

RESEARCH AND EDUCATION

Illuminant metameric effects on interbrand and intrabrand color differences of direct composite resins

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Composite resins are the main direct restorative material in dentistry, and, although the material is sensitive to restorative techniques,¹ most practitioners are experienced with their use and can match tooth color with only imperceptible differences. Nevertheless, if color mismatches do occur, they are only apparent after the restoration has been placed.

All composite resins, even those of the same type, have differences in their matrix, composition, filler amount, pigments, initiators, and coupling agents.² These affect the light passing through, scattering and absorbing the light differently. Therefore, the optical properties of composite resins (refraction, reflection, absorption, transmission, opacity or translucency, and color) differ because of differences in light scattering (S) and absorption coefficients (K).³⁻⁵

Measurements of color have been based either on the visual Munsell system⁶ or the mathematical CIELab

ABSTRACT

Statement of problem. Information on the illuminant metameric effects on the intrabrand and interbrand differences in color of direct composite resins is lacking.

Purpose. The purpose of this in vitro study was to evaluate the effects of different illuminations on the color differences of the same or different brands of composite resins.

Material and methods. Sixty-four disks were prepared from 8 different direct dental composite resins of A3 shade, and, after polymerization and hydration for 48 hours, their color coordinates were measured in the Commission Internationale de l'Eclairage (CIE) L*a*b* color space with a portable colorimeter on a black and white background under D65 (daylight), F2 (cool white fluorescence), and A (incandescence) illuminations. Translucency parameters (TP) and fluorescence intensities (FI) of the brands were also measured to assist in the interpretation of brand behavior under the illuminations. The Kruskal-Wallis and Friedman nonparametric tests with post hoc multiple comparisons tests were applied to analyze the data for differences within and between brands under all illuminations ($\alpha=.05$), while regression analysis was used to estimate the relationship between D65 and F2 or A illumination data.

Results. Statistical analysis showed significant differences among brands ($P<.05$) for all color coordinates under all illuminations, with a strong linear relationship between them ($R^2=0.72-0.97$). Intrabrand differences were significantly different across brands ($P<.05$) and ranged from 0.06 to 3.1 across illuminations in ΔE^*_{ab} units (0.05 to 2.4 in ΔE_{00} units). Interbrand differences were also significantly different ($P<.05$), with a range of 0.15 to 8.7 ΔE^*_{ab} units or 0.14 to 5.7 ΔE_{00} units.

Conclusions. Primary color coordinates of composite resins were affected by A or F2 illumination and were strongly associated with D65 values. Redder or yellower composite resins were affected more under A or F2 illumination. Intrabrand differences, although small, may contribute to clinical mismatches under A or F2 illuminations. Clinicians should be aware that certain brand pairs may present acceptable differences under D65 illumination but could become unacceptable under A or F2 illumination. (J Prosthet Dent 2021;■:■-■)

system.⁷ Differences between colors are based on specific equations for the Munsell system⁸ or the CIELab system, for which the ΔE^*_{ab} ⁹ formula or its improved version ΔE_{00} have been used.¹⁰ Differences in color may be

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Clinical Implications

A possible mismatch between restorative composite resin and the replacement structure under fluorescent or incandescent illumination may be predicted by the L^* , a^* , and b^* levels under daylight.

visually imperceptible under one illumination source but under another might be significantly perceptible; this phenomenon is called illuminant metamerism, and the materials are considered to be metameric.¹¹ For this reason, small and physiologically imperceptible differences under the illumination in the dental office may become more visible under common incandescent or fluorescent illumination. Illuminants have different spectral power distributions and have been classified into standard illuminant categories from A to F to provide a basis for comparing images under different lighting conditions. An A illuminant represents domestic incandescent light of 2856 K color temperature, D50 to D75 the natural daylight of 5003 K to 7504 K, F1 to F11 the various types of fluorescent lighting of 2940 K to 6500 K, and lately LED the light-emitting diodes, which range from 2700 K to 6600 K.¹²

In their offices, clinicians usually work under fluorescent illumination, which is closer to daylight than incandescent lights. However, cool white illuminant (CWF or F2) contains minimal wavelengths >600 nm (yellow and red) in its spectrum, while incandescent illuminant (A) contains twice the >600-nm wavelength intensity contained in natural daylight.¹² Therefore, some restorative materials may behave differently from others under A or F2 illumination, and such behavior should be investigated to predict change under these lights.

Reports on direct composite resin materials tested under different illumination sources are sparse.^{13–18} However, the available studies have reported that composite resins and teeth¹³ or porcelains are metameric,¹⁴ as are different brands of composite resins.¹⁵ The metamerism index (MI) in composite resins has been reported to be low ($MI < 0.5$), with darker shades being more metameric than lighter shades.¹⁵ The ultraviolet (UV) wavelengths contained in daylight have been reported to increase the metamerism effects of composite resins,^{16,17} and the highest effect on the metamerism of composite resins of C, D65, FCW, and A illuminants has been associated with the A illuminant.¹⁵ The changes in color of composite resins under A or F2 illumination have been reported to be in the range of 0.42 to 1.27 for the L^* parameter, 0.25 to 2.23 for C (chroma), and 1.13 to 3.02 units for ΔE^*_{ab} .¹⁸

Studies on the intrabrand color differences of composite resins or dental materials other than for denture teeth¹⁹ are lacking. Intrabrand color difference refers to differences between all possible pairs in a group of specimens and identifies the clinical practice variability problem. If it is large, this inherent variability may be responsible for imperfect matches and perceptible differences under different illuminations, and the problem may become even larger if clinicians combine different composite resins of the same or even different shades. Therefore, the extent of intrabrand variability in color, whether this variability remains the same or changes under different illumination, which materials exhibit more color difference under fluorescent or incandescent illumination, and which color coordinate is the most affected, is important clinical information. Blending different materials of the same shade is also a source of variation. Composite resins of the same shade but of different manufacture have been reported to have color differences and mismatches with the shade guide,^{20–22} but whether this mismatch is affected by different illumination is unclear.

The purpose of this study was to evaluate the effects of different illuminants on the color coordinates of direct dental composite resins and calculate the extent of differences within the same brand, or between different brands of the same shade, under the different illuminations. The null hypothesis was that no significant differences would be found within or between the brands used in the study under the same or different illuminations.

MATERIAL AND METHODS

Sixty-four Ø10×1.5-mm (± 0.1 mm) disks were prepared from 8 different direct dental composite resins of A3 shade ($n=8$). Detailed compositions based on manufacturer data are shown in Table 1. The required sample size was estimated a priori with a software program (G*Power v.3.1.9.2; Universität Kiel) for ANOVA tests, with or without interactions. Input parameters were $\alpha=.05$, $1-b=0.90$, and an effect size (f) of 0.60, approximately half of the value found in a pilot study (1.15). Computations indicated a total size of 64 (8 for each brand), with an actual power of 0.905 to 0.933.

The specimens were prepared by the same experienced investigator (I.B.) and polymerized with a large-area tip of a light-emitting diode (LED) polymerization device (Mini Led Standard; Satelec Acteon) at 1250 mW/cm² for 20 seconds from the top and 20 seconds from the bottom surface. The thickness of the specimens was confirmed by a precision micrometer (Nr.537; Feinmess Suhl GmbH), and their surface was visually examined for defects. The disks remained dry in a dark chamber and

Table 1. Description of materials used

Material (Code)	Company	Type	Composition	Filler Loading	Shade	Exp. Date	Batch No
Essentia (A)	GC Dental Corp	mh	UDMA, BisMEPP, silicon dioxide, fluoro-alumino-silicate glass	76 wt % (63 vol %)	Dark enamel	2020-01	1601121
Herculite XRV Ultra (B)	Kerr Corp	nh	BisGMA, TEGDMA, barium glass filler (0.4µm) silicon dioxide (0.02-0.05µm)	78 wt %	A3	2022-02	7090524
Opallis (C)	FGM Produtos Odontologicos	mh	BisGMA, BisEMA, TEGDMA, (resin matrix = 21-22.5%), and barium glass, aluminum silicate and silica dioxide fillers.	77-79 wt %	EA3	2021-02	270218
Herculite Classic (D)	Kerr Corp	mh	BisGMA, TEGMA, borosilicate-aluminum glass (average particle size 0.6µm).	79 wt %	A3	2020-03	6323214
G-aenial (E)	GC Dental Corp	mh	UDMA and dimethacrylate co-monomers, strontium-lanthanum-fluoride prepolymerized fillers, silica, fumed silica, 16-17 µm (400-nm strontium glass, 100-nm lanthanum fluoride, 16-nm silica)	76 wt % (62 vol %)	A3	2021-10-02	1810031
TPH Spectrum (F)	Dentsply/Caulk	mh	BisGMA, BisEMA, TEGDMA, Barium aluminum borosilicate glass (mean particle size < 1 µm), and highly dispersed silicon dioxide (particle size 10-20 nm)	77 wt % (57 vol %)	A3	2021-10-31	1,81E+09
Inspiro (G)	Edelweiss DR	nh	BisGMA-based matrix with barium-alumino-fluoride glass, (size 0.02-2 µm).	83 wt %	Skin neutral	2021-10	201234
Mosaic (H)	Ultradent	nh	BisGMA, PEGDMA, TEGDMA, zirconia-silica glass ceramic and nanometer silica fillers	56 vol %	A3	2020-09	BG777

BisEMA, ethoxylated bisphenol-A dimethacrylate; BisGMA, bisphenylglycidyl dimethacrylate; BisMEPP, bisphenol A methacryloxy etoxy phenyl propane; mh, microhybrid; nh, nanohybrid; PEGDMA, polyethylene glycol dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.

were then hydrated in a 37 °C distilled water bath for 48 hours before the measurements.

The CIELab coordinates (L^* , a^* , and b^*) were made with a portable colorimeter (FRU-WR18; Shenzhen Wave Optoelectronics Technology Co, Ltd) with a reported accuracy of $\Delta E < 0.06$. The measurements were made on a black ($36.96L^*$, $-0.005a^*$, $-1.23b^*$) and a white ($97.79L^*$, $-1.19a^*$, $0.87b^*$) background under D65 (6504 K), F2 (4200 K), and A (2856 K) light sources. The measuring window was Ø4 mm, and the observer angle was 10 degrees. The average of 3 measurements of each parameter, made in the center of the same specimen surface blindly by the same experienced person (N.P.) was recorded. Color differences for pairs under the different illuminations were calculated from $\Delta E^*_{ab} = ([L^*_1 - L^*_2]^2 + [a^*_1 - a^*_2]^2 + [b^*_1 - b^*_2]^2)^{1/2}$.²³ The calculated ΔE^*_{ab} values of all possible pairs of the same material (intra-brand differences) were $28(n \times [n-1]/2)$, where $n=8$, while the differences of pairs between different brands (inter-brand differences) for the same illumination were $1792([N \times [N-1]/2] - [28 \times 8])$, where $N=64$.

The authors are unaware of a study reporting differences under different illuminations in ΔE_{00} units of the newer CIEDE2000 definition for differences.¹⁰ Therefore, the formula $\Delta E_{00} = ([\Delta L'/K_L S_L]^2 + [\Delta C'/K_C S_C]^2 + [\Delta H'/K_H S_H]^2 + RT[\Delta C'/K_C S_C][\Delta H'/K_H S_H])^{1/2}$ was also used. Factors $\Delta L'$, $\Delta C'$, $\Delta H'$ represent differences in lightness, chroma, and hue. K_L , K_C , and K_H are weighted factors. S_L , S_C , and S_H are averaging factors for lightness, chroma, and hue. RT is an overall correction factor based on differences in hue and chroma. The weighted parametric factors K_L , K_C , and K_H were set to 2, 1, and 1.²⁴ For the interpretation of the results, the translucency parameter (TP) was considered necessary and

calculated²⁵ from $TP = ([L^*_b - L^*_w]^2 + [a^*_b - a^*_w]^2 + [b^*_b - b^*_w]^2)^{1/2}$, where b and w denote black and white backgrounds.

The fluorescence of materials was measured by using a reflectance spectrophotometer (Ci64 UV; X-Rite Inc) of a repeated accuracy $\Delta E^*_{ab} < 0.015$, with and without the use of a UV 365-nm band pass filter. Fluorescence intensities (FI) were based on the highest difference in the reflectance spectra of the materials, in the area between 400 to 480 nm.

Data were analyzed for differences within and between brands by using 1-way nonparametric Kruskal-Wallis tests with Dunn post hoc pairwise multiple comparisons ($\alpha=.05$), since Kolmogorov-Smirnov for normality and the Levene statistic for equality of error variances showed a violation of normality ($P>.05$) and equality of variances ($P>.05$). For the differences between the illumination modes, the Friedman test was used with a statistical software package (MedCalc v.10.2.0; MedCalc Software Ltd).

RESULTS

The mean L^* , a^* , and b^* values and standard deviation of all brands under D65, F2, and A illuminations are presented graphically in Figure 1. The Kruskal-Wallis and Friedman tests showed significant differences among brands ($P<.001$) and illuminations ($P<.001$) for all color coordinates. Table 2 indicates these differences located by multiple comparison tests. Regression analysis showed a strong linear relation of D65 values with F2 and A values for all coordinates (Table 3).

Differences in color between specimens of the same brand (intra-brand differences) in ΔE^*_{ab} and ΔE_{00} values

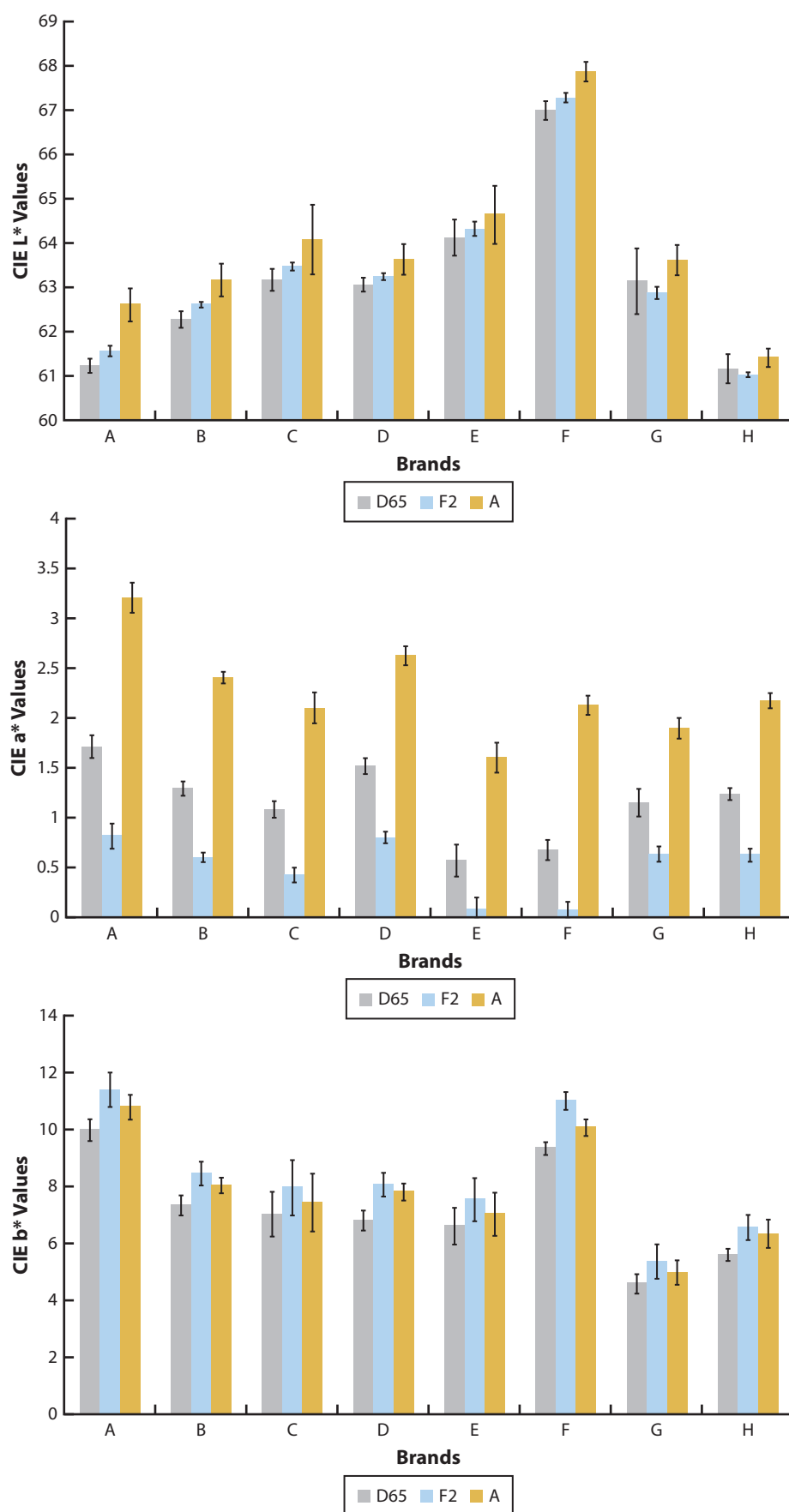


Figure 1. Mean values with standard deviation bars of composite resins under D65, F2, and A illuminations. A, CIE L*. B, CIE a*. C, CIE b*.

Table 2. Results of statistical evaluation between brands and illuminants of primary color coordinates (L^* , a^* , and b^*) ($n=8$)

Brand	L^*			a^*			b^*		
	D65	F2	A	D65	F2	A	D65	F2	A
A	bc\ a	de\ a	cd\ b	a\ a	a\ ab	a\ b	a\ a	a\ b	a\ ab
B	bc\ a	cde\ ab	bcd\ b	abc\ a	abcd\ ab	abc\ b	ab\ a	ab\ b	abc\ ab
C	ab\ a	abc\ ab	abc\ b	bcde\ a	bcd\ ab	cde\ b	abc\ a	abc\ b	bcd\ ab
D	abc\ a	abcd\ ab	abc\ b	ab\ a	ac\ ab	ab\ b	bc\ a	abc\ b	abc\ ab
E	a\ a	ab\ ab	ab\ b	e\ a	d\ ab	e\ b	c\ a	bc\ b	d\ ab
F	a\ a	bcde\ ab	a\ b	de\ a	d\ ab	bcde\ b	ab\ a	a\ b	ab\ ab
G	ab\ a	a\ ab	abcd\ b	cde\ a	ab\ ab	de\ b	c\ a	c\ b	d\ ab
H	c\ a	e\ a	d\ a	abcd\ a	abc\ ab	bcd\ b	c\ a	bc\ b	cd\ b

Same subscript letters before slash indicate no differences between brands for the same column, while after slash no differences between illuminations for same brand and coordinate ($P>.05$).

are presented in Table 4. They were significantly different as indicated by the Kruskal-Wallis ($P<.001$) and Friedman tests ($P<.001$) (Table 4). Regression analysis showed a linear relationship of medium strength for D65 differences with those under F2 and A illumination, either in ΔE^*_{ab} or ΔE_{00} values (Table 3).

Color differences in pairs of different brands (inter-brand differences) are shown in Table 5, and many of them exceed the level of 3 to 4 units. The Kruskal-Wallis tests revealed significant differences among pairs ($P<.001$) located by post hoc multiple comparisons (Table 5). Regression analysis indicated a strong linear relationship of ΔE^*_{ab} or ΔE_{00} values under D65 illumination with those under F2 and A (Table 3).

Mean TP and FI values of all brands under D65 illumination are shown in Table 6. The Kruskal-Wallis and 1-way ANOVA tests showed significant differences in TP values ($P<.001$) and FI values ($F=9.2$, $P<.001$) among brands. ANOVA tests were used because the Kolmogorov-Smirnov and Levene tests were showing no violation of normality ($P>.05$) or homoscedasticity ($P>.05$). Regression analysis showed a weak coefficient of determination ($R^2=0.272$) of TP values with those of FI.

DISCUSSION

The study led to the rejection of the null hypothesis, that there are no significant color differences either within (intra-) or between (inter-) brands of dental restorative composite resins of the same shade under the investigated D65, F2, and A illuminations. Under D65 illumination, L^* values across brands were significantly different, with brand F showing the highest value and A and H the lowest. Parameters a^* and b^* were also significantly different. The values were consistent with, but slightly higher than, those reported by Kim and Lee,²¹ probably because of differences in the investigated brands. Under F2 illumination, the L^* and b^* values increased, while the a^* values decreased. Under A illumination, all values increased at levels close to those under F2 illumination. Based on these values, the expected mean color difference was estimated to be 1.27

Table 3. Coefficient of determination (R^2) and regression equations of L^* , a^* , and b^* color coordinates and intrabrand or interbrand ΔE^*_{ab} and ΔE_{00} values for illumination pairs ($n=64$)

Parameter	Illum.pair	R R^2	Equation
L^*	D65,F2	0.963	$y=1.01x-0.542$
—	D65,A	0.955	$y=0.99x+0.956$
a^*	D65,F2	0.839	$y=0.718x-0.321$
—	D65,A	0.717	$y=1.058x+1.044$
b^*	D65,F2	0.971	$y=1.144x+0.092$
—	D65,A	0.974	$y=1.057x+0.234$
ΔE^*_{ab}	D65,F2	0.488	$y=0.752x+0.328$
Intrabrand	D65,A	0.694	$y=0.967x+0.163$
ΔE_{00}	D65,F2	0.567	$y=0.864x+0.156$
—	D65,A	0.697	$y=1.004x+0.060$
ΔE^*_{ab}	D65,F2	0.940	$y=1.077x+0.19$
Interbrand	D65,A	0.943	$y=1.007x+0.152$
ΔE_{00}	D65,F2	0.925	$y=1.091x-0.093$
—	D65,A	0.930	$y=1.005x+0.058$

ΔE^*_{ab} units under F2 and 1.42 under A illumination. Such values seem capable of leading to a visual mismatch for a selected material if a small difference from the ideal match is already present. Regression analysis indicated a strong linear relationship of F2 and A values with D65, indicating that the changes could be easily predicted.

Most of the color changes were primarily the result of illuminant interaction with the materials. Illuminant F2 had a weak intensity at wavelengths >600 nm, and therefore, with low red reflectance. Illuminant A, in contrast, was strong at wavelengths >600 nm, and therefore, a^* and b^* reflectance were higher. For the same reason, materials with higher a^* and b^* values showed more intense changes under F2 and A illumination. These results were consistent with those of Park et al,¹⁵ who reported that illuminant A induced greater metamerism than illuminants C or FCW. They also reported that dark shades of composite resin were more metameric than light ones. A stronger metameric effect of A than F2 illumination was also reported by Lee and Powers.¹⁸ They reported an overall range of changes in the L^* parameter of 0.42 to 1.27 similar to the present results. The same authors¹⁸ investigated the color

Table 4. Differences in color (in ΔE^*_{ab} and ΔE_{00} values) between pairs of same brand (intra-brand differences) under D65, F2, and A illuminations (n=28)

Brand	ΔE^*_{ab}			ΔE_{00}		
	D65	F2	A	D65	F2	A
A	0.55 $\pm$ 0.26 _{b\ a}	0.93 $\pm$ 0.42 _{b\ b}	0.62 $\pm$ 0.34 _{a\ a}	0.44 $\pm$ 0.17 _{abc\ b}	0.59 $\pm$ 0.26 _{c\ a}	0.44 $\pm$ 0.21 _{c\ b}
B	0.52 $\pm$ 0.27 _{b\ a}	0.57 $\pm$ 0.32 _{bc\ a}	0.55 $\pm$ 0.25 _{b\ a}	0.38 $\pm$ 0.20 _{cd\ a}	0.40 $\pm$ 0.23 _{c\ a}	0.32 $\pm$ 0.14 _{d\ a}
C	1.03 $\pm$ 0.58 _{a\ a}	1.24 $\pm$ 0.69 _{a\ a}	1.35 $\pm$ 0.74 _{a\ a}	0.77 $\pm$ 0.45 _{a\ a}	0.90 $\pm$ 0.52 _{a\ a}	0.97 $\pm$ 0.56 _{a\ a}
D	0.48 $\pm$ 0.24 _{b\ a}	0.63 $\pm$ 0.29 _{bc\ a}	0.58 $\pm$ 0.29 _{b\ a}	0.36 $\pm$ 0.18 _{cd\ a}	0.42 $\pm$ 0.21 _{c\ a}	0.36 $\pm$ 0.18 _{cd\ a}
E	1.01 $\pm$ 0.47 _{a\ a}	1.14 $\pm$ 0.57 _{a\ a}	1.11 $\pm$ 0.61 _{a\ a}	0.73 $\pm$ 0.36 _{a\ a}	0.78 $\pm$ 0.40 _{ab\ a}	0.79 $\pm$ 0.44 _{a\ a}
F	0.42 $\pm$ 0.21 _{b\ a}	0.49 $\pm$ 0.22 _{c\ a}	0.55 $\pm$ 0.24 _{b\ a}	0.29 $\pm$ 0.15 _{d\ a}	0.32 $\pm$ 0.14 _{c\ a}	0.35 $\pm$ 0.14 _{cd\ a}
G	1.04 $\pm$ 0.57 _{a\ a}	0.97 $\pm$ 0.39 _{a\ a}	1.07 $\pm$ 0.51 _{a\ a}	0.61 $\pm$ 0.28 _{b\ a}	0.68 $\pm$ 0.33 _{ab\ a}	0.63 $\pm$ 0.26 _{ab\ a}
H	0.51 $\pm$ 0.26 _{b\ a}	0.84 $\pm$ 0.35 _{c\ b}	0.85 $\pm$ 0.40 _{a\ b}	0.31 $\pm$ 0.13 _{b\ b}	0.53 $\pm$ 0.24 _{b\ a}	0.54 $\pm$ 0.31 _{bc\ a}

Same subscript letters before slash indicate no differences between brands for same column, while after slash no differences between illuminations for same brand and formula ($P > .05$).

Table 5. ΔE^*_{ab} values between brands (inter-brand differences), under all illuminations (n=64)

Brand Pair	D65	F2	A
A-B	2.89 $\pm$ 0.42 _{e\ a}	3.19 $\pm$ 0.58 _{f\ b}	2.94 $\pm$ 0.47 _{e\ a}
A-C	3.63 $\pm$ 0.64 _{d\ a}	4.02 $\pm$ 0.87 _{e\ b}	3.85 $\pm$ 0.95 _{a\ b}
A-D	3.69 $\pm$ 0.38 _{d\ a}	3.78 $\pm$ 0.54 _{e\ a}	3.24 $\pm$ 0.46 _{d\ b}
A-E	4.61 $\pm$ 0.57 _{bc\ a}	4.87 $\pm$ 0.71 _{d\ b}	4.60 $\pm$ 0.75 _{c\ a\ b}
A-F	5.91 $\pm$ 0.22 _{a\ a}	5.82 $\pm$ 0.37 _{b\ a}	5.45 $\pm$ 0.27 _{b\ b}
A-G	5.79 $\pm$ 0.46 _{a\ a}	6.21 $\pm$ 0.75 _{b\ b}	6.07 $\pm$ 0.55 _{a\ b}
A-H	4.41 $\pm$ 0.40 _{c\ a}	4.89 $\pm$ 0.70 _{d\ a}	4.74 $\pm$ 0.65 _{bc\ b}
B-C	1.26 $\pm$ 0.36 _{a\ a}	1.36 $\pm$ 0.46 _{k\ a\ b}	1.50 $\pm$ 0.48 _{h\ b}
B-D	1.08 $\pm$ 0.26 _{j\ a}	0.95 $\pm$ 0.29 _{j\ a}	0.77 $\pm$ 0.26 _{b\ b}
B-E	2.24 $\pm$ 0.38 _{h\ a}	2.19 $\pm$ 0.39 _{i\ a}	2.11 $\pm$ 0.49 _{a\ a}
B-F	5.18 $\pm$ 0.33 _{a\ a}	5.37 $\pm$ 0.40 _{b\ b}	5.15 $\pm$ 0.40 _{a\ a}
B-G	2.98 $\pm$ 0.47 _{e\ a}	3.13 $\pm$ 0.67 _{fg\ a\ b}	3.21 $\pm$ 0.46 _{de\ b}
B-H	2.08 $\pm$ 0.45 _{a\ a}	2.50 $\pm$ 0.56 _{b\ b}	2.51 $\pm$ 0.52 _{g\ b}
C-D	0.94 $\pm$ 0.33 _{j\ a}	1.05 $\pm$ 0.42 _{j\ a}	1.26 $\pm$ 0.47 _{h\ b}
C-E	1.50 $\pm$ 0.47 _{j\ a}	1.52 $\pm$ 0.56 _{jk\ a}	1.43 $\pm$ 0.65 _{h\ a}
C-F	4.52 $\pm$ 0.56 _{c\ a}	4.94 $\pm$ 0.71 _{c\ b}	4.69 $\pm$ 0.68 _{bc\ a\ b}
C-G	2.57 $\pm$ 0.79 _{f\ a}	2.73 $\pm$ 1.05 _{h\ a}	2.63 $\pm$ 1.02 _{f\ a}
C-H	2.56 $\pm$ 0.58 _{f\ a}	2.96 $\pm$ 0.65 _{g\ b}	3.07 $\pm$ 0.59 _{e\ b}
D-E	1.62 $\pm$ 0.29 _{j\ a}	1.67 $\pm$ 0.33 _{j\ a\ b}	1.83 $\pm$ 0.43 _{b\ b}
D-F	4.76 $\pm$ 0.33 _{b\ a}	5.07 $\pm$ 0.43 _{c\ b}	4.85 $\pm$ 0.43 _{b\ a}
D-G	2.36 $\pm$ 0.47 _{gh\ a}	2.77 $\pm$ 0.67 _{h\ b}	3.00 $\pm$ 0.48 _{e\ c}
D-H	2.29 $\pm$ 0.43 _{h\ a}	2.73 $\pm$ 0.54 _{h\ b}	2.75 $\pm$ 0.54 _{f\ b}
E-F	3.99 $\pm$ 0.52 _{a\ a}	4.60 $\pm$ 0.68 _{b\ b}	4.52 $\pm$ 0.58 _{c\ b}
E-G	2.47 $\pm$ 0.70 _{fg\ a}	2.76 $\pm$ 0.85 _{h\ a}	2.45 $\pm$ 0.81 _{g\ a}
E-H	3.27 $\pm$ 0.49 _{a\ a}	3.57 $\pm$ 0.63 _{b\ b}	3.48 $\pm$ 0.52 _{a\ b}
F-G	6.15 $\pm$ 0.63 _{a\ a}	7.19 $\pm$ 0.60 _{a\ b}	6.66 $\pm$ 0.67 _{a\ c}
F-H	6.95 $\pm$ 0.42 _{a\ a}	7.70 $\pm$ 0.52 _{a\ b}	7.48 $\pm$ 0.51 _{b\ b}
G-H	2.32 $\pm$ 0.61 _{h\ a}	2.31 $\pm$ 0.62 _{j\ a}	2.70 $\pm$ 0.68 _{f\ b}

Same subscript letters before slash indicate no differences between pairs for same column while after slash no differences between illuminations for same pair ($P > .05$).

differences using CIE $L^*C^*h^*$ coordinates and reported changes in chroma of a range between 0.25 and 2.23 units. Based on the formula $C^* = (a^{*2} + b^{*2})^{1/2}$ chroma was calculated for the present data, and the range found was slightly lower (0.74 to 1.35) but within a similar range. The small differences between the 2 studies were presumably because of differences in the investigated brands.

While the differences of L^* , a^* , and b^* were below the physiologically unacceptable level,²⁶ with a change

Table 6. Translucency parameters (TP) and fluorescence intensities (FI) of brands under D65 illumination (n=8)

Brand	TP	FI
A	8.30 $\pm$ 0.83 ab	0.98 $\pm$ 0.21 a
B	7.72 $\pm$ 0.33 bc	0.64 $\pm$ 0.14 b
C	7.05 $\pm$ 0.54 bcd	0.69 $\pm$ 0.25 b
D	5.71 $\pm$ 0.33 bcd	0.78 $\pm$ 0.21 b
E	12.12 $\pm$ 0.55 a	0.95 $\pm$ 0.15 a
F	3.15 $\pm$ 0.13 d	0.35 $\pm$ 0.06 c
G	8.10 $\pm$ 0.59 ab	0.74 $\pm$ 0.30 b
H	5.01 $\pm$ 0.24 cd	0.44 $\pm$ 0.17 c

Same letters in column indicate no differences between materials ($P > .05$).

of illumination from D65 to F2 or A they may lead to mismatches if added to an existing inter-brand difference, as for repairs where different brands might be combined. Therefore, if a composite resin that is slightly redder than correct is selected, it will probably appear the same or less red under F2 illumination but redder under A. If a yellower composite resin is chosen, an even yellower appearance would be expected, especially under F2 illumination. Finally, if a resin that is a little lighter than correct is chosen, the difference would not increase under F2 but would appear much lighter under A. The result depends on the size of the differences in the primary color coordinates (L^* , a^* , and b^*) under D65 illumination. Therefore, measuring the color differences between composite resins and the neighboring structures under D65 illumination is important for predicting composite resin behavior under F2 or A. However, this should be done in terms of primary color coordinates and not only in secondary ΔE^*_{ab} values, as has been customary practice.

Intra-brand differences under D65 illumination were higher in C, E, and G brands. Under F2 illumination, the differences remained similar to those under D65, and only A and H brands showed a significant increase. Under A illumination, intra-brand differences did not change significantly, except for brand H, which increased as much as under F2 illumination. The differences of composite resins under D65 illumination were probably

the result of the materials' internal structure and composition or the manufacturing processes.

The F2 and A illuminations seemed to affect the intrabrand differences of the materials insignificantly, with 2 exceptions (brands A and H). Brand A is a material with high a^* and b^* values and high FI that may partly explain why, under F2 illumination, its intrabrand difference is doubled (1.0 unit). Brand H has low FI and TP values, and its increased difference under F2 illumination was not a result of low fluorescence but translucency (high opacity). Opacity is the result of high absorption and/or scattering of the light entering a material and determines the quality and quantity of light emerging from it.²⁷ Therefore, absorbance studies are essential for a detailed investigation of material behavior under different illuminations. In practice, even though a composite resin with high internal color variability may be used, a change of illumination from D65 to F2 or A should not result in significant changes in appearance. However, with high-chroma shades or high fluorescence and opacity materials, significant changes under F2 illumination that could alter the esthetic result may be seen. For this reason, this effect is important clinically, and additional investigation is needed.

The largest interbrand differences in color under D65 illumination were related to F-G and F-H pairs and the smallest to C-D and B-D. The range of color differences was similar to that of 0.7 to 11.0 units reported by Kim and Lee.²¹ Under A and F2 illumination, overall ΔE^*_{ab} values increased by only a small but still significant amount in several pairs, as under D65 illumination. For this reason, some of the materials are inappropriate substitutions. The largest differences were related to the F brand. Brand F is a microhybrid composite resin with low FI but high L^* and b^* values, explaining its greater color differences from other brands. Under A and F2 illuminations, the differences increase at a greater level, and therefore, substituting for other materials is not appropriate. Large differences were also related to brand A. Again, brand A is a material of high a^* and b^* values, and therefore, its color difference from the others is large, with a further increase under F2 illumination. Therefore, brand A is also a material to avoid as a substitute. When the color of a composite resin is selected, it should be close to that of the structure being replaced, since a small and unnoticed mismatch will increase under F2 or A illumination. It would be wise to test the appearance of a restoration under daylight conditions and also under incandescent or fluorescence lights.

Limitations of this study included the potential to underestimate the color and translucency of composite resins as a result of the edge loss effect. Edge loss occurs with contact colorimeters when part of the reflected light from the device's measuring opening is lost. The loss concerns the magnitude of the transmitted light wave

(lightness), as well as its length (hue). However, this was a comparative study, and this phenomenon affected the evaluated materials equally, which were all enamel types with similar translucency. Since most dental composite resins are translucent, future studies should characterize the light lost from teeth and dental materials because of edge loss. Changes to the color of composite resins under other common light sources, such as warm fluorescence lights (WFL), tube luminescence 830 (TL830), or light emission diodes (LEDs), also need more investigation.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. The color coordinates, translucency parameter, and fluorescence intensities of composite resins of the same shade presented significant differences under D65 illumination ($P < .05$). Color changes under F2 or A illumination light were small but highly predictable from D65 data, with redder or yellower composites more affected.
2. Mean intrabrand differences in color under D65 illumination were material dependent, with values of $0.69 \Delta E^*_{ab}$ or $0.49 \Delta E_{00}$ units. Under A or F2 illumination light, these either increased or decreased, depending on brand and illumination.
3. Mean interbrand differences were $3.3 \Delta E^*_{ab}$ or $2.15 \Delta E_{00}$ units under D65 illumination and increased linearly under F2 or A illumination.

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