doi.org/10.1016/j.jmbbm.2020.103977.

[30] K. Suputtamongkol, C. Tulapornchai, J. Mamani, W. Kamchatphai, et al., Effect of the shades of background substructures on the overall color of zirconia-based all-ceramic crowns, J. Adv. Prosthodontics 5 (2013) 319–325, https://doi.org/10.4047/jap.2013.5.3.319.

[31] G. Aljanobi, Z.H. Al-Sowygh, The effect of thermocycling on the translucency and color stability of modified glass ceramic and multilayer zirconia materials, Cureus 12 (2020) e6968, https://doi.org/10.7759/cureus.6968.

[32] M. Tejada-Casado, M.M. Pérez, A. Della Bona, H.Lübbe H, et al., Chroma-dependence of CIEDE2000 acceptability thresholds for dentistry, J. Esthet. Restor. Dent. 36 (2024) 469–476, https://doi.org/10.1111/jerd.13153.

[33] R.D. Paravina, M.M. Pérez, R. Ghinea, Acceptability and perceptibility thresholds in dentistry: a comprehensive review of clinical and research applications, J. Esthet. Restor. Dent. 31 (2019) 103–112, https://doi.org/10.1111/jerd.12465.

[34] M. Menini, L. Rivolta, J. Manauta, M. Nuvina, et al., Dental color-matching ability: comparison between visual determination and technology, Dentistry Journal 12 (2024) 284, https://doi.org/10.3390/dj12090284.

[35] R.D. Paravina, R. Ghinea, L.J. Herrera, A.D. Bona, et al., Color difference thresholds in dentistry, J. Esthet. Restor. Dent. 27 (2015) S1–S9, https://doi.org/10.1111/jerd.12149.

[36] O.E. Pecho, R. Ghinea, R. Alessandretti, M.M. Pérez, et al., Visual and instrumental shade matching using CIELAB and CIEDE2000 color difference formulas, Dent. Mater. 32 (2016) 82–92, https://doi.org/10.1016/j.dental.2015.10.015.

[37] C. Gómez-Polo, M. Portillo Muñoz, M.C. Lorenzo Luengo, P. Vicente, et al., Comparison of two color-difference formulas using the Bland-Altman approach based on natural tooth color space, J. Prosthet. Dent. 115 (2016) 482–488, https://doi.org/10.1016/j.prosdent.2015.07.013.

[38] J.A. Medeiros, O.E. Pecho, M.M. Pérez, F. Carrillo-Pérez, et al., Influence of background color on color perception in dentistry, J. Dent. 108 (2021) 103640, https://doi.org/10.1016/j.jdent.2021.103640.

[39] H.K. Kim, S.H. Kim, Optical properties of pre-colored dental monolithic zirconia ceramics, J. Dent. 55 (2016) 75–81, https://doi.org/10.1016/j.jdent.2016.10.001.

[40] N.K. Yu, M.G. Park, Effect of different coloring liquids on the flexural strength of multilayered zirconia, J. Adv. Prosthodontics 11 (2019) 209–214, https://doi.org/10.4047/jap.2019.11.4.209.

[41] L. Shamseddine, Z. Majzoub, Relative translucency of a multilayered ultratranslucent zirconia material, J. Contempor. Dental Practice 18 (2017) 1099–1106, https://doi.org/10.5005/jp-journals-10024-2183.

[42] A. Della Bona, O.E. Pecho, R. Ghinea, J.C. Cardona, M.M. Pérez, Colour parameters and shade correspondence of CAD-CAM ceramic systems, J. Dent. 43 (6) (2015) 726–734, https://doi.org/10.1016/j.jdent.2015.02.015. JunEpub 2015 Mar 6. PMID: 25748670.