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Color Evaluation of Pre-Shaded Monolithic Zirconia Restorations on Different Substrates and Resin Cements

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Abstract: This study evaluated if the material, the substrate, and the cement have no influence on the color of pre-shaded monolithic zirconia crowns. The specific effect of the cement over each substrate/brand group was also studied. Two commercial brands of zirconia, Amann Girrbach (AG) and Zirkonzahn (ZZ), were used to produce crowns that were placed over three substrates (natural tooth, zirconia, metal) using two different resin cements (Ivoclar AG (Shaan, Liechtenstein) Neutral and Light) or glycerol (as the control) ($n = 10$). Lightness (L*), chroma (C*), hue (h*), and color difference (ΔE) of each crown were measured using a VITA Easyshade V® spectrophotometer (VITA Zahnfabrik, Bad Säckingen, Germany), following the standardized reference. Since normality was not verified by the Shapiro–Wilk test, data were statistically analyzed using the Kruskal–Wallis test for group comparisons and Tukey's post-hoc test for multifactorial variance analysis ($\alpha = 0.05$). ΔE medians ranged between 1.3 in the AG/zirconia substrate/glycerol group and 8.0 in the ZZ/metal substrate/light cement group. In general, lower values of ΔE were recorded in AG restorations compared to ZZ ($p < 0.05$), zirconia, and natural tooth substrates compared to metal ($p < 0.001$) and neutral compared to light cements ($p < 0.05$). Specifically, over the metal substrate, AG crowns with neutral cement and ZZ crowns with neutral cement and glycerol showed lower ΔE values ($p < 0.05$). Over the zirconia substrate, light cement presented higher ΔE values than glycerol in both brands but similar to neutral cement. Over the natural tooth, no significant differences were observed between cements ($p > 0.05$) in the AG brand, while in the ZZ group, light cement showed higher ΔE values ($p < 0.05$). The final color of the restorations was significantly influenced by the zirconia brand, substrate type, and resin cement. Light cement led to greater color variations, particularly in ZZ restorations. These findings highlight the importance of material selection in achieving esthetically pleasing zirconia restorations.

Keywords: color measurement; zirconia; resin cements; substrates

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1. Introduction

Esthetic considerations have long influenced the development of restorative materials that closely mimic the optical properties of natural teeth. Traditional feldspathic ceramics were among the first materials used for this purpose. However, their limited mechanical strength restricted their use as stand-alone restorations, necessitating their combination with metal frameworks to improve durability. As a result, extensive research has been dedicated to enhancing the bond between veneering ceramics and the metal alloys used in these substructures [1,2].

Metal–ceramic restorations have been widely used in fixed prosthodontics for several decades, offering a reliable combination of mechanical strength and long-term durability. However, the presence of metal can hinder light transmission, leading to a less natural, opaque appearance. Moreover, the visibility of the metallic margin—especially through translucent surrounding tissues—poses a significant esthetic limitation [3,4].

Technological advancements have brought substantial progress, particularly with the introduction of CAD–CAM (computer-aided design and computer-aided manufacturing) ceramic restorations in the late 1980s. This innovation enabled the standardization of material quality, reduced production costs, and improved predictability throughout the manufacturing process. In the 1990s, yttria-stabilized zirconia ceramics were introduced, offering excellent mechanical properties and biocompatibility. However, their inherently opaque, whitish appearance presented an esthetic challenge, necessitating the application of a veneering ceramic layer. Despite enhancing esthetics, this veneering layer is prone to chipping, characterized by fractures in the outer ceramic that expose the underlying zirconia core, which typically remains intact [5,6].

To address this limitation, monolithic zirconia restorations were developed. Composed of highly crystalline ceramics, these materials exhibit reduced translucency, which can compromise esthetic outcomes. Nevertheless, their high flexural strength makes them well-suited for use in posterior regions, where mechanical performance is prioritized over esthetic considerations [7,8].

Pre-colored zirconia ceramics have been introduced to offer a combination of high mechanical strength and enhanced esthetics. Their increased translucency enables their application in both anterior and posterior restorations. A major advantage of these materials lies in the consistent color achieved during manufacturing, eliminating the variability associated with conventional infiltration or staining techniques, which are highly operator-dependent. Studies, such as that by Kim et al. [9], have demonstrated that applying metallic oxides to sintered zirconia results in weak adhesion between the pigment and the zirconia surface. Additionally, the immersion technique can produce uneven coloration due to the limited penetration of metal ions.

Color perception can be evaluated qualitatively through subjective visual comparison or quantitatively using electronic measurement devices. Portable spectrophotometers Vita Easyshade® Compact V are widely used for shade-matching research, and shade measurement reliability and accuracy have been supported by several studies. Measures of tooth or restoration color and color differences (ΔE) can be made, allowing researchers to establish perceptibility and acceptability thresholds [10–15].

In color science, color differences are measured using the ΔE formula, giving a quantitative representation of the perceived difference between paired colored specimens measured under set experimental conditions. The smallest perceptible color difference or perceptibility threshold refers to the smallest color difference detected by the human eye, while the highest acceptable or acceptability threshold refers to the largest color difference accepted by 50% of the observers as an imperceptible color difference [12].

In this context, the present study aimed to evaluate the influence of different substrates (dentin, zirconia, and CoCr alloy) and cements (neutral and light) on the final color of pre-shaded zirconia ceramics from two different commercial brands. Unlike previous research, which often examined these factors individually in standardized specimens, this study innovates by analyzing the combined interaction between the restorative material, the substrate, and the cement, providing a more comprehensive understanding of the elements affecting the final esthetic outcome of ceramic crowns. Additionally, by incorporating two distinct commercial brands of pre-shaded zirconia, this study enables a comparison between different industrial formulations, offering valuable insights for optimizing currently available materials. The use of quantitative color analysis through electronic measuring devices adds objectivity to the research, minimizing the subjectivity of traditional visual evaluations. Ultimately, by investigating new approaches to enhance the predictability of esthetic outcomes, the findings of this study may contribute to the development of more effective clinical protocols and color prediction algorithms [14], aiding dentists and dental technicians in selecting the most suitable materials for each clinical case. The null hypotheses were that neither the crown brand nor the substrate nor the cement has an influence on the final color of pre-shaded zirconia restorations. In addition, for helping in the clinical decision of what cement to use with specific brand/substrate combinations, an additional null hypothesis was added that stated that the type of cement has no effect on the color of each substrate/brand group.

2. Materials and Methods

A power analysis was performed to estimate the sample size (n = 10) required to provide statistical significance ($\alpha = 0.05$) at 80% power and an effect size of 0.25, based on a previous pilot study.

2.1. Fabrication of the Three Substrates

2.1.1. Natural Tooth Substrate

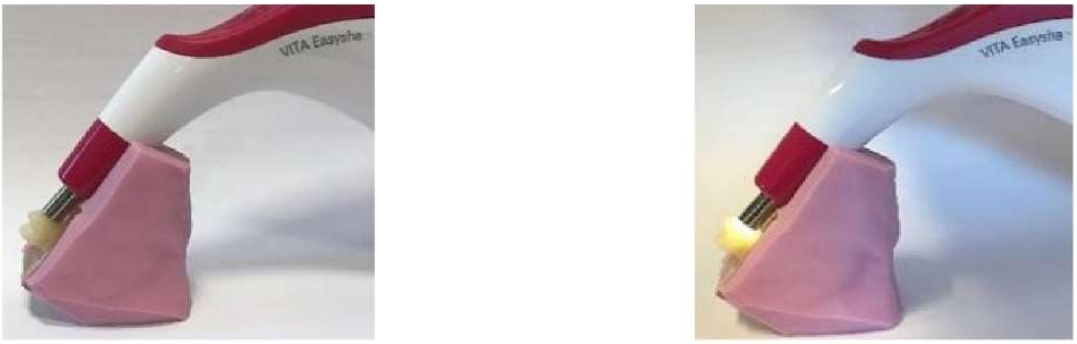
For the fabrication of the natural tooth substrate, a sound premolar tooth, previously extracted for orthodontic treatment reasons, was selected. The study protocol was reviewed and approved by the Ethics Committee for Life of the Faculty of Lisbon, Universidade de Lisboa. The donation of the tooth for research purposes was possible after the donor provided informed consent.

The tooth was positioned within a transparent acrylic cube, leaving the coronal portion exposed, ensuring a stable and suitable support (Figure 1).

(a) (b) (c)

Figure 1. Placement of the premolar tooth in a transparent acrylic block, ensuring proper support and exposure of the coronal area: (**a**) lateral view, (**b**) top view, (**c**) frontal view.

To ensure a consistent positioning for color measurement of the coronal surface, a pink silicone key was created, allowing a VITA Easyshade® V (VITA Zahnfabrik, Bad Säckingen, Germany) spectrophotometer to be placed in the same position for each measurement. This ensured that all measurements were taken in the middle third of the buccal surface of the tooth (Figure 2).



(a) (b)

Figure 2. Creation of a pink silicone key and placement of the Easyshade V spectrophotometer to ensure all measurements were consistently taken in the middle third of the buccal surface of the tooth. (**a**) Position; (**b**) reading.

Three consecutive tooth color measurements were performed using the VITA Easyshade® V (VITA Zahnfabrik, Bad Säckingen, Germany) in the Natural Tooth Shade Determination program. The closest color obtained was A2, corresponding to the VITAPAN Classical shade guide (Figure 3).

Figure 3. Determination of the tooth color (VITA A2) upon selection on the menu of the equipment and after three consecutive color measurements performed with the Easyshade V spectrophotometer.

To preserve and reproduce the tooth shape, the acrylic block was placed in a S600 Arti Scanner (Zirkonzahn, Gais, Italy) and the premolar tooth was scanned using the Zirkonzahn Modellier software version 9530, generating the first STL file (STL1) (Figure 4).

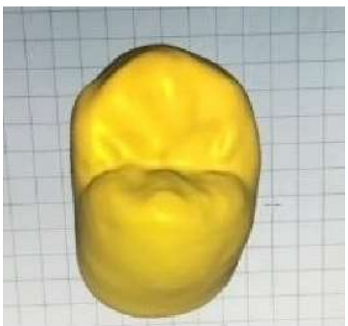


Figure 4. Digitization of the premolar tooth using the S6000 Arti scanner and the Zirkonzahn Modellier software.

Tooth preparation was guided using a silicone matrix to control a homothetic 1.5 mm thickness across all surfaces of the crown (Figure 5).

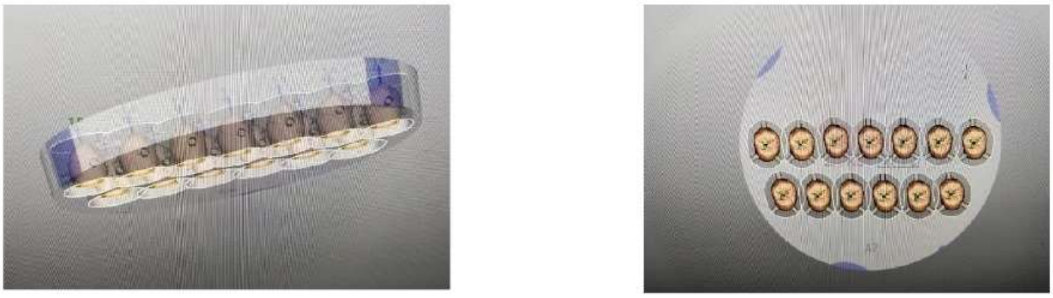
(a) (b) (c)

Figure 5. Preparation performed on the premolar tooth: (**a**) lateral view, (**b**) top view, (**c**) front view.

After tooth preparation, a new scanning of the prepared tooth was performed, generating the second STL file (STL2).

Considering the previously identified tooth shade (VITA A2), pre-shaded zirconia blocks from two commercial brands with different formulations were selected: Amann Girrbach (AG, Maeder, Austria)—Ceramill Zolid HT+ Preshades (98 mm in diameter, 14 mm in height, batch 190006); and Zirkonzahn (ZZ, Gais, Italy)—Anatomic Coloured zirconia (95 mm in diameter, 12 mm in height, batch ZB7173C).

STL 1 and STL 2 files were processed in each brand's software, and 10 crowns were milled using a Ceramill Motion 2 milling machine (AG, Maeder, Austria); another 10 crowns were milled using an M1 Heavy Metal milling machine (ZZ, Gais, Italy) (Figure 6).



(a) (b)

Figure 6. Placement and positioning of crowns on the AG zirconia block used: (**a**) perspective view, (**b**) top view.

The sintering cycles for the zirconia crowns were used according to the manufacturers' recommendations: for the AG brand, the crowns underwent a 10-h sintering process, reaching a maximum temperature of 1450 °C, and for the ZZ brand, the sintering cycle lasted 8 h, with a maximum temperature of 1500 °C.

2.1.2. Metal/Zirconia Substrates

For the fabrication of the other two substrates, STL2 was used to mill two replicas. The first, designed to simulate the characteristics of a zirconia abutment, was milled in zirconia Ceramill Zirconia (batch 160007, Amann Girrbach, Maeder, Austria), and the second, simulating a Co–Cr abutment, was milled in Ceramill Sintron (batch 180004, Amann Girrbach, Maeder, Austria) (Figure 7).

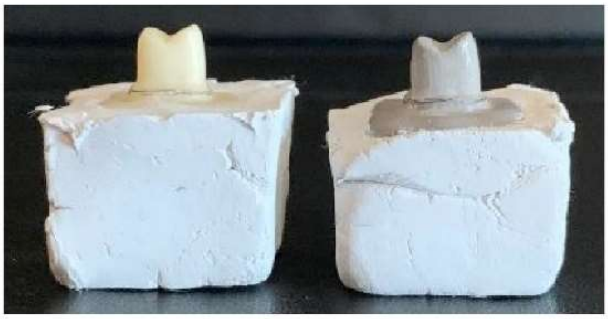


Figure 7. Photograph of the two obtained substrates (zirconia, metal), which are faithful replicas of the preparation performed on the natural tooth.

2.2. Resin Cements

The substrate was cleansed with steam water before placement of each crown. Two different try-in pastes from Ivoclar AG (Shaan, Liechtenstein) were used: Variolink Esthetic Neutral, with translucency of ca. 17% (batch Y07845), and Variolink Esthetic Light, with translucency of ca. 12% (batch X55680) (Figure 8). Glycerol was used as a control that does not alter the color of the crown.

Figure 8. Try-in resin cement pastes from Ivoclar used in this laboratory study.

2.3. Crown Finishing

Crowns were glazed separately using Zirkonzahn glaze paste and the oven P500 (Ivoclar Vivadent, Shaan, Liechtenstein) (Figures 9 and 10). Finally, restorations were numerically ordered from 1 to 10 (Figure 11).

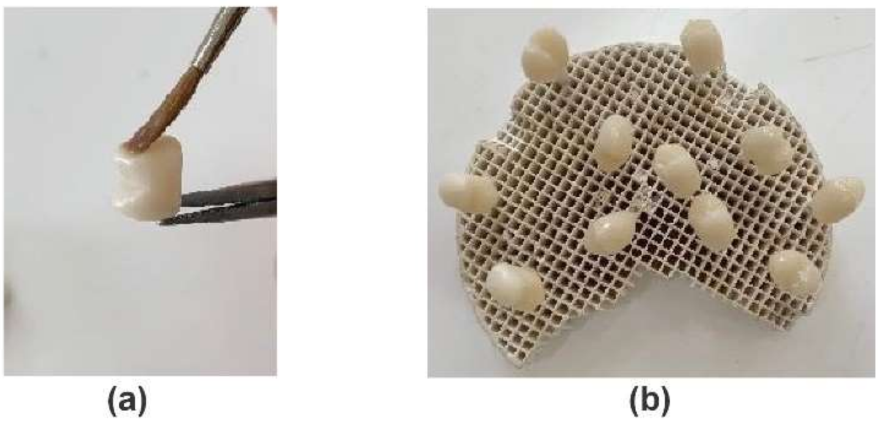


Figure 9. Application of glaze (**a**) to the brand group (**b**).

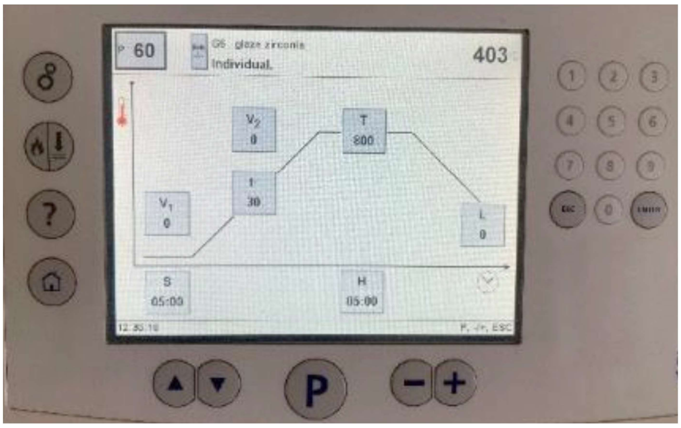


Figure 10. Glaze sintering program.

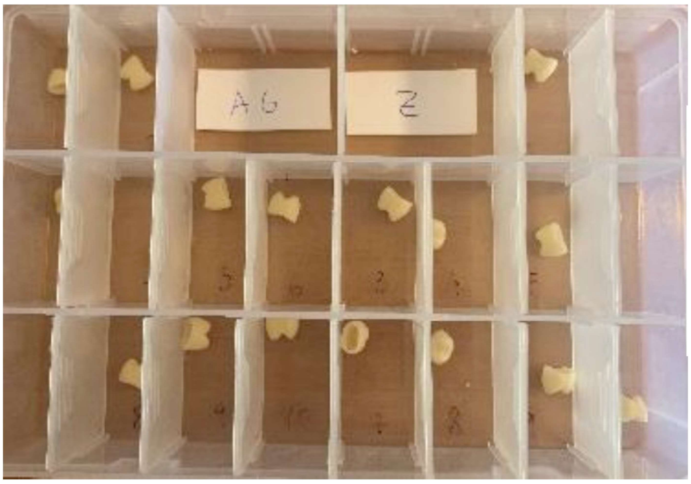


Figure 11. Numbering of the crowns according to the brand.

2.4. Color Measurement

In this study, color measurements were performed using a VITA Easyshade® V spectrophotometer (serial number H50953, version V507d; VITA Zahnfabrik, Bad Säckingen, Germany). This device is equipped with a standard D65 light source (daylight) and is calibrated using white balance. The Dental Restoration Measurement mode was selected on the device, with A2 as the reference color. The zirconia crowns were placed over the natural tooth substrate, using glycerol as a cement and having digital pressure applied. The device was positioned in the holder to ensure color measurement in the middle third of the restoration, recording values for lightness (L*), chroma (C*), hue (h*), and ΔE. Five measurements were taken for each specimen, and the mean for each parameter was calculated. After readings, the crowns were cleaned using a cotton swab moistened with ethyl alcohol, dried with air, and the entire process was repeated for the zirconia and metal substrates. The ΔE values were obtained sequentially, corresponding to the numbering of the crowns. For the light and neutral try-in resin cement pastes, a similar procedure was used, applying it between the restoration and the substrate.

2.5. Statistical Analysis

SPSS software for MacBook, version 25.0 (INC, Chicago, IL, USA), was used for statistical analysis. Descriptive statistics were performed on the ΔE results for each experimental group.

The normality of the sample distribution was assessed using the Shapiro–Wilk test. Since the sample did not follow a normal distribution for ΔE results, the non-parametric

Kruskal–Wallis test was applied for comparisons within each variable under study (zirconia brand, substrate type, and cement type) and within the zirconia brand/substrate combinations, followed by multiple comparisons with Mann–Whitney tests with Bonferroni corrections. For all statistical tests, a significance level of 0.05 was set.

3. Results

3.1. Analysis of ΔE Values

Descriptive Statistics

The descriptive statistics related to the ΔE results are presented in Table 1.

Table 1. Mean (M) values, standard deviations (SD), medians (Mdn), and interquartile ranges (IR) of color differences (ΔE) for each experimental group.

Zirconia Brand	Substrate	Cement	ΔE				
			M	SD	Mdn	IR	Group Differences
Amann Girrbach (AG)	Metal	Glycerol	7.1	0.30	7.0	7.00	b
		Light	7.1	0.20	7.1	7.55	b
		Neutral	5.8	0.30	5.8	5.75	a
	Zirconia	Glycerol	1.3	0.10	1.3	1.30	a
		Light	1.9	0.10	1.9	1.95	b
		Neutral	1.7	0.10	1.8	1.65	a, b
	Tooth	Glycerol	2.1	0.20	2.1	1.80	a
		Light	1.9	0.10	1.9	1.85	a
		Neutral	2.5	0.20	2.5	2.20	a
Zirkonzahn (ZZ)	Metal	Glycerol	4.5	0.20	4.5	4.50	a
		Light	8.0	0.60	8.0	7.90	b
		Neutral	3.8	0.10	3.8	3.90	a
	Zirconia	Glycerol	3.7	0.10	3.7	3.60	a
		Light	4.6	0.10	4.7	4.60	b
		Neutral	4.1	0.20	4.1	4.40	a, b
	Tooth	Glycerol	4.1	0.10	4.1	4.00	a
		Light	5.6	0.20	5.6	5.65	b
		Neutral	3.5	0.10	3.5	3.45	a

Identical letters represent no significant differences between cements in each brand/substrate combination ($p > 0.05$).

The highest median value found was 8, corresponding to ZZ zirconia using the metal substrate and light cement. The lowest median value was 1.3 in the AG brand, with zirconia as the substrate and glycerol as the cement (Table 1).

The ΔE values were significantly influenced ($p < 0.05$) by the type of restoration, substrate, and cement.

Statistically significant differences ($p = 0.035$) were found in the ΔE values obtained for the two zirconia brands under study, with the lower median values recorded for the AG brand (2.1) compared to ZZ (4.2) (Figure 12).

Regarding the ΔE values obtained for the different substrates under study, statistically significant higher levels of ΔE ($p < 0.05$) were observed in metal compared to zirconia ($p < 0.001$) or natural teeth ($p < 0.001$), but no significant differences were found between the last two ($p = 0.933$). The lowest median value recorded was 2.65 for the zirconia substrate, while the highest was 6.00 for the metal substrate (Figure 13).

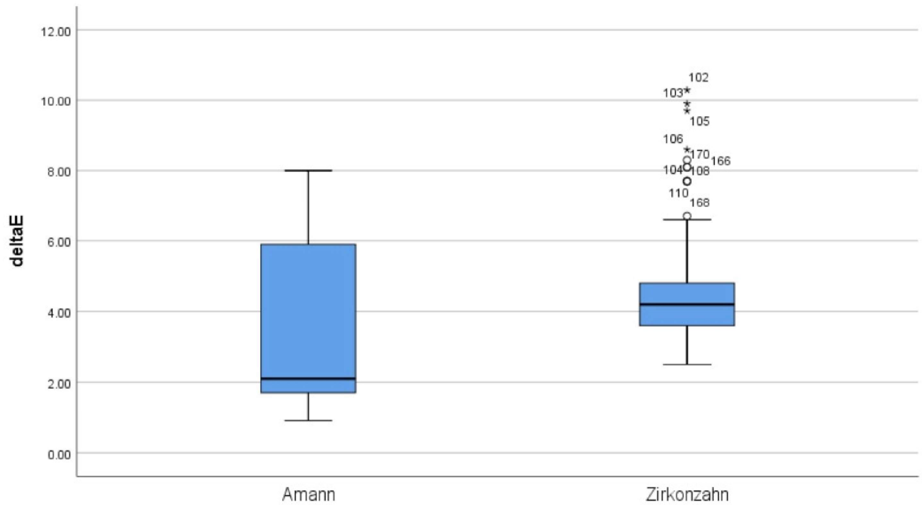


Figure 12. Box plots of the ΔE values acquired from the two zirconia brands used (p = 0.035) (* and circles represent outliers).

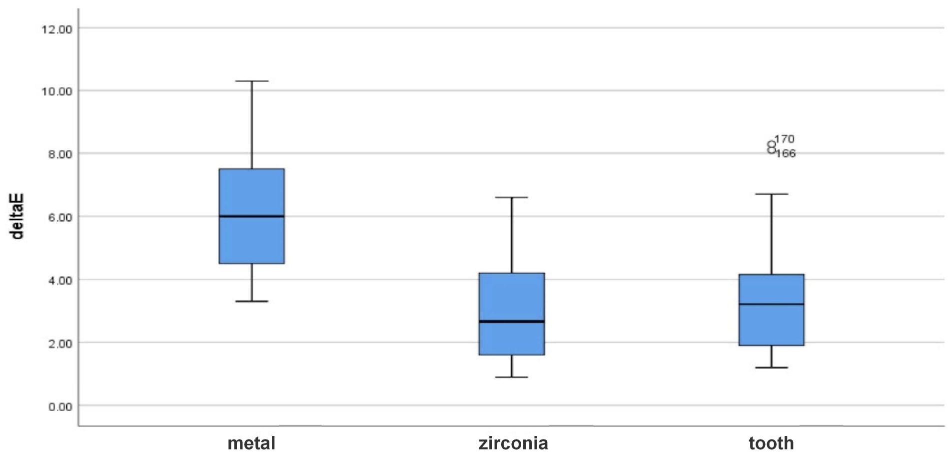


Figure 13. Box plots of the ΔE values related to the three substrates used (metal vs. zirconia, metal vs. natural tooth; p < 0.001; zirconia vs. tooth: p = 0.933) (circles represent outliers).

Statistically significant differences (p < 0.05) were also observed in the ΔE values obtained for the studied cements. However, no significant differences were found between glycerol and light cement (p = 0.072) or neutral cement (p = 1.000). Statistically significant lower levels of ΔE values were detected in neutral compared to light cements (p = 0.032). The lowest median value recorded was 3.65 for neutral cement, while the highest was 4.60 for light cement (Figure 14).

For brand AG and the metal substrate, statistically significant lower levels of ΔE (p < 0.05) were detected using neutral cement compared to both light cement and glycerol, whereas they did not show significant differences between them (p > 0.05) (Table 1).

Regarding the ZZ brand restorations and the metal substrate, statistically significantly higher levels of ΔE (p < 0.05) were found using light cement compared to both neutral cement and glycerol, while no significant differences were observed between them (p > 0.05) (Table 1).

For the zirconia substrate, both in the AG and ZZ brands, statistically significantly lower levels of ΔE (p < 0.05) were shown using glycerol compared to light cement (p < 0.05), but no differences were observed in comparison to neutral cement (p > 0.05) (Table 1).

For brand AG and the natural tooth substrate, no statistically significant differences (p > 0.05) were found between the two cements and glycerol. However, for brand ZZ, statistically significant higher levels of ΔE (p < 0.05) were observed in light cement compared to neutral cement and glycerol, while no significant differences were detected between them ($p > 0.05$) (Table 1).

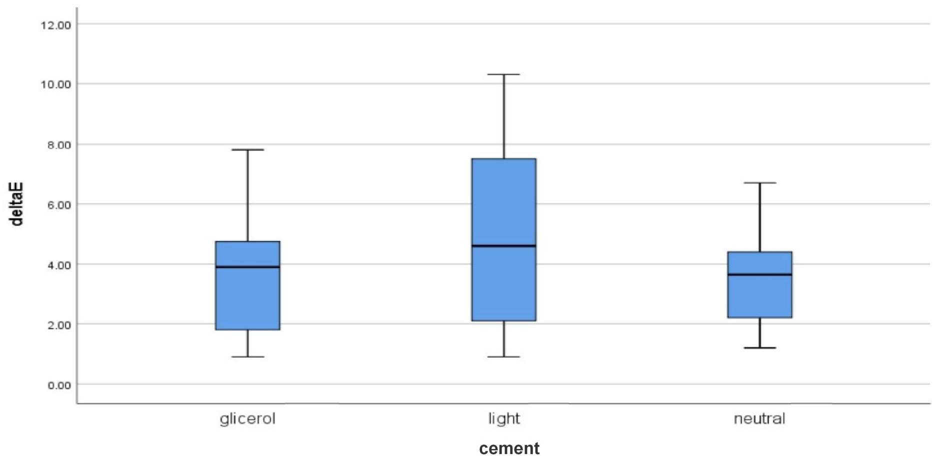


Figure 14. Box plots of the ΔE values related to glycerol and the two cements used (glycerol vs. light, $p = 0.072$; glycerol vs. neutral, $p = 1.000$; neutral vs. light, $p = 0.032$).

4. Discussion

The study of color is fundamental in dental esthetics as the shade of a restoration is often one of the most critical factors influencing a patient's perception of its quality. Consequently, a comprehensive understanding of tooth color, restorative materials, and the dental cements used in clinical practice is essential for achieving optimal esthetic outcomes [15].

Although zirconia ceramics are widely available, pre-colored zirconia represents a more streamlined option; however, it remains relatively underexplored in the literature. Therefore, the aim of this study was to evaluate the color outcomes of restorations fabricated from pre-colored zirconia provided by two commercial brands, applied over three different substrate types using two distinct resin cements. According to studies by Tabatabaiam [16] and Gdoshi et al. [17], the final color of restorations is influenced by ceramic thickness, the translucency level of zirconia, the type of cement, and the underlying substrate [16–18]. To minimize the influence of variables such as differences in testing methods or material composition on the final restoration color, this study utilized pre-colored zirconia blocks from two distinct commercial brands. This approach ensured that the restoration color remained independent of operator technique. Furthermore, all color measurements were performed under consistent conditions—at the same location and with standardized illumination, despite the manufacturer's claims that ambient light does not affect the final color of a restoration [19].

To simulate various clinical scenarios, three substrate types were selected: metal and white zirconia, representing post-core rehabilitations and abutments for implant-supported restorations, and enamel/dentin, simulating a natural tooth preparation for a full monolithic crown. The results demonstrated that the ΔE values were significantly influenced by the substrate, cement, and ceramic brand, thus rejecting the null hypotheses initially proposed. Although the relationship between thickness and translucency is perceptible, there is limited information regarding the translucency of different types of zirconia when prepared at clinically required thicknesses, especially for pre-shaded materials, making it difficult to select an appropriate thickness for a specific abutment color [13,20].

In this study, the tested samples were produced with a uniform thickness of 1.5 mm, simulating the average thickness of a crown-type restoration determined in another study [11]. With a higher thickness for a monolithic restoration, the influence of the substrate was expected to be null. However, even though the restorations had a constant thickness and a standardized A2 color, the obtained ΔE values varied among the different substrates. Only the AG crowns over the zirconia substrate with interposed glycerol had an acceptable result (ΔE = 1.35), close to imperceptibility and well below the clinical acceptability threshold limits [12]. Several in vivo tests detected the mean values of $\Delta E^*_{ab} = 1.6$ for a color match between a natural tooth and an all-ceramic restoration and $\Delta E^*_{ab} < 3.7$ as the most commonly used for the clinical acceptability threshold.

The reference color used in this study for the brand materials was VITA A2, where the spectrophotometer analyzes color based on the VITA scale. However, there is a known lack of consistency between different ceramic material brands and shade guides [21]. Because the zirconia blocks used were not manufactured by VITA, the use of equipment based on VITA original colors may have influenced the study results. Nevertheless, the VITA shade guide remains the gold standard for color selection in dentistry, and companies should be consistent when using it for their color notation.

The market offers various pre-colored monolithic zirconia shades, most of which align with the VITA Classical scale. According to Alghazzawi et al. [22], color differences have been reported among different zirconia materials, as they exhibit slight dimensional and structural variations at the grain level, affecting light absorption and scattering properties. These variations, specific to the individual commercial formulation of each brand, may explain the observed differences [17,22].

The two tested zirconia brands showed statistically significant differences, with the AG brand exhibiting lower ΔE values. This difference could be attributed to two main factors: differences in the composition and variations in the manufacturer's coloring procedures.

Regarding the composition, information is not disclosed by either manufacturer on their commercial websites or in brochures in the material packaging. However, small differences in yttrium and/or alumina content or even in the size of particles may be responsible for small changes in the optical behavior of zirconia [23]. The reduction of alumina content from 0.25 to 0.05 wt% is responsible for increasing translucency of the second generation of 3Y zirconia, and its content is approximately >70% of tetragonal and <30% of cubic zirconia, depending on the sintering temperature. This information was not disclosed by the manufacturers to allow for a better interpretation of material behavior [24]. In terms of zirconia coloring, only the ZZ brand provides details on how the material is colored to achieve the desired shade. Coloring substances are added to the zirconia powder during the early production stages, ensuring a more homogeneous and uniform coloration throughout the material. Zirkonzahn also states that manual coloring is becoming obsolete, and this type of pre-colored zirconia aims to increase production efficiency while eliminating shade variations caused by different dental laboratory techniques, thus improving the reliability of the manufacturing process.

Regarding sintering temperatures, these play a crucial role in defining the ceramic's properties, as they directly affect microstructure and crystalline phase formation [25]. In this study, the sintering cycles differed between the two zirconia brands, but were made according to the manufacturers' instructions. Both manufacturers have sintering furnaces with pre-programmed cycles that cannot be altered by the user. For the AG brand, the cycle was longer (10 h) but at a lower final temperature (1450 °C), whereas for the ZZ brand, the cycle was shorter (8 h) but reached a higher maximum temperature (1500 °C). However, there is disagreement in the literature regarding the effects of sintering temperature. Ebeid et al. [26] suggested that higher sintering temperatures and longer sintering times enhance translucency, improving light transmission, as there is a direct correlation between temperature increase and grain size [26]. On the other hand, studies by Stawarczyk et al. [27] and Jiang et al. [25] contradict this assumption, reporting that higher sintering temperatures resulted in larger grains, which are generally associated with lower translucency [25,27].

The results obtained in this study support Ebeid's findings, as the ZZ zirconia, which underwent higher sintering temperatures, exhibited higher ΔE values. Higher sintering temperatures enhance translucency; however, increased translucency also results in a higher influence of the underlying substrate.

In a restoration, one of the final steps in the dental laboratory is glazing and/or polishing. These procedures can alter the optical properties of the ceramic, as they affect surface gloss, roughness, and brightness [16]. According to Kim et al. [9], in terms of translucency, no significant difference was observed between polishing and glazing, as the color difference remained below the perceptibility threshold, with both processes leading to a reduction in L* values. Conversely, Lee et al. [28] observed that color changes in zirconia restorations caused by glazing were greater than those induced by polishing. However, in monolithic restorations, glazing is generally recommended to avoid the need for additional adjustments using rotary instruments [16].

According to the literature, a substrate such as a natural dental core can affect the color of a restoration, especially when a translucent restorative material is used, introducing significant esthetic limitations. The impact of the substrate on color depends on the intensity and amount of light transmission through the ceramic material [29,30]. In this case, and based on the obtained results, the metal substrate showed ΔE values that differed from those of the other substrates, which aligns with findings in the literature. As an alternative to metal substrates, zirconia substrates are available [31]. In this study, the zirconia substrate displayed ΔE values similar to those of the natural tooth substrate.

In the present study, two resin cements were selected, both from Ivoclar (Liechtenstein). According to the company brochure available on the website, the Light cement has a lower translucency of 12%, compared to the Neutral cement that exhibits 17%, and its effect on a restoration or crown is to "slightly lighten" the final shade. The manufacturer recommends using non-polymerizable try-in pastes to better assess the final result.

In this study, statistical analysis showed that the ZZ crowns' ΔE values were higher when the Light cement was used, regardless of the substrate. This suggests that, because this zirconia is more translucent, and the cement try-in is also more translucent (12%) when compared to the Neutral cement (17%), it is more affected by the cement, resulting in a final restoration color that deviated further from the intended A2 shade, leading to increased ΔE values. Conversely, for the AG crowns, no direct relationship was observed with any of the cements used. Specifically, for the metal substrate, the highest ΔE value was obtained when glycerol was placed between the restoration and the substrate, whereas no significant differences were observed for the natural tooth substrate. Clinically, the use of a more translucent zirconia should be taken with caution since it has a greater potential to be affected by the background substrate and also the cement color, increasing ΔE values. In implant cases, using zirconia abutments is advisable when possible instead of using metallic abutments since they lower ΔE values.

Caution regarding the assumption of these results should be taken, since the literature also shows that the final color of cemented crowns can be slightly different from the observed results when using try-in pastes [32]. Even considering the risk of small differences in results, the use of try-in pastes is meaningful in clinical and research settings as it allows trying different conditions without compromising the tooth integrity. In an in vitro setup, such as the one used for this research, using twenty different teeth with the same shape and color would be nearly impossible.

According to the literature, resin cements can influence the final color of feldspathic ceramics and lithium disilicate ceramics due to their high translucency. However, in zirconia ceramics, despite their lower translucency, the effect of the cement on the final color can still occur, as it depends on the type of zirconia used [16,33]. Not all authors agree on the influence of cement on the color of restorations. In the in vivo study of Ayash et al. [34], two different cements were used with monolithic and layered zirconia restorations and no influence of cement was observed in contrast with other studies that reported an influence of the cement when restoration thickness decreased from 2 mm to 1.5 mm in thickness, but using IPS-Empress glass ceramic [20]. The present study confirmed that in pre-colored zirconia ceramics of 1.5 mm thickness, the cements used influenced the final color of the restorations, as the ΔE values varied depending on the color of the cement. Using two different cements with a 5% difference in translucency, according to the manufacturers' information, allowed confirmation that even slight differences in the color of the cement may have an impact on the final color of the restoration. This should be taken into consideration in cases with discolored crown areas to be covered by a restoration. Nevertheless, differences in cement thickness (0.1 or 0.2 mm) may also slightly affect the final color of monolithic ceramic crowns. However, since cement thickness cannot be completely controlled by clinicians, it should not be considered a reliable method for color correction [16].

According to Paravina et al., the perceptibility threshold is $\leq$1.2 [35]. In this study, all ΔE values exceeded this threshold, and the only brand considered acceptable, as it fell within the acceptability range (>1.3 and $\leq$2.7), was AG, specifically for zirconia on natural tooth substrates, regardless of the cement used.

Although pre-colored zirconia restorations are expected to facilitate the achievement of the desired tooth shade, as the color is standardized, further research is needed on these zirconia materials, given the limited literature available on the subject.

According to the literature, systematic errors in color-measuring devices are difficult to control and can affect their accuracy [21]. During the study, after multiple consecutive color readings, the VITA Easyshade spectrophotometer displayed excessively high ΔE values, not consistent with previous results. This required some additional measurements, repeated multiple times. To minimize this issue, the number of consecutive measurements was limited to 3 consecutive measurements per crown.

Limitations of the present study can be identified since a limited sample size was used. The number of crowns used in each zirconia disk limited our sample size since disks can vary in intrinsic color, and the purpose was to eliminate every factor that could add differences in color measurements.

Color evaluation can be very sensitive to extrinsic factors, such as room light and tip inclination, and easily cause dispersion of the results. The authors tried to limit this factor by adding a pink silicone key that limited variations of tip inclination in each reading. Clinical factors such as tooth coloration, different cements, and various brands of zirconia ceramics can affect the final color of a restoration [16]. Therefore, future research on pre-colored zirconia should explore additional aspects, including increasing the number of commercial brands studied, testing different restoration thicknesses, and incorporating additional brand shade guides.

Additionally, it would be valuable to compare these results using resin cements with different opacities (try-in cements), as these factors could influence the outcomes observed in this study. Other potential research directions include measuring color across different thirds of the tooth and comparing the values, as well as analyzing the L*, C*, and h* values independently to better understand the factors that most influenced the results.

Given the limited research on pre-colored zirconia ceramics, further studies should explore factors such as higher sample sizes, different thicknesses of crowns, additional commercial brands, and variations in cement opacity. A deeper understanding of these interactions will lead to more predictable color outcomes and improved esthetic integration of zirconia restorations in clinical practice.

5. Conclusions

The choice of a ceramic system is crucial to the esthetic outcome of restorations and their seamless integration into the oral environment, especially when substrates different from natural tooth color are used.

Despite the limitations of this in vitro study based on a single tooth experiment, it can be concluded that:

– The ZZ zirconia crowns exhibited greater color changes than the AG restorations.
– Zirconia crowns placed over metal substrates revealed higher color differences than the reference color.
– In general, zirconia crowns cemented with the neutral cement led to fewer color differences than when the light cement was used.
– Both light and neutral cement influenced the AG and ZZ crowns over the zirconia substrate.
– Both light and neutral cement influenced AG over the natural tooth substrate.
– The neutral cement had the least impact when applied over a metal substrate for the AG crowns or over natural tooth substrates for the ZZ crowns.
– Higher sintering temperatures can enhance translucency but may also increase the restoration's sensitivity to underlying substrates, potentially leading to greater color deviations.

Potential bias could occur when different crown thicknesses and different tooth preparations are made on different morphological teeth to be restored. To avoid those problems, tooth preparation and crown thicknesses were standardized through the same tooth sample, and equivalent tooth materials from different brands were used. This study should be replicated by varying each of the variables at a different time to confirm the results obtained with an upper first premolar and understand if conclusions can be generalized to other teeth in the mouth.

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Abbreviations

The following abbreviations are used in this manuscript:

L*	Lightness
C*	Chroma
h*	Hue
ΔE	Color difference
AG	Amann Girrbach
ZZ	Zirkonzahn
CAD–CAM	Computer-aided design–computer-aided manufacturing

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