Research Article

Engin Kariper, and Aylin Cilingir*

Evaluation of color matching of three single-shade composites employing simulated 3D printed cavities with different thicknesses using CIELAB and CIEDE2000 color difference formulae

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Abstract: This study assessed the color-matching capability of three single-shade composites that employ simulated resin 3D-printed cavities with different cavity depths using CIELAB and CIEDE2000 formulas. A cylindrical model with standardized cavities was generated. One hundred and fifty blank specimens were fabricated and divided into three groups (n = 50) and then into five subgroups. The five subgroups included four groups of specimens with 0.5, 1, 2, and 4 mm cavities and a control group of specimens without cavities (n = 10). Cavities were filled with Vittra Unique (VU), Omnichroma (OC), and OptiShade (OS). Color measurements were done using a clinical spectrophotometer. The color differences for all composites were calculated as ΔE and ΔE_{00} using CIELAB coordinates. The color parameter data were analyzed (α = 0.05). OS had significantly lower ΔE and ΔE_{00} values than the other composites for all layer thicknesses ($p < 0.05$). VU, OC, and OS had the lowest ΔE and ΔE_{00} values at 0.5 mm ($p < 0.05$). Color matching of monochromatic composites decreased as the layer thickness increased. OS achieved the best color matching in this study. Single-shade composites are important for reducing chairside time and gaining confidence in clinical practice. CIELAB and CIEDE2000 color difference formulae can be used in different studies with similar results.

Keywords: single-shade composite, color difference formula, blending effect, esthetic resin restoration, shade matching

*** Corresponding author: Aylin Cilingir,** Department of Restorative Dentistry, Faculty of Dentistry, Trakya University Balkan Campus, 22030, Edirne, Turkey, e-mail: aylincilingir@trakya.edu.tr, tel: +90-5324457648
Engin Kariper: Department of Restorative Dentistry, Faculty of Dentistry, Trakya University Balkan Campus, 22030, Edirne, Turkey

1 Introduction

Resin composites are widely utilized as dental restorative materials due to their esthetics, conservative nature, low cost, and good mechanical properties, making them suitable for many clinical situations [1]. However, significant disadvantages of resin composites are abrasion, microleakage, secondary caries, polymerization shrinkage, water absorption, and color stabilization [2].

Choosing the appropriate color for composite restorations can be challenging due to various environmental and operator-dependent factors. Restoring anterior teeth with direct composites can present a challenge for clinicians due to the significant impact of color layering on the final esthetic outcome [3–5]. In addition to the selection of the appropriate shade, the layering of the restoration is dependent on the expertise of the clinician to understand the correlation between the translucency of the composite and the thickness of the applied layer.

The color of resin composite is influenced by pigments that interact with incoming light to produce color [3]. However, achieving color matching with surrounding tissues may require increased translucency and structural color, which is defined as the color produced by the interactions between the incident light and structured materials with different refractive indices and can be a useful tool in achieving this goal [6]. The addition of well-dispersed spherical nanoparticles smaller than 380 nm, the lower limit of visible light, to the restorative material provides structural color in dentistry [7].

The way light interacts with the dentin tubules and enamel hydroxyapatite crystals affects the color of teeth. Therefore, the final color is related to the thickness and curvature of the tooth surfaces by changing the direction of the reflected light [8–11].

Resins with the ability to shade toward adjacent tooth structures are useful for restorations. The color shift or color adjustment potential of the composite may be attributed to its mixing effect and translucency [12–15].

The shade of a resin composite is mostly determined by dyes or pigments of the resin matrix, which is referred to as “chemical coloration” [16–18]. The color match of the resin composite is influenced by its “blending effect” (BE), which refers to the ability of the composite to reflect and color the surrounding tooth structure, resulting in improved esthetics [19]. Manufacturers and dentists also use the term “chameleon effect” for BE [19,20].

As the thickness of the composite increases, it can become less capable of mimicking adjacent surfaces because the thickness of the composite is closely correlated with the light transmission [8].

Resin composites are the ideal choice for direct restorations in both anterior and posterior teeth due to their superior esthetic and mechanical properties. Resin composites have been associated with several issues. However, with proper technique and material selection, these potential problems can be minimized. It is important to consider the benefits of resin composites, such as their esthetic properties and conservative preparation when selecting a restorative material [21]. Resin composites are highly valued by clinicians due to their ability to shorten chair time and minimize technical sensitivity. The introduction of universal shade composites has simplified the process of selecting shades for composite restorations despite the challenges posed by environmental and operator-related variables [22]. Universal shade composites have a distinct advantage in their enhanced potential for shade adaptation. This is due to the strong interaction between perceptual components and physical components. Notably, this statement is objective and free from any subjective evaluations [1].

The use of resin-based composite for esthetic purposes originated with the introduction of composite kits that provided enhanced physical and optical properties. These kits were integrated with the Vita Classical shade guide to simplify shade selection [23,24].

CIELAB has been the primary system used in dentistry to study color and discoloration. This system calculates color changes (ΔE) using lightness–darkness and red–green and blue–yellow coordinates. + L^* represents lightness, − L^* represents darkness, + a^* represents red, − a^* represents green, + b^* represents yellow, and − b^* represents blue. However, since 2001, the CIE has recommended the use of CIEDE2000 (ΔE_{00}), a new formula that incorporates the concepts of hue and chroma and thus reinforces the importance of the original concept proposed by Munsell [25].

This study confidently evaluates the color-matching capability of three single-shade composites using simulated 3D-printed cavities with different thicknesses. The evaluation was conducted using CIELAB and CIEDE2000 formulae.

The null hypothesis stated that thickness does not affect color matching and that the use of both the CIELAB and CIEDE2000 color difference formulae would not yield similar color change measurements.

2 Materials and methods

2.1 Specimen preparation

Three types of single-shade universal composites were selected for this study. More information about the universal single-shade resin composites that have been tested and the Formlabs Temporary CB Resin composite (Formlabs, MA, USA) used to prepare standardized blank cavities in this study are presented in Table 1.

A cylindrical model (diameter = 10 mm; height = 5 mm) with standardized cavities (diameter = 4 mm; height = 0.5, 1, 2, and 4 mm) was generated in TinkerCAD (running online, Autodesk) software (Figure 1).

The tested specimens were fabricated using temporary crown and bridge (Temporary Crown and Bridge A2 Formlabs Inc., Somerville, MA, USA) resin. The resin was loaded into the PreForm (Formlabs, MA, USA) software. Using the specific exposure time provided by the software for this particular resin, the parameters were set to a layer thickness of 50 µm. Specimens were printed with the resin temperature set to 35°C using the Formlabs 2 automated printer (Formlabs, MA, USA). Formlabs Form Wash (Formlabs, MA, USA), an automatic washer using 99% isopropyl alcohol, was selected for the removal of uncured resin after printing. Post-cure was carried out with FormCure (Formlabs, MA, USA) at 60°C for 20 min, as recommended by the manufacturer [26].

One hundred and fifty blank specimens were fabricated to standardize the initial color according to the manufacturer’s instructions. The prepared specimens were divided into three groups (n = 50) and then into five subgroups (four subgroups, including specimens with 0.5, 1, 2, and 4 mm cavities and a control group of specimens without cavities) within each group (n = 10). Forty specimens of each group were prepared with simulated class I cavities. The cavities had a diameter of 4 mm and heights of 0.5, 1, 2, and 4 mm and were formed by a small cylindrical projection inside the specimens. A thin layer of light-cure adhesive was applied to the cavity walls following the manufacturer’s instructions (Clear S Bond, Kuraray, Tokyo, Japan).

Table 1: Materials used in the study

Resin composite	Manufacturer	Type	Organic matrix	Inorganic filler	Filler w/V%
VU	FGM, Joinville, SC, Brazil	Nanohybrid	UDMA, TEGDMA	Active ingredients: photoinitiator composition (APS), co-initiators, stabilizers, and silane. Inactive ingredients: the nanospheres of a complex of silica zirconia	82/72
OC	Tokuyama, Tokyo, Japan	Supra-nanospherical	UDMA, TEGDMA	260 nm spherical SiO_2–ZrO_2	79/68
OS	Kerr Corporation, CA, USA	Nanohybrid	Bis-EMA, Bis-GMA, TEGDMA	Barium glass, silica, ytterbium trifluoride	81/64.5
FormLabs Temporary CB Resin	Formlabs, Somerville, MA, USA	Resin composite	Esterification products of 4,40-isopropylidene diphenol, ethoxylated, and 2-methyl prop-2-enoic acid diphenyl(2,4,6-trimethyl benzoyl)phosphine oxide		

Abbreviations: Bis-GMA = bisphenol A-glycidyl methacrylate, TEGDMA = triethylene glycol di methacrylate, UDMA = urethane dimethacrylate, Bis-EMA = bisphenol A ethoxylated dimethacrylate. The data were provided by the manufacturers.

The first group of specimens was filled with Vittra Unique (VU), the second group of specimens was filled with Omnichroma (OC), and the third group of specimens was filled with OptiShade (OS) single-shade universal resin. The filling of 0.5 mm cavities involved the placement of resin composite at a thickness of 0.5 mm. Similarly, 1 mm cavities were filled using a thickness of 1 mm, and 2 mm cavities were filled using a thickness of 2 mm. Then, 4 mm cavities were filled in two layers with a thickness of 2 mm, and all specimens were pressed using a mylar strip and glass slides to achieve a flat surface. The specimens underwent light polymerization for 20 s using a visible, blue, light-emitting diode light device (Valo Cordless Ultradent Products, Inc., South Jordan, UT, USA) (395–480 nm). After curing, the surfaces of the restoration and control groups were polished with 1,500-grit silicon carbide paper and finished with fine and superfine OptiDisc discs (Kerr Corporation, USA) for 30 s each. All specimens were stored in distilled water at 37°C for 24 h to ensure proper preservation.

2.2 Color measurements

Color measurements were obtained using a clinical spectrophotometer (VitaEasyShade® V VITA, Zahnfabrik, Bad Sackingen, Germany) in a custom-made viewing booth with D65 illumination (Master TL-D 90 De Luxe 18 W/965 1SL, Philips, Eindhoven, Netherlands). A custom-made viewing booth with D65 illumination was employed to mitigate the impact of external light sources and to establish a more consistent lighting environment. The spectrophotometer was calibrated for each measurement, with the detector positioned perpendicular to the surface of the sample in front of a white background (Figure 2). The spectrophotometer was set to “single tooth” mode, and the sensor was positioned in the middle of the sample. Three consecutive measurements were taken to record the mean values of L^*, a^*, and b^* for each sample and were utilized for subsequent analysis. The luminance (L^*), red–green coordinate (a^*), and yellow–blue coordinate (b^*) measurements were evaluated using the CIELAB color system.

The color evaluations were performed with different thicknesses (0.5, 1, 2, and 4 mm) for all three single-shade composites to obtain ΔL^*, Δa^*, and Δb^* values. The following formula represents the total color change: $\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$ [27,28].

The ΔE_{00} color differences ($\Delta E_{00} = [(\Delta L^*/k_L S_L)^2 + (\Delta C^*/k_C S_C)^2 + (\Delta H^*/k_H S_H)^2 + R_T. (\Delta C^*/k_C S_C) \times (\Delta H^*/k_H S_H)]^{0.5}$) for three different single-shade composites with different

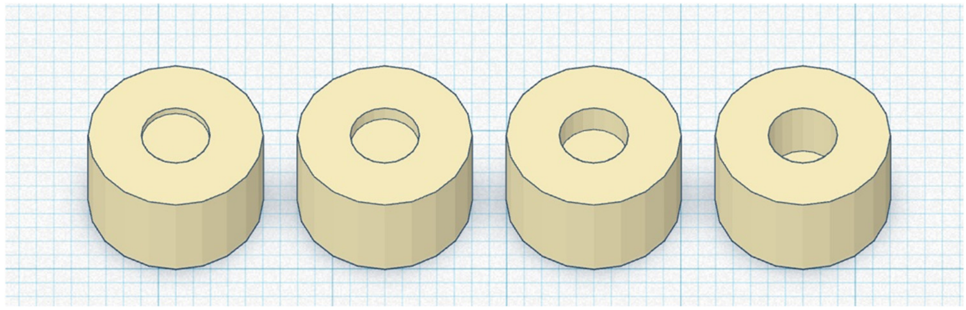

Figure 1: CAD view of specimens in STL format.

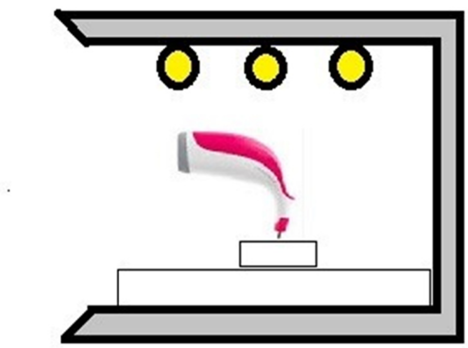

Figure 2: Schematic representation of the color measurement setup.

thicknesses were calculated using Sharma's CIEDE2000 color difference formula in an Excel spreadsheet [29].

2.3 Statistical analysis

The study findings were subjected to statistical analysis using the IBM SPSS Statistics 22 program. The suitability of the parameters for the normal distribution was assessed using the Kolmogorov–Smirnov and Shapiro–Wilks tests. The study evaluated the effect of material and depth on ΔE through a two-way analysis of variance (ANOVA) test, followed by the Tukey honestly significant difference test for *post hoc* analyses. Pearson correlation analysis was used to correlate ΔE_{00} with ΔE. The level of significance was set to $p < 0.05$.

3 Results

When the ΔE value was evaluated in terms of both material and layer thickness, there were statistically significant differences (p = 0.000; $p < 0.05$). The joint influence of the material and depth had a statistically significant effect on ΔE. Moreover, the joint effect of material and depth on ΔE was also statistically significant (p = 0.000; $p < 0.05$). Detailed explanations of the results mentioned in Table 2 are provided in Table 3.

Based on the two-way ANOVA test, OS had significantly lower ΔE values than the other composites at all layer thicknesses ($p < 0.05$). VU and OC values showed no significant difference in ΔE values at layer thicknesses of 1 and 4 mm, while at layer thicknesses of 0.5 and 2 mm, all monochromatic composites had statistically different ΔE values ($p < 0.05$) (Figure 3).

An evaluation of the ΔE values of each material in different layers reveals that all materials had lower values at a thickness of 0.5 mm than other layer thicknesses. For VU and OS, the ΔE values were lower at 1 mm than at 2 and 4 mm, while for OC, the values at 1 and 2 mm were lower than at 4 mm ($p < 0.05$).

The two-way ANOVA indicates that ΔE_{00} significantly varied regarding both material and layer thicknesses. Additionally, the combined effect of factors on ΔE_{00} was found to be significant ($p < 0.05$). Detailed explanations of the results listed in Table 4 are provided in Table 5.

As demonstrated in Table 5, the findings revealed that all observed ΔE_{00} values for VU, OC, and OS 4 mm products exceeded the established thresholds of detectability and

Table 2: Evaluation of the effect of the material and layer thickness on ΔE

ΔE	Type III sum of squares	df	Mean square	F	p
Material	2651.279	2	1325.639	4087.183	0.000*
Layer thickness	358.731	3	119.577	368.677	0.000*
Material × layer thickness	73.87	6	12.312	37.959	0.000*

Two-way ANOVA test: *$p < 0.05$.
Df: degree of freedom; F: F-distribution.

Table 3: Variation in Δ*E* according to the material and depth

	Δ*E* VU	Δ*E* OC	Δ*E* OS	
Layer thickness	**Mean ± SD**	**Mean ± SD**	**Mean ± SD**	***p***
0.5 mm	7.58 ± 0.56^{Aa}	8.78 ± 0.31^{Ba}	0.52 ± 0.28^{Ca}	0.000*
1 mm	12.03 ± 1.27^{Ab}	11.94 ± 0.54^{Ab}	0.59 ± 0.23^{Ba}	0.000*
2 mm	13.84 ± 0.62^{Ac}	12.11 ± 0.54^{Bb}	2.36 ± 0.46^{Cb}	0.000*
4 mm	13.61 ± 0.41^{Ac}	13.54 ± 0.57^{Ac}	3.36 ± 0.25^{Bc}	0.000*
p	0.000*	0.000*	0.000*	

Two-way ANOVA test: *$p < 0.05$.
SD: standard deviation.
Note: Different capital letters in the lines indicate the difference between the materials. Small letters in the columns indicate the difference between the depths.

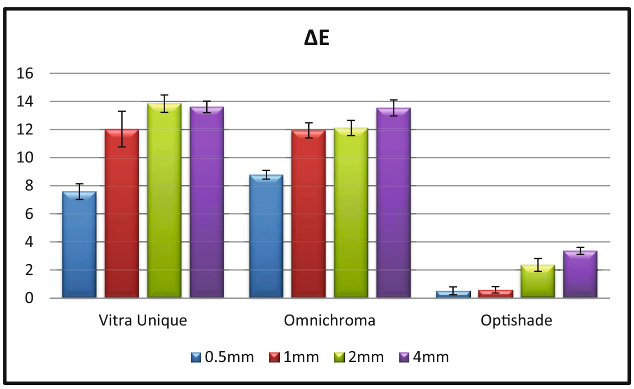

Figure 3: Δ*E* values materials with different layer thicknesses.

acceptability, *i.e.*, 0.8 and 1.8, respectively. However, this was not the case for OS with thicknesses of 0.5, 1, and 2 mm [30].

Based on the two-way ANOVA, OS had significantly lower ΔE_{00} values at a thickness of 0.5 mm than at other thicknesses, and all materials had significantly lower values at a thickness of 0.5 mm than at other layer thicknesses ($p < 0.05$). Additionally, OS had significantly lower ΔE_{00} values than the other composites at all thicknesses ($p < 0.05$). There was no significant difference between VU and OC at thicknesses of 1 and 4 mm. However, at a thickness of 2 mm, VU exhibited higher values than OC ($p < 0.05$) (Figure 4).

The color difference values determined by both CIELAB and CIEDE2000 formulae at all thicknesses (0.5, 1, 2, and 4 mm) were statistically similar (Figure 5). The Pearson correlation test revealed a positive and statistically significant relationship between ΔE_{00} and Δ*E* in each of the three single-shade composites at every depth (0.5, 1, 2, and 4 mm), with the exception of VU at 1 and 4 mm. There was no statistically significant relationship between ΔE_{00} and Δ*E* for VU at depths of 1 and 4 mm ($p < 0.05$) (Table 6).

Table 4: Evaluation of the effect of material and depth on ΔE_{00}

ΔE_{00}	Type III sum of squares	df	Mean square	*F*	*p*
Material	778.853	2	389.427	2678.855	0.000*
Layer thickness	169.806	3	56.602	389.363	0.000*
Material × layer thickness	28.861	6	4.81	33.089	0.000*

Two-way ANOVA test: *$p < 0.05$.
Df: degree of freedom; *F*: *F*-distribution.

4 Discussion

In dentistry research, color comparison requires considering various factors, including underlying color, storage conditions, the instrument used for the measurement, the background used for readings, the color-changing method, and the color difference evaluation formula (such as CIELAB or CIEDE2000) used for calculating color changes [25]. However, failure to report or reproduce all criteria in future studies will result in conflicting and incomparable data in the literature [25]. According to the International Commission on Illumination (CIE), color differences can be quantified using both CIELAB and CIEDE2000 (ΔE_{ab} and ΔE_{00}) [16,31].

To capture color parameters relevant to human color perception in all three regions of the color space, the CIE established the L^* a^* b^* color space in 1978. The system utilizes the values of a^* and b^* as chromaticity coordinates and L^* as a lightness value, which is proportional to the Munsell scale [31]. To further improve the CIELAB formula, which measures the difference between two colors, the CIE developed CIEDE2000, a more intricate formula, in 2001.

Table 5: Variation in ΔE_{00} according to the material and depth

	ΔE_{00}			
	VU	**OC**	**OS**	
Layer thickness	**Mean ± SD**	**Mean ± SD**	**Mean ± SD**	***p***
0.5 mm	3.86 ± 0.33^{Aa}	4.46 ± 0.20^{Ba}	0.29 ± 0.12^{Ca}	0.000*
1 mm	6.75 ± 0.89^{Ab}	6.62 ± 0.36^{Ab}	0.37 ± 0.12^{Ba}	0.000*
2 mm	7.95 ± 0.43^{Ac}	6.96 ± 0.34^{Bb}	1.62 ± 0.33^{Cb}	0.000*
4 mm	7.95 ± 0.27^{Ac}	7.74 ± 0.37^{Ac}	2.26 ± 0.15^{Bc}	0.000*
p	0.000*	0.000*	0.000*	

Two-way ANOVA test: $*p < 0.05$.
SD: standard deviation.
Note: Different capital letters in the lines indicate the difference between the materials. Small letters in the columns indicate the difference between the depths.

Comparative studies of CIELAB and CIEDE2000 have shown that CIEDE2000 is a more reliable measure than CIELAB. According to these reports, the CIEDE2000 formula almost precisely reflects color differences as perceived by human eyes, as proven by the nearly identical results of the observer [29,32,33]. While CIELAB is the most commonly employed technique, CIEDE2000 is a more sophisticated and complex system that yields results that are more consistent with visual results [29,34].

The quality of color matching between dental restorations and/or adjacent natural teeth is largely contingent upon the degree and axis of the color difference. The smallest color difference that can be perceived by an observer is referred to as the just-noticeable difference or perceptibility threshold (PT). A 50:50% PT denotes a scenario in which 50% of the observers discern a discrepancy in color between two objects, whereas the remaining 50% perceive no such difference. Similarly, the difference in color that is deemed acceptable for 50% of the observers corresponds to a 50:50% acceptability threshold (AT). In other words, 50% of the observers would consider the dental restoration to require color correction, while the other 50% would consider the color difference acceptable. The difference between these two thresholds is referred to as industry tolerance and indicates the extent to which we can deviate from the perceptible difference while still achieving an acceptable color match. The results obtained from studies investigating the effects of PT and AT have been variable, with differing outcomes reported in different studies conducted over a number of years [35,36]. The values are determined through the utilization of the CIELAB formula. Different surfaces may not be directly comparable with the results obtained from this formula and, therefore, should be interpreted with caution. Additionally, it is important to avoid comparing results obtained using the CIEDE2000 formula with those obtained using the CIELAB formula [25].

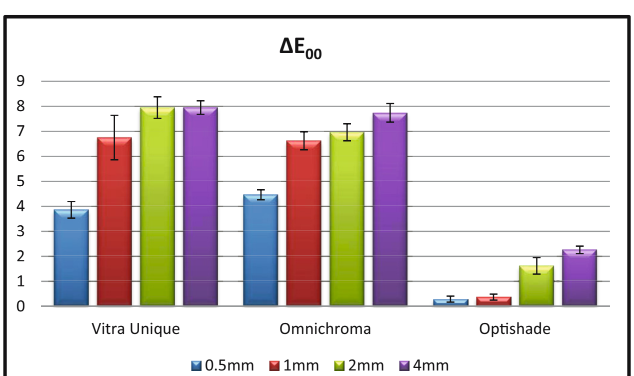

Figure 4: ΔE_{00} values for materials with different layer thicknesses.

Both systems, CIELAB and CIEDE2000, were employed and compared in the present study. At a thickness of 0.5 mm, when ΔE_{00} and ΔE values were examined, both systems had statistically significantly higher color change values with OC than with VU and OS. Although the CIEDE2000 color measurement system is a more sensitive calculation method, all statistically significant values for all thicknesses (0.5, 1, 2, and 4 mm) showed the same results performed with CIELAB and CIEDE2000 in this study. The statistical results were the same, although different numerical values were obtained in the two measurement systems, possibly because the same L^*, a^*, and b^* values are used in both systems.

To achieve a good color match, it is necessary to ensure color harmony by taking reinforcements from the walls and floor of the applied cavity [16]. In this study, simulated 3D-printed resin cavities in color A2 were produced, and the color matching of monochromatic composites in different layer thicknesses was examined. The straight-line color transmission properties and diffusion balance of

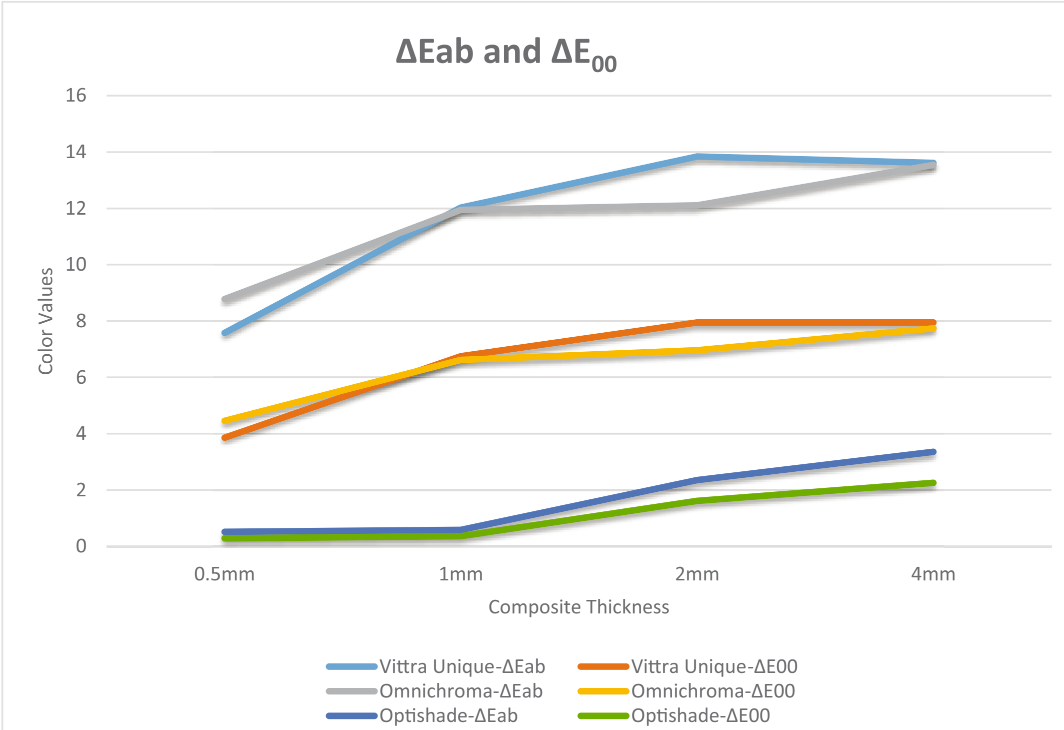

Figure 5: Values of ΔE_{ab} and ΔE_{00} in composites of varying thicknesses.

Table 6: Correlation of ΔE_{00} and ΔE in different materials and depths

Material	Depth		ΔE_{00} – ΔE
Vitra Unique	0.5 mm	*r*	0.987
		p	0.001*
	1 mm	*r*	0.130
		p	0.720
	2 mm	*r*	0.634
		p	0.049*
	4 mm	*r*	−0.052
		p	0.887
OC	0.5 mm	*r*	0.984
		p	0.001*
	1 mm	*r*	0.989
		p	0.001*
	2 mm	*r*	0.992
		p	0.001*
	4 mm	*r*	0.988
		p	0.001*
OS	0.5 mm	*r*	0.945
		p	0.001*
	1 mm	*r*	0.882
		p	0.001*
	2 mm	*r*	0.992
		p	0.001*
	4 mm	*r*	0.933
		p	0.001*

Pearson correlation analysis: $*p < 0.05$.

the resin composite affect the color matching with the underlying tooth or material. The color matching of the resin composite with the underlying tooth develops due to the reflection from the cavity floor and cavity walls. Additionally, the filler content of the composite affects whether the color transmits in a straight or diffuse manner [16]. The possible advantages offered by supra-nanotechnology are most likely seen in resin composites shaded with structural color. These composites may experience fewer color changes over time due to a reduction in photochemical degradation and discoloration. It could be argued that the pattern of filler particles matches the wavelengths of visible light [16].

Manufacturers claim that OC is a composite with the capability of matching any shade by incorporating uniformly sized, 260 nm supra-nanospherical fillers into the composite, which provides a red-to-yellow color as surrounding light passes through the resin structure [1]. OS achieved the lowest ΔE_{00} and ΔE values, indicating a better BE than OC, which may be attributed to the filler content or the fact that OS offers three shades (light, medium, and dark) instead of one shade.

The influence of the color surrounding the specimen and its thickness were evaluated. When the outer cavity shade was A1, the color difference values tended to decrease as the thickness increased, as demonstrated by VU testing.

Conversely, the color difference values for the other shades increased as the thickness increased [8]. The present study demonstrated comparable findings with Barros *et al.*; as the thickness increased, ΔE_{00} values correspondingly increased for shade A2 [8].

The color of dental composites is produced by the reflection of specific wavelengths and by existing pigments [7,37]. Instead of pigments, animals such as peacocks and butterflies present their colors due to photonic crystals, which affect light propagation by periodically changing the refractive index [38]. This phenomenon can be achieved in dental composites by reflecting light at a specific wavelength using filler particles of a specific size and shape [37]. According to the manufacturer, OC is a pigment-free, single-shade composite. The optical features of the resin composite are managed by chromatic technology, which is related to the color features of the surrounding structural properties. To improve the ability to match the color of natural teeth, 260 nm spherical fillers are used to create a color from red to yellow [37]. The increased transparency of OC after polymerization increases its ability to change color.

The increased transparency after polymerization increases the ability to change color, as shown by color matching in VU. It has been observed that composites with high color-matching potential allow for satisfactory esthetic restorations and can compensate for failures related to color selection. The advanced polymerization system (APS) used by VU could have led to better performance in terms of color change [39]. The utilization of APS technology as a transparent photoinitiator in VU may have potentially resulted in an improved color change. Additionally, the product is free of bisphenol A-glycidyl methacrylate (Bis-GMA) and contains triethylene glycol dimethacrylate (TEGDMA), urethane dimethacrylate (UDMA), and a smaller quantity of camphorquinone, as indicated by the manufacturer. The BE for VU is influenced by the surrounding color, with a greater BE occurring when the surrounding color of VU was light (A1); increased thickness led to cavity hues, and thick layer composites were employed [8]. This study partially agrees with the results of Barros *et al.*, who obtained an enhanced BE. In the current research, only A2 was used as the surrounding color for VU, and ΔE_{00} values increased as the thickness increased. Our findings indicate that the surrounding color affects the BE, decreasing as the color becomes darker [8].

While color-matching studies commonly use composite layers thicker than 2 mm, some parts of the upper incisor's incisal edge are less than 2 mm thick. Additionally, the impact of the dark background in the oral cavity becomes more prominent as the composite's translucency is enhanced [40]. Therefore, when conducting research or clinical procedures, it is important to acknowledge that the transparency of single-shade composites increases after polymerization. Single-shade composites are typically used in thin layers for anterior restorations, where the oral cavity, which may appear darker in color, is reflected in the background. In the posterior region, they are applied in thicker layers and are usually supported by enamel and dentin rather than the oral cavity, which has a lighter background.

The BE was found to increase with increasing translucency [19]. When Bis-GMA, UDMA, and TEGDMA monomers were examined, it was observed that Bis-GMA had higher translucency, which increased as the amount of monomer increased. There is a correlation between the refractive indices of unfilled resin mixtures and those of cured composites between the color and translucency of conventional composites and those of low-shrinkage composites [41]. In addition, monomer content in resin composites affects color matching. Bis-GMA monomers display less color alteration than TEG-DMA and more color alteration than UDMA and Bis-EMA due to the formation of a rigid network [42]. OS containing Bis-GMA exhibited the lowest ΔE and ΔE_{00} levels, which is consistent with previous research in this study [1,42]. The higher ΔE and ΔE_{00} levels of VU and OC may depend on their partial content of TEGDMA and UDMA monomers. However, these results may depend on the filler content and adaptive response technology (ART) of OS. The manufacturer states that the primary filler in OS is derived from molecular suspension, which consists of spherical silica and zirconia particles. OS has an average filler ratio of 50 nm [43,44]. ART is a two-component system that comprises zirconia and silica nanoparticles arranged to reveal distinctive optical properties [44].

OS exhibits light diffusion properties that are similar to those of natural enamel. Enamel reflects light diffusely at shorter wavelengths. It reflects light specularly at longer wavelengths [44]. The zirconia and silica particles work in tandem to imitate this characteristic, leading to a more coherent restoration or the "chameleon effect." The manufacturer claims that OS provides optimum opacity to imitate tooth structure, effectively hides the underlying background color, and blends well with the adjacent dentition, resulting in a more natural-looking restoration. This could be attributed to the variance in average particle sizes within the OS. Better polishability and smoother surfaces are attributed to a smaller average particle size.

The differences in ΔE values observed in this study could be attributed to variations in the types and sizes of inorganic and organic fillers, as well as the differences in color reflection systems [3]. The structural color and translucency of composites can be influenced by a variety of factors, including the refractive index of the organic matrix and filler content [3,45].

The null hypothesis is partially rejected due to the effect of thickness on color-matching scores and is partially accepted because the CIELAB and CIEDE scores produced similar results.

This study has certain limitations. It was conducted *in vitro*, and clinical conditions may vary. The translucency and the degree of conversion of the composites used in the study were not evaluated, the spectrophotometer used in the study may have introduced errors, and more detailed results may be obtained with different instruments. Additionally, since all cavities were produced from standard 3D printed resin in the present study, enamel and dentin tissue in each tooth under clinical conditions will differ. Furthermore, varying outcomes may result when the diameter of the composite samples is altered. Hence, further research is required to validate the results of this study.

5 Conclusion

The study suggests that there were differences in the absolute values calculated using the CIELAB and CIEDE2000 color difference formulae, although the difference was not statistically significant. Furthermore, the study found that the BE of OS was superior to that of OC and VU with different thicknesses.

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