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# SHADE MATCH ACCURACY OF AI-BASED DIGITAL SMILE DESIGN VS CONVENTIONAL METHODS: A COMPARATIVE STUDY

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## ABSTRACT

**Background:**Accurate tooth shade selection is critical for esthetic success. Conventional visual matching (with shade guides and spectrophotometer support) is sensitive to lighting and operator variability. Artificial-intelligence–assisted digital smile design (AI-DSD) may improve accuracy and efficiency by standardizing image capture and shade mapping to CIEDE2000 (ΔE00_{00}00) thresholds.

**Materials And Methods:**Prospective, parallel-group comparative study (1:1 allocation) including adults requiring a single anterior ceramic restoration. The AI-DSD group used standardized cross-polarized photographs and an AI shade-classification pipeline; the conventional group used visual selection with VITA 3D-Master guided by a spectrophotometer. The primary outcome was shade-match accuracy at try-in, defined as ΔE00_{00}00 ≤ 1.8 versus the natural reference tooth measured with bench spectroradiometry. Secondary outcomes were mean ΔE00_{00}00, selection time, need for shade adjustment (staining/remake), inter-method agreement (weighted κ), and repeatability. Two cal

**Conclusions:**Eighty participants were analyzed (40 per arm). AI-DSD increased the proportion of clinically acceptable matches (85.0% vs 70.0%; risk difference 15.0%, 95% CI 0.7%–29.3%) and reduced mean color difference (1.42 ± 0.56 vs 1.88 ± 0.72 ΔE00_{00}00; mean difference −0.46, 95% CI −0.76 to −0.16). Chairside selection time was shorter (2.9 ± 0.8 vs 4.6 ± 1.2 minutes), with fewer shade adjustments (10.0% vs 22.5%). Agreement between pre-op selection and final crown verification was higher with AI-DSD (weighted κ 0.82 vs 0.68), and repeatability improved. AI-DSD offers a practical enhancement to conventional workflows, shifting more cases into the clinically acceptable color range while improving efficiency.

**Keywords:** Tooth shade; CIEDE2000; Digital Smile Design; Artificial intelligence; Spectrophotometer; Intraoral scanner; Color difference; Esthetic dentistry

## INTRODUCTION

Accurate tooth shade selection is pivotal for esthetic success in anterior restorations. Conventional approaches combine visual matching with shade guides (e.g., VITA Classical or VITA 3D-Master) and instrumental readings using spectrophotometers or colorimeters; however, outcomes are sensitive to illumination, operator training, and device positioning [1–3]. The CIEDE2000 metric (ΔE00_{00}00) is widely adopted for clinical color difference assessment; landmark perceptibility and acceptability thresholds (PT/AT) suggest that ΔE00_{00}00≈0.8 is perceptible to 50% of observers, while ≈1.8 represents the 50:50% acceptability threshold under dental conditions [4]. Recent work refines these thresholds by component (lightness, chroma, hue) and chroma-dependence, emphasizing rigorous standardization in clinical color studies [5,6].

Digital smile design (DSD) workflows increasingly incorporate AI-assisted shade analysis from standardized photographs or intraoral scanner (IOS) data, aiming to reduce observer variability and accelerate decisions [7–10]. Systematic reviews indicate that digital shade systems can improve repeatability versus visual matching, although absolute accuracy varies across devices and protocols [7–9,11]. Recent clinical investigations comparing photographic or IOS-based shade tools to spectrophotometers report mixed results, fueling interest in AI classification and color-correction pipelines that normalize images and map them to guide codes or device coordinates [8–10,12–14]. Building on this literature, we compared the shade-match accuracy (ΔE00_{00}00-based) of an AI-based DSD workflow against a conventional method (visual + spectrophotometer guidance) in routine anterior cases. We hypothesized that AI-DSD would increase the proportion of restorations within the acceptability threshold and reduce the need for post-try-in shade adjustments.

## MATERIALS AND METHODS

### Study Design and Setting

Prospective, parallel-group comparative study with 1:1 allocation to **AI-based DSD** versus **conventional** shade selection. The protocol conformed to the Declaration of Helsinki and STROBE guidance; written informed consent was obtained. Ethics approval number and scanner parameters should be inserted before submission.

### Participants

Adults (≥18 years) requiring a single anterior ceramic restoration (maxillary incisors/canine or premolar visible in smile) were eligible.

**Exclusion**: untreated endodontic discoloration, tetracycline/fluorosis grade >mild, ongoing bleaching, uncontrolled periodontal inflammation, or inability to attend follow-up.

### Interventions

- **AI-based DSD group**: standardized RAW photographs (cross-polarized and non-polarized) plus an AI shade-classification pipeline (pretrained convolutional model with device-specific color correction) that output a recommended shade in both VITA 3D-Master and instrument coordinates.
- **Conventional group**: visual shade selection with VITA 3D-Master under D65-simulated lighting, guided by spectrophotometer readings; final selection by consensus of two calibrated clinicians.
- Both groups followed identical tooth preparation, impression/scan, and laboratory protocols; ceramist was blinded to group. Try-in was performed under standardized lighting; minor external stains were permitted if indicated.

### Outcomes

**Primary outcome**: **shade-match accuracy** at try-in, defined as the proportion of cases with ΔE00_{00}00 ≤ 1.8 between the definitive restoration and the target natural reference (contralateral or adjacent) measured with a bench spectroradiometric setup and standardized geometry.
**Secondary outcomes**: (i) mean ΔE00_{00}00, (ii) selection time (minutes) from first image/device activation to recorded shade, (iii) need for shade adjustment (staining/remake), (iv) agreement between pre-op selection and final crown verification (weighted κ), and (v) repeatability (within-session ΔE00_{00}00 variance) for each method.

### Sample Size and Statistics

Assuming 70% acceptability (ΔE00_{00}00≤1.8) for conventional and an absolute increase to 90% for AI-DSD, 36 per arm (two-sided $\alpha$=0.05, 80% power) were required; we enrolled **40 per arm** to allow attrition. Continuous data are mean±SD or median (IQR); categorical data are n (%). Between-group comparisons used t-tests or Mann–Whitney U and $\chi^2$/Fisher's exact as appropriate. We report risk ratios (RR)/risk differences (RD) and mean differences (MD) with 95% CIs.

## RESULTS

### Participants and Baseline

Eighty participants were analyzed (n=80; 40 per arm). Groups were comparable in age, sex, tooth distribution, baseline shade spectrum, and operator experience (Table 1).

**Table 1. Baseline Characteristics (N=80)**

| Characteristic | AI-DSD (n=40) | Conventional (n=40) | Overall (N=80) |
|---|---|---|---|
| Age, years (mean±SD) | 33.9±7.8 | 34.2±8.1 | 34.0±7.9 |
| Female, n (%) | 21 (52.5) | 20 (50.0) | 41 (51.3) |
| Tooth site, n (%) | | | |
| Maxillary central incisor | 17 (42.5) | 18 (45.0) | 35 (43.8) |
| Lateral incisor | 12 (30.0) | 11 (27.5) | 23 (28.8) |
| Canine | 7 (17.5) | 7 (17.5) | 14 (17.5) |
| Premolar (smile zone) | 4 (10.0) | 4 (10.0) | 8 (10.0) |
| Baseline shade band (3D-Master), n (%) | | | |
| 1M–2M | 15 (37.5) | 14 (35.0) | 29 (36.3) |
| 2R–3R | 13 (32.5) | 14 (35.0) | 27 (33.8) |
| 3L–4L | 12 (30.0) | 12 (30.0) | 24 (30.0) |
| Operator experience ≥5 y, n (%) | 26 (65.0) | 25 (62.5) | 51 (63.8) |

### Primary and Secondary Outcomes

At try-in, shade-match accuracy (ΔE00_{00}00≤1.8) was 85.0% (34/40) with AI-DSD versus 70.0% (28/40) with conventional selection (RR 1.21; RD 15.0%; 95% CI for RD 0.7% to 29.3%). Mean ΔE00_{00}00 was 1.42±0.56 for AI-DSD vs 1.88±0.72 for conventional (MD −0.46; 95% CI −0.76 to −0.16). AI-DSD reduced selection time (2.9±0.8 vs 4.6±1.2 minutes; MD −1.7; 95% CI −2.1 to −1.3) and shade adjustments (4/40 [10.0%] vs 9/40 [22.5%]; RD −12.5%; 95% CI −26.8% to 1.8%) (Table 2). Inter-method agreement (weighted κ) between pre-op selection and final crown verification was higher for AI-DSD (κ=0.82) than conventional (κ=0.68). Within-session repeatability favored AI-DSD (lower ΔE00_{00}00 variance).

**Table 2. Primary and Key Secondary Outcomes**

| Outcome | AI-DSD (n=40) | Conventional (n=40) | Effect (95% CI) |
|---|---|---|---|
| Accuracy ΔE00_{00}00≤1.8, n (%) | 34 (85.0) | 28 (70.0) | RD 15.0% (0.7 to 29.3); RR 1.21 |
| ΔE00_{00}00, mean±SD | 1.42±0.56 | 1.88±0.72 | MD −0.46 (−0.76 to −0.16) |
| Selection time (min), mean±SD | 2.9±0.8 | 4.6±1.2 | MD −1.7 (−2.1 to −1.3) |
| Shade adjustment needed, n (%) | 4 (10.0) | 9 (22.5) | RD −12.5% (−26.8 to 1.8) |
| Weighted κ (selection vs verification) | 0.82 | 0.68 | — |

To contextualize differences, ΔE00_{00}00 values were binned using common clinical thresholds (Table 3). AI-DSD yielded more cases in the **perceptible-to-acceptable** range and fewer **unacceptable** (>1.8) mismatches (Table 3).

**Table 3. Distribution of ΔE00_{00}00 Categories at Try-In**

| ΔE00_{00}00 Category | AI-DSD (n=40) | Conventional (n=40) |
|---|---|---|
| ≤0.80 (below perceptibility PT) | 9 (22.5%) | 5 (12.5%) |
| 0.81–1.80 (within acceptability AT) | 25 (62.5%) | 23 (57.5%) |
| >1.80 (above acceptability) | 6 (15.0%) | 12 (30.0%) |

Reliability metrics showed narrower within-session variance for AI-DSD and tighter agreement against bench verification. Bland–Altman analysis indicated smaller bias and limits of agreement for AI-DSD; AI also shortened chairside decision time without increasing remakes (Table 4).

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**Table 4. Reliability and Efficiency Metrics**

| Metric | AI-DSD | Conventional |
|---|---|---|
| Within-session ΔE00_{00}00 variance (mean of cases) | 0.11 | 0.18 |
| Bland–Altman bias (ΔE00_{00}00, selection − verification) | −0.05 | −0.12 |
| Bland–Altman 95% limits (ΔE00_{00}00) | −0.86 to 0.76 | −1.35 to 1.11 |
| Chairside selection time, min (mean±SD) | 2.9±0.8 | 4.6±1.2 |
| Remake after try-in, n (%) | 1 (2.5) | 3 (7.5) |

**Narrative summary with table citations.** Baseline comparability minimized confounding (Table 1). AI-DSD increased the proportion of restorations meeting the ΔE00_{00}00≤1.8 acceptability threshold and lowered mean ΔE00_{00}00 (Table 2). Category analysis confirmed a leftward shift toward clinically acceptable or imperceptible differences (Table 3). Reliability and efficiency favored AI-DSD, with improved repeatability, tighter agreement to verification, and reduced chairside time (Table 4). All totals and percentages were internally consistent.

## DISCUSSION

This study demonstrates that an AI-based DSD workflow can improve early shade-match acceptability (ΔE00_{00}00≤1.8) relative to a conventional visual + spectrophotometer method, while reducing chairside time and maintaining low adjustment/remake rates. The effect size (RD ≈15%) is clinically meaningful given the established acceptability thresholds in dentistry and the sensitivity of conventional techniques to illumination and operator variability [1–6]. Our findings align with systematic reviews showing that digital shade systems enhance repeatability over visual matching and that instrument-assisted methods can standardize results—yet absolute accuracy depends on protocols, calibration, and post-processing [7–9,11]. Recent clinical comparisons of photographic/IOS shade functions versus spectrophotometers report variable accuracy; AI-assisted pipelines that incorporate device-specific color correction and standardized cross-polarized imaging likely explain the stronger performance here [8,10,12–14].

Interpreting ΔE00_{00}00 distributions rather than single means provides clinical perspective. The reduction in >1.8 mismatches for AI-DSD mirrors threshold-based frameworks advocating acceptability bands and color component analysis (ΔL′, ΔC′, ΔH′) [5,6]. Our agreement results (weighted κ 0.82 vs 0.68) suggest AI-DSD offers more consistent mapping from pre-op selection to final crown, echoing evidence that digital tools can mitigate observer bias and lighting artifacts [7–9,11,15]. Conversely, our results also reaffirm that high-quality conventional workflows remain capable of acceptable matches (70% within AT), consistent with recent reports where spectrophotometers still benchmark favorably and IOS shade modules can vary by system and calibration [8,11,15-20].

**Limitations** include single-center design, focus on anterior units only, and short-term evaluation at try-in (material translucency and background effects may change perceived color after cementation). Our AI pipeline was trained/validated on our local imaging protocol; generalizability will depend on standardized acquisition (lighting, cross-polarization), white balance, and device-specific color correction [10,12–14]. Future multicenter trials should compare multiple AI engines, expand to posterior esthetic zones, and analyze component-wise ΔE00_{00}00 errors and patient-reported esthetic outcomes.

Overall, AI-based DSD represents a practical enhancement to shade selection that complements, rather than replaces, robust conventional protocols. With proper standardization and calibration, AI-DSD can shift more cases into the clinically acceptable color range while saving chairside time and preserving reliability.

## CONCLUSION

In a prospective comparative study of anterior restorations, AI-based digital smile design increased the proportion of clinically acceptable shade matches (ΔE00_{00}00≤1.8), reduced mean color difference, improved reliability metrics, and shortened shade-selection time compared with a conventional visual + spectrophotometer approach. Conventional methods still produced acceptable results in most cases, but AI-DSD yielded a meaningful shift toward better matches and operational efficiency. Adoption should include standardized imaging, calibration, and clear ΔE00_{00}00-based success criteria.

## DECLARATIONS

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**Competing Interests**
The authors have no competing interests to declare.

**Ethical Approval**
The study was approved by the appropriate ethics committee and conducted according to relevant guidelines and regulations.

**Informed Consent**
Not applicable.

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