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Color matching and stability of single-shade paste, single-shade flowable bulk-fill, and simplified shade-system bulk-fill composites

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Abstract

Background: The growing demand for efficient aesthetic restorations has driven the development of single-shade and simplified shade-system resin composites, which are designed to streamline clinical workflows without compromising optical integration. However, their initial color-matching capabilities and long-term stability following dietary staining remain critical clinical concerns. Therefore, this study aimed to evaluate the color matching and stability of a single-shade paste composite, a single-shade flowable bulk-fill composite, and a simplified shade-system paste bulk-fill composite.

Materials and Methods: Thirty extracted human molars were allocated to three groups (n=10): Charisma Topaz One, Charisma Bulk Flow One, and Opus Bulk Fill APS. Standardized buccal cavities (4x4 mm) were prepared and restored following selective etching and universal adhesive application. Instrumental color (VITA Easyshade V) was recorded at baseline, 24 h post-restoration, after 7-day coffee staining, and after repolishing; visual matching (five calibrated observers, 5-point scale) was recorded at the last three of these time points. Data were analyzed using CIEDE2000 (ΔE_{00}), ANOVA, Kruskal-Wallis, Friedman tests, and GEE models ($\alpha=0.05$).

Results: A significant intergroup difference occurred only at the post-restoration/baseline interval ($p<0.001$), where the simplified shade-system showed lower ΔE_{00} than both single-shade materials. No significant differences were found after staining or repolishing ($p>0.05$). All materials showed significant phase-related (ΔE_{00}) changes ($p<0.001$). Repolishing significantly reduced the color change produced by staining in all groups. Visual acceptability remained high but showed significant time and group×time interactions.

Conclusions: All composites exhibited similar staining susceptibility, with repolishing reversing much of the staining-related color change. Initial color matching differed among the materials but was influenced by baseline tooth color.

Key words: Chameleon effect, color stability, repolishing, single-shade composite, universal composites.

Introduction

Resin composites are indispensable materials in restorative dentistry, as they preserve remaining tooth structure while providing favorable physical and mechanical properties together with esthetic outcomes that closely mimic natural tooth color [1]. Since their widespread clinical adoption, numerous composite resin formulations have been developed for direct and indirect applications, featuring different viscosities, filler loading levels, and shade systems designed to improve handling characteristics and esthetic integration. Among these developments, bulk-fill composites have gained increasing popularity because they allow placement in increments of up to 4-5 mm while reducing polymerization shrinkage-related stress [2].

Following the clinical introduction of paste-type bulk-fill composites, lower-viscosity flowable bulk-fill materials were subsequently developed to further simplify restorative procedures. Beyond placement thickness, bulk-fill composites may influence optical behavior and color stability through differences in resin matrix composition, filler content, filler particle characteristics, translucency, and photoinitiator systems [3,4]. Accordingly, the esthetic performance of bulk-fill materials cannot be explained solely by their mechanical advantages but must also be evaluated in terms of their optical interaction with surrounding tooth tissues.

In this context, color matching has emerged as a critical determinant of clinical success in esthetic restorations. Color matching is closely related to the concept of color adaptation, which refers to a material's ability to achieve clinically acceptable color matching with the surrounding tooth structure through optical blending and light interaction, a phenomenon commonly described as the chameleon effect [5]. To enhance this effect, composite resin systems have been simplified according to the number of available shades and are marketed under polyshade, simplified-shade, and single-shade (monoshade) categories. Single-shade composites do not rely on predefined shade selections; instead, they adapt to the color of the cavity and adjacent tooth tissues by reflecting and transmitting light, thereby exhibiting a pronounced color-mimicking ability [6].

Consequently, single-shade composites have been associated with favorable esthetic outcomes and high color stability, particularly in situations where shade selection is challenging or time-consuming [7]. In parallel, the development of flowable composites that combine single-shade and bulk-fill characteristics has attracted increasing interest due to the clinical ease they provide [8]. However, despite these advantages, the optical behavior of such materials (especially when placed in thicker increments typical of bulk-fill techniques) remains a subject of ongoing investigation.

The existing literature includes studies evaluating the

color matching of monoshade composites using acrylic teeth, extracted natural teeth, or composite blocks as substrates [5,9,10]. Several recent systematic reviews have addressed this material class. A systematic review of single-shade chameleon composites reported color differences within commonly cited acceptability thresholds across seven studies of mixed design, but could not pool them because of heterogeneity, and it reported staining exposure and cavity depth among the factors influencing color stability [11]. A systematic review with meta-analysis of four randomized clinical trials found single-shade and multi-shade composites to perform comparably in color match and color stability over 12 months, with the certainty of the evidence rated as low [12]. A further systematic review with meta-analysis reached a less favorable instrumental conclusion: Pooling *in vitro* data, it found that single-shade composites showed significantly larger color differences from the surrounding tooth than multi-shade materials, although the randomized trials it reviewed reported more promising outcomes for single-shade materials [13]. Visual work has further shown that cavity configuration and tooth shade both affect color adjustment, with more chromatic teeth yielding a higher proportion of unacceptable matches [14]. Nevertheless, the number of studies focusing on single-shade paste bulk-fill composites remains limited. Moreover, investigations assessing the color matching and color stability of single-shade bulk-fill flowable composites restored in standardized cavities prepared in natural teeth are particularly scarce. In addition, few studies have adopted multi-stage evaluation models that integrate instrumental color measurements with visual acceptability assessments following staining and repolishing procedures. Therefore, the aim of this *in vitro* study was to compare the color adaptation and color stability of three contemporary composite resin categories: A single-shade paste composite; a single-shade flowable bulk-fill composite; and a simplified shade-system paste bulk-fill composite. Instrumental color changes were assessed using the CIEDE2000 (ΔE_{00}) formula, together with visual color matching based on observer-based acceptability scores, across four clinically relevant phases: Before restoration, after restoration, after coffee staining, and after repolishing. The null hypotheses were that ΔE_{00} values would not differ among the composite groups at any measurement interval; ΔE_{00} values would not change across evaluation phases within each composite group; and visual color acceptability would not be influenced by time, composite group, or their interaction.

Materials and Methods

Sample size calculation

The sample size was determined by an a priori power analysis (G*Power v3.1.9.6, Heinrich Heine University,

Düsseldorf, Germany) based on CIEDE2000 color difference (ΔE_{00}) data reported by Khayat [15]. In that study, the expected effect size for a one-way ANOVA comparing three groups was calculated as Cohen's $f \approx 0.59$. The Type I error rate was set at $\alpha = 0.05$. With $n = 10$ specimens per group (total $n = 30$), the estimated power to detect this effect size was approximately 80%, corresponding to a Type II error rate of $\beta \approx 0.21$ ($\beta = 1 - \text{power}$).

Specimen preparation

Human permanent molars were obtained from patients for whom extraction was indicated as part of their clinical treatment plan for orthodontic or periodontal reasons. After extraction, following removal of soft-tissue remnants, the teeth were disinfected by storage in a 0.1% thymol solution at 4°C for 1 week. After disinfection, all specimens were stored in distilled water at room temperature between measurements, and the distilled water was renewed daily.

Prior to color measurements, teeth presenting restorations, caries, hypomineralized lesions, or pronounced discolorations on the buccal surface were excluded. Following this preliminary screening, baseline shade was measured using a contact-type spectrophotometer (Easyshade V, VITA Zahnfabrik, Bad Säckingen, Germany), and the resulting coordinates were used as the baseline reference for all subsequent color-difference calculations. The 30 included teeth had been selected visually during the preliminary screening so that their shade would be compatible with the range of shades available for the simplified shade-system composite (A1-A3).

Group allocation

The specimens were allocated to three groups ($n = 10$ teeth per group) by visual shade assessment, with the aim of obtaining groups of comparable appearance (Table 1):

G1 (Test Group 1): Charisma Topaz One

G2 (Test Group 2): Charisma Bulk Flow One

G3 (Test Group 3): Opus Bulk Fill APS

Standardized cylindrical cavities (4 mm in diameter and 4 mm in depth) were prepared on the middle third of the buccal surface of each tooth using a high-speed hand-piece under water cooling with a round diamond bur followed by a cylindrical bur. The burs were replaced after every five teeth. Cavity depth and diameter were verified using a periodontal probe and a digital caliper (Mitutoyo, Japan). Selective enamel etching was performed by applying 35% phosphoric acid gel (Gluma Etch 35 Gel, Kulzer, Germany) for 30 s, followed by rinsing with water for 30 s and air-drying. A universal adhesive (Gluma Bond, Kulzer, Germany) was applied to the tooth for 20 s using a microbrush (KG Brush, FGM, Brazil) with a rubbing motion and then air-thinned according to the manufacturer's instructions. The adhesive layer was light-cured for 20 s at an irradiance of 1000 mW/cm² using an LED curing unit (Bluephase Powercure, Ivoclar, Liechtenstein), with output verified by a radiometer.

Resin composites were placed in a single 4-mm increment for the bulk-fill materials, whereas the non-bulk-fill composite was applied in two 2-mm increments. For the simplified shade-system composite, the shade judged closest to the tooth was selected for each specimen; A2 and A3 were used. The surface of the final layer was contoured using a restorative instrument (OptraSculpt Pad, Ivoclar Vivadent, Liechtenstein) and a composite brush (No. 24, Tokuyama, Japan). Each increment was light-cured in accordance with the manufacturer's instructions, with the light tip positioned perpendicular to the buccal surface to ensure adequate coverage. Finally, the restorations were finished and polished for 30

Table 1: Materials used in the study.

Materials	Contents	Filler Ratio wt%/vol%	Photoinitiation	Curing time	Manufacturer/ LOT Number
Charisma Topaz One	TCD-urethane acrylate, UDMA, TEGDMA, barium aluminum borofluorosilicate glass, 5 nm-5 µm fillers	n/a-58	Camphorquinone (CQ)	20 s for 550-1550 mW/cm ²	Kulzer GmbH, Hanau, Germany / K010202
Charisma Bulk Flow One	UDMA, EBADMA, Barium aluminium borofluorosilicate glass, ytterbium fluoride, silicon dioxide, titanium dioxide, 20 nm-5 µm fillers	n/a-41	Camphorquinone (CQ)	20 s for 600-1550 mW/cm ²	Kulzer GmbH, Hanau, Germany / N010029
Opus Bulk Fill APS	Urethane-based methacrylic monomers, Inorganic load of silanized silicon dioxide (silica), stabilizers, pigments	79- n/a	Advanced Polymerization System (APS) and co-initiators	30 s for 1000-2000 mW/cm ²	FGM, Joinville, SC, Brazil /170424

*According to technical data sheets. UDMA: Urethane dimethacrylate; TEGDMA: Triethylene glycol dimethacrylate; EBADMA: Ethoxylated bisphenol A dimethacrylate.

s under intermittent pressure and water cooling using a flame-shaped one-step finishing/polishing rubber (OptiStep Polisher, Kerr, USA). All teeth were then stored in distilled water for 24 h before the evaluations. The overall study design and evaluation timeline, including baseline measurement, specimen allocation, restorative procedures, staining, and repolishing phases, are illustrated in Figure 1.

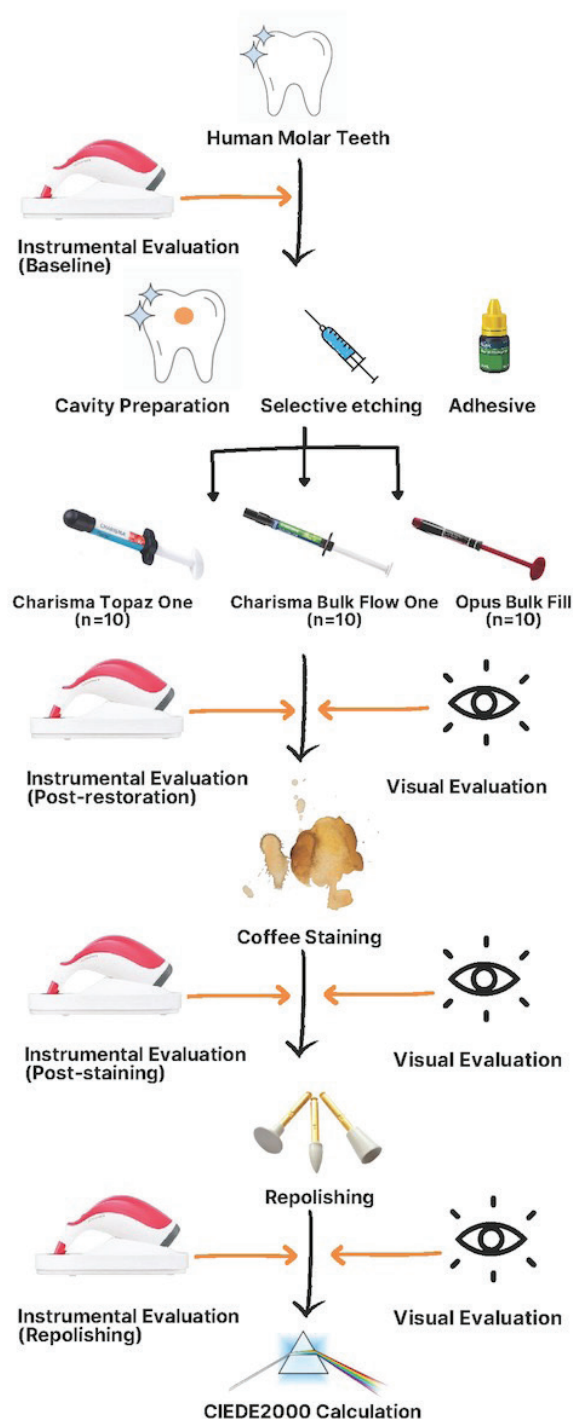


Fig. 1: Flowchart of the study design and evaluation timeline (Created with Canva, Canva Pty Ltd, Sydney, Australia).

Evaluation protocol

Instrumental assessment

All specimens were measured using a calibrated contact-type spectrophotometer (Easyshade V, VITA Zahnfabrik, Bad Säckingen, Germany) in “single tooth” mode. For each tooth, measurements were taken three times from the center of the buccal surface against a neutral gray background, and the mean of the three readings was used. The device was recalibrated after every three measurements. CIELab color coordinates (L^* , a^* , and b^*) defined by the International Commission on Illumination (CIE) were recorded for all included teeth.

Spectrophotometric analysis was performed at four time points: Baseline (before restoration); 24 h after restoration; after coffee staining; and after repolishing.

Visual assessment

Visual evaluation was performed by five female doctoral students experienced in esthetic restorative dentistry. All observers were calibrated in advance according to ISO/TR 28642:2016 and successfully passed the Ishihara color vision test. Assessments were conducted near a window under natural daylight conditions (equivalent to midday light) in a room with light-colored walls and flooring, at a viewing distance of 25 cm. Observers assessed each tooth in random order within 25 s against a neutral gray background. To reduce visual fatigue, visual rest breaks were provided using a neutral blue background after each assessment. Observers were blinded to the material group, and specimens were presented in coded form.

Visual color matching between the composite and the surrounding tooth structure was recorded using a five-point scale in accordance with ISO/TR 28642:2016: 1: Mismatch/completely unacceptable, 2: Poor match/barely acceptable, 3: Good/acceptable match, 4: Close match/minor difference, and 5: Perfect match/no color difference. Visual scoring was performed at three time points: 24 h after restoration; after coffee staining; and after repolishing.

Staining procedure

A coffee staining solution was prepared by dissolving 2 g of instant coffee powder (Nescafé Original; Nestlé, Araras-SP, Brazil) in 200 mL of distilled water. Specimens were immersed individually in 20 mL of the solution in separate containers and stored in an incubator at 37°C for 7 days. The coffee solution was freshly prepared and renewed daily. After staining, specimens were rinsed by immersion in distilled water for 1 min, and color measurements were repeated [16].

Repolishing

Repolishing was performed by applying a one-step finishing/polishing rubber (OptiStep Polisher, Kerr, USA) to the buccal surface for 30 s.

Color analysis

At the end of the experiment, color differences between

the measurement phases were calculated using the CIE-DE2000 color-difference formula, jointly recommended by the International Organization for Standardization (ISO) and the CIE.

Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 30.0 (IBM Corp., Armonk, NY). Instrumental color coordinates (L^* , a^* , and b^*) were recorded at four stages, and color differences were calculated using the CIEDE2000 formula (ΔE_{00}). Normality of continuous data was assessed using the Shapiro-Wilk test, and homogeneity of variances was evaluated using Levene's test. For between-group comparisons of ΔE_{00} at each stage or color-difference interval, one-way analysis of variance (ANOVA) followed by Tukey's HSD post hoc test was used when parametric assumptions were met. When these assumptions were violated, the Kruskal-Wallis test was applied, with Holm-adjusted Mann-Whitney U tests for pairwise comparisons. Within each composite group, changes in ΔE_{00} across repeated stages were analyzed using the Friedman test, followed by Holm-adjusted Wilcoxon signed-rank tests for post hoc comparisons. The relationship between baseline lightness and the color difference recorded immediately after restoration was examined using Pearson correlation, and the intergroup comparison at that interval was repeated in an analysis of covariance with baseline lightness and chroma entered as covariates.

Visual color matching was scored on a 1-5 scale and dichotomized as unacceptable (scores 1-2) or acceptable

(scores 3-5). Because each specimen was assessed repeatedly across three time points by multiple evaluators, visual acceptability data were analyzed using a binomial generalized estimating equations (GEE) model with a logit link, clustering by specimen with an exchangeable correlation structure. The model included time, composite group, their interaction, and rater as predictors. Overall effects were evaluated using Wald χ^2 statistics, and within-group pairwise comparisons across time points were adjusted using the Holm method. Inter-rater reliability among the five evaluators was assessed using the intraclass correlation coefficient (ICC) based on a two-way random-effects model with absolute agreement (ICC(2,k)). Statistical significance was set at $\alpha=0.05$.

Results

Intergroup analysis showed a significant difference only in the post-restoration vs baseline (2-1) interval (Kruskal-Wallis, $p<0.001$). Opus Bulk Fill APS (Group 3) exhibited lower ΔE_{00} than Charisma Topaz One (Group 1) and Charisma Bulk Flow One (Group 2), while Groups 1 and 2 were not different from each other. Baseline instrumental color differed among groups (L^* : 78.69 ± 2.76 , 72.55 ± 9.02 and 81.84 ± 5.74 for Groups 1-3; Kruskal-Wallis $p=0.015$), and baseline lightness was inversely related to ΔE_{00} (2-1) ($r=-0.74$, $p<0.001$). After adjustment for baseline lightness and chroma, the intergroup effect at this interval was no longer significant ($F(2,25)=0.94$, $p=0.404$). No significant intergroup differences were detected for the remaining intervals (3-1, 4-1, 3-2, 4-2, 4-3) ($p>0.05$) (Table 2). Intragroup

Table 2: Intergroup comparisons of CIEDE2000 color differences (ΔE_{00}) (mean $\pm$ SD).

ΔE_{00} interval	Charisma Topaz One (Group 1)	Charisma Bulk Flow One (Group 2)	Opus Bulk Fill APS (Group 3)	Statistical Test & Degrees of Freedom	Test Statistic	Effect Size	Overall p
Post-restoration vs Baseline (2-1)‡	10.26 $\pm$ 1.32 ^a	12.78 $\pm$ 4.10 ^a	8.04 $\pm$ 0.93 ^b	Kruskal-Wallis (df=2)	H=18.42	$\epsilon^2=0.64$	<0.001
Post-staining vs Baseline (3-1)‡	7.81 $\pm$ 2.35 ^a	7.32 $\pm$ 3.88 ^a	6.92 $\pm$ 2.42 ^a	Kruskal-Wallis (df=2)	H=1.14	$\epsilon^2=0.04$	0.566
Repolishing vs Baseline (4-1)‡	8.31 $\pm$ 1.69 ^a	9.71 $\pm$ 3.98 ^a	6.89 $\pm$ 1.12 ^a	Kruskal-Wallis (df=2)	H=4.66	$\epsilon^2=0.16$	0.097
Post-staining vs Post-restoration (3-2)‡	7.52 $\pm$ 0.67 ^a	7.00 $\pm$ 1.48 ^a	6.65 $\pm$ 2.33 ^a	Kruskal-Wallis (df=2)	H=1.87	$\epsilon^2=0.06$	0.393
Repolishing vs Post-restoration (4-2)†	4.29 $\pm$ 0.93 ^a	3.71 $\pm$ 1.68 ^a	3.47 $\pm$ 1.51 ^a	One-way ANOVA (df1=2, df2=27)	F=0.88	$\eta^2=0.06$	0.427
Repolishing vs Post-staining (4-3)†	3.44 $\pm$ 0.92 ^a	3.54 $\pm$ 1.67 ^a	3.65 $\pm$ 1.28 ^a	One-way ANOVA (df1=2, df2=27)	F=0.07	$\eta^2=0.00$	0.936

Values are presented as mean $\pm$ standard deviation (SD). Different lowercase letters within the same row indicate significant differences between groups ($p<0.05$). Test symbols: † one-way ANOVA (Tukey HSD when applicable); ‡ Kruskal-Wallis with pairwise Mann-Whitney U tests (Holm correction).

repeated-measures comparisons revealed a significant phase effect for all materials (Friedman, $p < 0.001$). Across groups, intervals involving repolishing-(4-2) and (4-3)-resulted in markedly lower ΔE_{00} values compared with earlier phases, indicating partial recovery of color match after repolishing (Table 3).

Table 3: Intragroup repeated-measures comparisons of ΔE_{00} across phases (mean $\pm$ SD).

Group	Post-restoration vs Baseline (2-1)	Post-staining vs Baseline (3-1)	Repolishing vs Baseline (4-1)	Post-staining vs Post-restoration (3-2)	Repolishing vs Post-restoration (4-2)	Repolishing vs Post-staining (4-3)	Overall χ^2 (df=5)	Kendall's W	Overall p
Charisma Topaz One	10.26 $\pm$ 1.32 ^A	7.81 $\pm$ 2.35 ^B	8.31 $\pm$ 1.69 ^B	7.52 $\pm$ 0.67 ^B	4.29 $\pm$ 0.93 ^C	3.44 $\pm$ 0.92 ^C	$\chi^2=40.63$	W=0.81	<0.001
Charisma Bulk Flow One	12.78 $\pm$ 4.10 ^A	7.32 $\pm$ 3.88 ^{CD}	9.71 $\pm$ 3.98 ^B	7.00 $\pm$ 1.48 ^{BC}	3.71 $\pm$ 1.68 ^D	3.54 $\pm$ 1.67 ^D	$\chi^2=40.23$	W=0.80	<0.001
Opus Bulk Fill APS	8.04 $\pm$ 0.93 ^A	6.92 $\pm$ 2.42 ^A	6.89 $\pm$ 1.12 ^A	6.65 $\pm$ 2.33 ^A	3.47 $\pm$ 1.51 ^B	3.65 $\pm$ 1.28 ^B	$\chi^2=36.51$	W=0.73	<0.001

Data are presented as mean $\pm$ standard deviation (SD). Within each group (row), different uppercase superscript letters across columns indicate statistically significant differences between evaluation intervals ($p < 0.05$) based on Friedman's omnibus test followed by pairwise Wilcoxon signed-rank post-hoc comparisons with Holm correction (p values derived from post-hoc Z-scores and effect sizes r).

When all five evaluators' visual color matching scores were considered (50 ratings per group and time point), acceptability rates (3-5) in Charisma Topaz One were 76% (38/50) after restoration, 78% (39/50) after staining, and 90% (45/50) after repolishing; in Charisma Bulk Flow One, 66% (33/50), 72% (36/50), and 70% (35/50); and in Opus Bulk Fill APS, 76% (38/50), 62% (31/50), and 72% (36/50), respectively. Overall acceptability across all groups was 72.7% (109/150) after restoration, 70.7% (106/150) after staining, and 77.3% (116/150) after repolishing. In the binomial GEE model, time-related terms were significant overall (Wald $\chi^2(6)=24.26$, $p=0.00047$) and the group $\times$ time interaction was also significant (Wald $\chi^2(4)=10.82$, $p=0.0286$), whereas the main effect of composite group was not significant (Wald $\chi^2(2)=1.85$, $p=0.396$). In Holm-adjusted within-group pairwise comparisons, only the staining vs repolishing comparisons (derived from post-hoc Z-scores and local effects sizes, r) in Group 1 remained significant ($p=0.0059$); all other within-group comparisons were not statistically significant ($p > 0.05$). Interrater agreement among the five evaluators differed across the evaluation phases: ICC(2,k) was 0.59 after restoration, 0.82 after staining and 0.84 after repolishing, and 0.75 when the three phases were pooled. Agreement was therefore moderate at the first time point and good thereafter.

Discussion

The present *in vitro* study evaluated the color matching and color stability of three contemporary composite resin categories using a multi-stage experimental model that integrated instrumental color measurements with visual assessments in standardized cavities prepared in natural teeth. The first and third null hypotheses were partially rejected, and the second was rejected. A significant intergroup difference was observed only in the immediate post-restoration phase, whereas staining and repolishing produced similar relative effects across materials. In addition, significant phase-related changes in color difference were detected within all composite groups, and visual acceptability was influenced by time and the group $\times$ time interaction. Although these phenomena have been examined separately in earlier reports, the present study integrates instrumental and perceptual outcomes for three distinct shade-simplification concepts within a single standardized four-stage protocol performed on natural teeth, which allows the relative contribution of each clinical phase to be compared directly. The recent syntheses of this literature do not agree with one another. The first reached a favorable but cautious conclusion, heterogeneity having prevented any pooled estimate, and it reported staining exposure and restoration depth among the factors influencing color stability without being able to quantify either

[11]. The second found single-shade and multi-shade composites clinically comparable over 12 months, although on evidence of low certainty [12]. The third, pooling *in vitro* data, found multi-shade composites to match better than single-shade materials under instrumental laboratory conditions [13]. The present design holds both constant, using a fixed 4-mm cavity depth and a defined chromogenic challenge followed by repolishing, and it extends the comparison to a single-shade flowable bulk-fill and a simplified shade-system bulk-fill material, categories that have received less attention than single-shade paste composites.

Regarding intergroup comparisons, a statistically significant difference among materials was detected only in the post-restoration versus baseline interval (2-1), in which the simplified shade-system bulk-fill paste composite (Opus Bulk Fill APS) exhibited lower ΔE_{00} values than both single-shade materials. This finding indicates a smaller color difference immediately after restoration. Similar observations have been reported in previous studies showing improved early color matching when shade selection is possible, compared with universal or monoshade systems [13,17,18]. This advantage should, however, be interpreted with caution. Although the specimens were distributed by visual assessment with the aim of obtaining comparable groups, visual matching could not equalize the instrumentally recorded color, and baseline color differed among the groups. The smaller color difference obtained with the simplified shade-system composite therefore reflects the combination of material and substrate rather than the material alone.

The lower early color difference recorded for the simplified shade-system bulk-fill composite may be attributed in part to its material design. Unlike true single-shade materials, this composite offers a limited range of predefined VITA-based shades, allowing selection of a shade closer to the original tooth color. In addition, differences in resin matrix composition, filler loading, filler particle characteristics, and photoinitiator systems may influence early optical behavior by affecting light transmission, scattering, and refractive index matching during polymerization [19,20]. The Advanced Polymerization System (APS) used in Opus Bulk Fill APS, together with its relatively high inorganic filler content, may promote more efficient early polymerization and optical stabilization, thereby enhancing the manifestation of the chameleon effect in the immediate post-restoration period.

In contrast, the single-shade materials evaluated in this study are designed to cover a wide range of tooth shades using a single chromatic formulation. Although high translucency is intended to enhance optical blending, the effectiveness of this mechanism is influenced by restoration thickness, cavity configuration, and the volume of

surrounding tooth structure contributing to light interaction [10,14,21]. In the present study, restorations were placed in standardized 4-mm-deep cavities, which may have limited the optical blending volume and allowed the intrinsic color components of the material (particularly chroma-related parameters) to remain more perceptible during the early post-polymerization phase.

When the results were evaluated using the CIEDE2000 formula, all group mean ΔE_{00} values exceeded the previously reported 50:50 perceptibility and acceptability thresholds ($PT \approx 0.8$; $AT \approx 1.8$) [22,23]. They are also higher than the values summarized in the syntheses cited above [11,13]. This is consistent with the measurement model used here, in which each color difference was recorded at the same site before and after restoration rather than between the restoration and an adjacent reference area, and with the relatively high chroma of the natural teeth used [14]. However, exceeding these thresholds does not necessarily imply clinical unacceptability. Perceptual factors such as restoration size, edge contrast, translucency, and surrounding color context may lead to discrepancies between instrumental measurements and visual perception [15,24]. Consistent with these reports, visual assessment in the present study demonstrated generally acceptable color matching despite relatively high ΔE_{00} values.

The coffee staining protocol used in this study represents an accelerated simulation of exposure to a commonly consumed chromogenic agent [25]. The observation that ΔE_{00} values in the post-staining versus baseline interval were lower than those observed immediately after restoration should not be interpreted as an improvement in true color matching. Rather, because the baseline reading was taken from the unrestored tooth before any staining, it reflects the direction in which staining moved the restored surface: Coffee immersion darkened that surface toward the chroma of the natural teeth used, which were themselves relatively dark, so the numerical difference from baseline fell without any gain in optical integration. The absence of significant intergroup differences in staining-related intervals further suggests that extrinsic discoloration is primarily governed by chromogen exposure and surface characteristics rather than by intrinsic material differences. In line with this interpretation, a previous *in vitro* model combining thermocycling, coffee immersion, and simulated brushing reported color changes exceeding the clinical acceptability threshold for both a bulk-fill flowable and an ORMOCER-based composite, irrespective of their composition [26].

Repolishing significantly reduced the ΔE_{00} values recorded against the post-restoration and post-staining states in all composite groups, which is consistent with the attention given to surface finishing in published *in vitro* staining protocols [27]. The removal of the superficial pigmented layer, together with surface smoothing,

improves light reflection and scattering, shifting the color back toward its post-restoration state. The difference from the unrestored tooth, however, did not fall below the level recorded after staining in any group, and in the single-shade flowable bulk-fill group it was significantly greater. This finding highlights repolishing as a conservative and clinically effective approach for managing extrinsic staining.

The significant time-related effects and group×time interaction observed in visual acceptability further emphasize that color perception is dynamic and influenced by both material properties and surface condition. Visual acceptability after repolishing improved significantly in one group only, so perceptual and instrumental outcomes did not move together in every material, which reinforces the importance of combining objective color measurements with observer-based evaluations when assessing esthetic outcomes.

This study has certain limitations. As an *in vitro* investigation, it cannot fully replicate the complexity of intra-oral conditions. The use of natural human teeth, while improving clinical relevance, introduces a source of variability that standardized acrylic or composite substrates do not have: Tooth color cannot be made uniform across specimens, and visual assessment could not equalize it. Baseline instrumental color consequently differed among groups, and baseline lightness was inversely related to the color difference recorded immediately after restoration. The intergroup difference at that interval should therefore be interpreted as exploratory rather than as evidence of material superiority. In addition, surface roughness and gloss were not directly measured, preventing correlation of ΔE_{00} changes with surface characteristics. Furthermore, only one representative commercial product was evaluated for each composite category, so the present findings reflect the optical behavior of these specific formulations and cannot be generalized to all single-shade, flowable bulk-fill, or simplified shade-system materials. Similarly, a single chromogenic agent (coffee) and a single accelerated staining protocol (7 days at 37°C) were used; because staining susceptibility depends on the chemistry, pH, and exposure pattern of the chromogen, the discoloration recorded here may not represent the full range of dietary staining encountered clinically. Future studies should include different chromogens, longer aging protocols, and direct surface analyses to further elucidate the mechanisms underlying color adaptation and stability.

Within the limitations of this study, the simplified shade-system bulk-fill composite demonstrated the lowest initial color difference, although the groups also differed in baseline tooth color, whereas staining and repolishing affected all materials similarly. Repolishing reversed much of the staining-related color change in all composites, supporting its role as a conservative clinical strategy for managing extrinsic discoloration.

Conclusions

Within the limitations of this *in vitro* study, the bulk-fill composite with a simplified shade system demonstrated the lowest initial color difference compared with the single-shade materials, although the groups also differed in baseline tooth color, whereas staining and repolishing produced similar relative effects across all composites. Instrumental color differences exceeded established perceptibility and acceptability thresholds; however, visual assessments indicated generally acceptable color matching, underscoring the importance of integrating perceptual evaluation with instrumental measurements. Coffee staining primarily resulted in extrinsic discoloration affecting both the restoration and the tooth structure, while repolishing reversed much of the staining-related color change in all materials. These findings suggest that repolishing represents an effective and conservative clinical approach for managing extrinsic discoloration in composite restorations.

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Institutional Review Board Statement

Ethical approval for the study was obtained from the Istanbul Kent University Health Sciences Research Ethics Committee (Approval No: E-10420511-050-51901). All procedures in this study were conducted in accordance with the Declaration of Helsinki.

Data Availability Statement

The datasets generated and analyzed during this study are available from the corresponding author upon reasonable request.

Author Contributions

Conceptualization and methodology of the study were developed by MS and EEK. Project administration and supervision were managed by MS. Investigation, specimen preparation, and restorative procedures were performed by MGK, CI, and BAD. Data curation and statistical analyses were conducted by MGK, CI, MS and BAD. The original draft of the manuscript was written by MS. Critical evaluation, validation, and final editing of the manuscript were performed by BAD and EEK. All authors read and approved the final version of the manuscript.

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Conflict of Interest

The authors declare no competing interests.

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