GRADUATION PROJECT

Degree in Dentistry

TITLE

EVALUATION OF DENTAL SHADE GUIDE USING CROSS-POLARIZED PHOTOGRAPHY

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ABSTRACT

Introduction: In contemporary restorative dentistry, the objective of achieving aesthetic harmony evolved from simple functional repair toward the pursuit of rigorous biomimesis, defined as the precise replication of natural tooth structure and optical properties. However, conventional visual shade matching using prefabricated tabs and subjective human judgment remained characterized by high intra-examiner variability and a lack of clinical predictability. **Objectives**: The primary purpose of this investigation was to evaluate whether the implementation of photographs taken with cross-polarization filters increased the accuracy of dental color matching compared to the use of a conventional ring flash. **Material and Methods**: The study employed an in vitro observational design involving fifteen prosthodontic post-graduate students who evaluated eight randomized shade tabs from the Vita Classical guide under strictly controlled conditions. Observers analyzed images captured with a Nissin digital MF18 Macro ring flash and a DSLR camera configured to neutralize external variables, comparing them against captures utilizing a Polaris polarization filter. **Results**: Statistical analysis via a Paired Student's T-test yielded a p-value of 0.0032 and a t-statistic of 3.5555, necessitating the rejection of the null hypothesis. The data demonstrated that polarized photography significantly enhanced the percentage of correct matches from a mean of 17.60% to 41.80% by eliminating specular glare. **Conclusions**: It was concluded that cross-polarized photography represents a reliable, objective, and economically sustainable alternative to high-cost spectrophotometers, facilitating superior clinical communication and predictable aesthetic outcomes in modern dentistry.

KEYWORDS: Dentistry, cross-polarized photography, shade matching, aesthetic dentistry, ring flash.

RESUMEN

Introducción: En el ámbito de la odontología restauradora contemporánea, el objetivo de alcanzar la armonía estética evolucionó desde la simple reparación funcional hacia la consecución de una biomímesis rigurosa, definida como la replicación exacta de la estructura dental natural y sus propiedades ópticas. Sin embargo, la toma de color visual convencional mediante guías prefabricadas y el juicio humano subjetivo se mantuvo como un proceso caracterizado por una alta variabilidad intra-examinador y una falta de predictibilidad clínica. **Objetivos:** El propósito principal de este estudio consistió en evaluar si la implementación de fotografías tomadas con filtros de polarización cruzada incrementaba la precisión en la selección del color dental en comparación con el uso del flash anular convencional. **Material y Métodos:** Se empleó un diseño observacional in vitro que involucró a quince estudiantes de posgrado de prótesis dental, quienes evaluaron ocho muestras de color de la guía Vita Classical bajo condiciones estrictamente controladas. Los observadores analizaron imágenes capturadas con un flash anular Nissin digital MF18 Macro y una cámara DSLR configurada específicamente para neutralizar variables externas, comparándolas con capturas que integraban un filtro de polarización Polaris. **Resultados:** El análisis estadístico mediante la prueba T de Student para muestras relacionadas arrojó un valor p de 0,0032 y un estadístico t de 3,5555, lo que permitió rechazar la hipótesis nula. Los datos demostraron que la fotografía polarizada aumentó significativamente el porcentaje de aciertos de una media del 17,60% al 41,80% al eliminar el brillo especular. **Conclusiones:** Se concluyó que la fotografía de polarización cruzada representa una alternativa fiable, objetiva y económicamente sostenible frente a los espectrofotómetros de alto costo, facilitando una comunicación clínica superior y resultados estéticos predecibles en odontología.

PALABRAS CLAVE: Odontología, fotografía de polarización cruzada, toma de color, odontología estética, flash anular.

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1. INTRODUCTION

1.1. Background and rational

In restorative dentistry, the goal of aesthetic harmony has changed clinical practice from only concentrating on functional repair to accomplishing bio mimesis, which is the precise replication of natural tooth structure and optical properties(1). The ability of any restorative or prosthetic procedure to blend indistinguishably with the surrounding dentition is a critical component of its success in the modern dental landscape. Over the past few years, patient expectations have risen significantly due to this requirement for superior aesthetics(2).

Therefore, shade matching goes beyond a straightforward technical necessity and develops into a basic "holistic approach" that incorporates exact scientific principles, advanced technological tools, and crucial psychological considerations regarding patient perception(3). Minimizing color mismatch is not only an aesthetic objective for dentists; it is also essential to the success of restorative procedures and the general sustainability of their practice(3).

However, replicating the intricate color and optical characteristics of natural teeth with restorative materials is still highly challenging, though. It is challenging to adequately depict and convey the subtle qualities of natural teeth, such as opalescence, translucency, and the halo effect at the incisal third(3,4). The need for strict protocols and objective measurement technologies is validated by the inherent clinical complexity and increased patient demand. Meeting these increasing aesthetic standards and reducing the high frequency of esthetic failures seen in clinical settings require a shift from subjective, uncertain shade determination techniques to standardized, trustworthy techniques(5).

1.2. Importance of accurate shade selection in dentistry

In restorative dentistry, choosing the right tooth shade is frequently referred to as the "foundation for superior esthetics(2)." Asymmetrical restorations compromise the aesthetic result and directly cause patient dissatisfaction when the proper color match is not achieved. Delivering an aesthetic restoration that "symmetrically blends" with the patient's natural teeth is the restorative dentist's main goal(2).

Dental professionals must have a "full understanding of the science of color and color perception" in order to meet this standard, which goes beyond clinical proficiency(2). However, a lack of understanding of the complexities of color science presents a challenge for many

dentists, which is made worse by the abundance and complexity of available shade guide systems(2). A fundamental conflict is highlighted by this discrepancy between the required scientific understanding and current clinical application: complex scientific variables coupled with high patient expectations demand the use of dependable, user-friendly technological aids. The use of objective systems is crucial to enhancing the practitioner's capacity to accurately assess and replicate the shape and appearance of teeth, which will satisfy the patient and the dentist(2).

1.3. Limitations of conventional visual shade matching.

The conventional approach to visual tooth shade selection, which uses prefabricated shade tabs and subjective human judgment, is universally criticized in the literature for its poor accuracy and inherent unreliability(5). Due to a variety of subjective and contextual factors, this approach is characterized by "high intra-examiner variability and unpredictability(6)." As a result, using visual techniques alone is not enough to produce repeatable and clinically acceptable results(7).

The observer, the environment, and the state of the teeth are the three main sources of cumulative uncertainty related to visual matching. First, there is a great deal of physiological variability due to operator dependence. The human eye rapidly accommodates to certain colors, particularly red and yellow, mandating that the viewing time be limited to "less than 5 s" to prevent chromatic fatigue and subsequent biasing after-images(8). Furthermore, factors beyond immediate visual ability, such as operator training, gender, and experience, have been shown to influence accuracy(9). Second, interference is caused by environmental factors. Variations in lighting conditions and the presence of background colors (e.g., blue drapes) can bias perception toward complementary colors (e.g., orange)(8,10).

Standard protocols advise using a neutral background to reduce perceptual bias and filter out background glare in order to minimize this(8). Third, the outcome is directly impacted by the condition of the teeth. When the tooth surface is over-dried or completely dehydrated, its optical characteristics change, making it appear lighter in color than it actually is. This alteration, if not controlled through gentle air-drying techniques, introduces inaccuracies into the shade captured(11).

This cumulative uncertainty results in unacceptable aesthetic deficiencies in the ensuing restorations. A significant amount of evidence indicates that clinicians should not depend exclusively on their subjective perceptions for shade assessment but should adopt

quantitative, objective methodologies. The development of instrumental color measurement technologies is a direct clinical response to the recognized inadequacies of human perception and environmental interference(5).

1.4. Shade Guides: Types and Characteristics

Despite being entirely subjective tools for measuring color, shade guides continue to be the most widely used tool for shade selection. The Vita Classical (VC) (Figure 1) and Vita 3D Master (V3M) (Figure 2) guides are the most commonly used systems.

Based on the predominant color, such as red/brown in group A or red/yellow in group B, the Vita Classical guide is organized around four main Hue groups (A, B, C, and D)(12). There are subdivisions indexed 1 through 4 within each letter group, where the value (lightness) decreases and the chroma (saturation) increases as the index number rises(12). The non-linear distribution of the VC guide's shade tabs within the color space is a major drawback that makes accurate shade interpolation more difficult and increases selection subjectivity(10).

In order to address this, the Vita 3D Master system was created, which offers a more consistent distribution of shades based first on Value, then Chroma, and finally Hue. The effectiveness of any shade guide is greatly impacted by the measurement technique used, even though it is theoretically better in structure. Research points to a clear interaction effect: a comparative study discovered that the VC guide produced higher accuracy when combined with a spectrophotometric method, while the V3M guide performed better when used for traditional visual shade selection(13). Additionally, recent research comparing objective instrumental methods found that the shade guide used affected inter-device consistency (specifically, between spectrophotometry and cross-polarized photography), with larger discrepancies found for the V3M system compared to the VC system(14).



Figure 1. Vita classical shade guide (12).



Figure 2. Vita 3D master shade guide (12).

1.5. Role of Photography in Color Communication

In dentistry, digital photography has undergone a significant transformation, evolving from simple case documentation to a "indispensable tool" for impartial clinical communication(15). One of the main issues with traditional shade selection is the incapacity of digital cameras to transmit the precise, intricate optical characteristics of the tooth to the dental lab(16). Important individual characteristics like opalescent areas, surface texture, and the halo effect are not conveyed by simple written shade codes like A2 or A1(16). To achieve a truly biomimetic restoration, these minute details must be communicated through a series of standardized digital images(4).

For digital photography to function effectively as a tool for quantitative shade selection, it requires meticulous standardization and an in-depth knowledge of camera function. The camera must be able to "immaculately capture the true colors of the patient's teeth"(16). This involves rigorous control over variables such as exposure, flashlight use, and, critically, White Balance (WB) calibration using a gray reference card (figure 3) (17). Studies confirm the efficacy of this standardization, demonstrating that calibrating the camera’s white balance significantly improves the accuracy of color matching(9). Moreover, standardized digital photography has shown high correlation (r >0.96) between its measurements and those obtained from a spectrophotometer (figure 4) (9), and its standardized images can depict the true shade with

significant agreement(18). This establishes digital imaging as a viable, quantitative platform, provided technical protocols are rigorously followed.

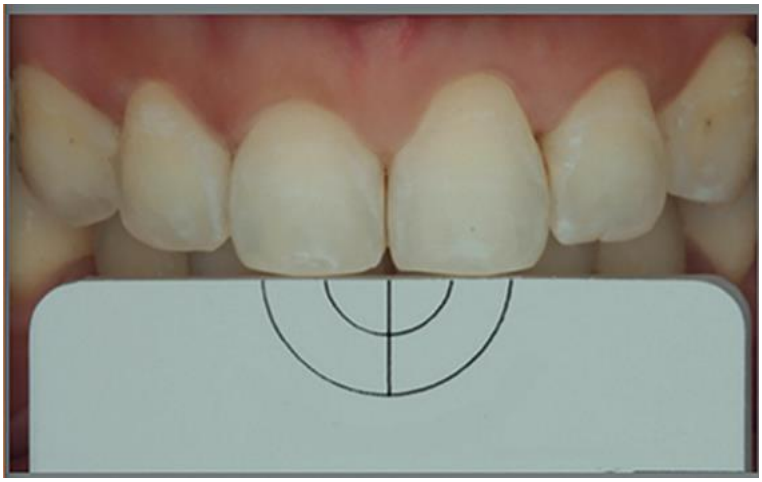


Figure 3: Grey reference card (19)

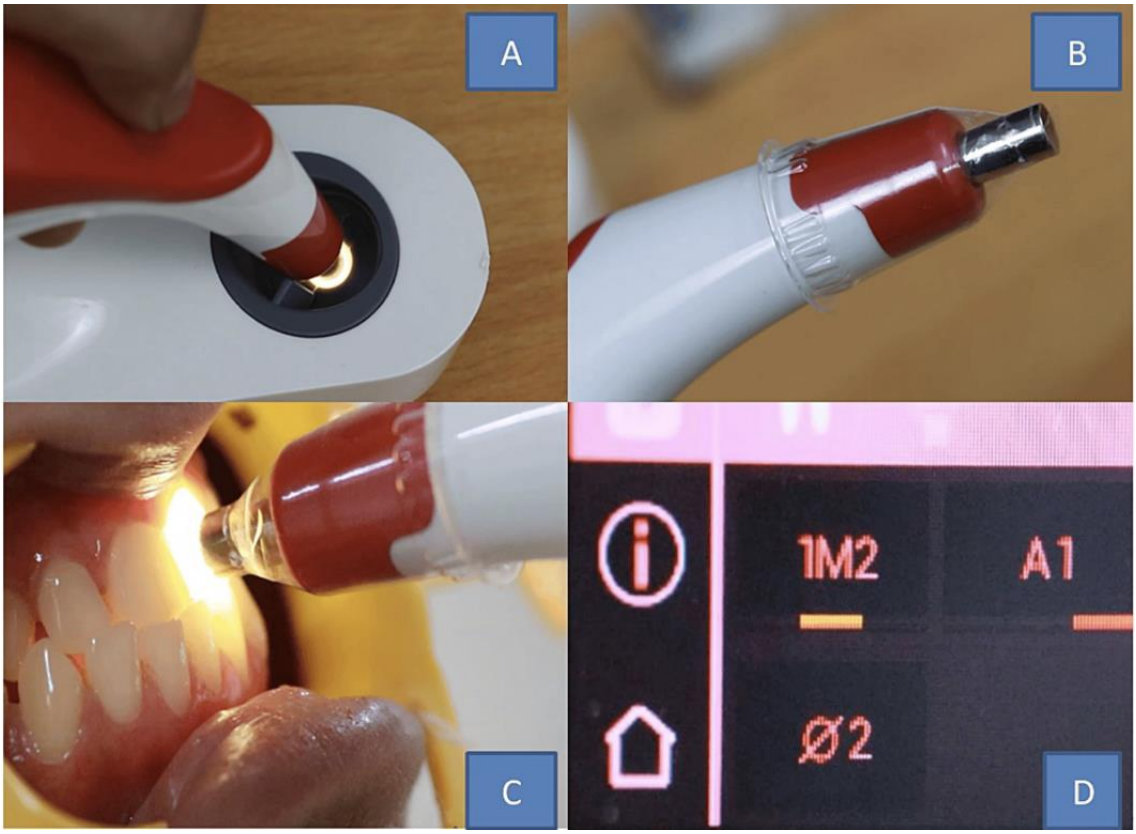


Figure 4: Shade taking with spectrophotometer(18). A) Calibration of the device, B) Infection control shield, C) Device probe set at right angle, D) Shade display in Classical & 3D Master systems(18).

1.6. Principle of Cross-Polarized Photography

Cross-polarized (CP) photography represents a technological advancement that enhances the quantitative capability of digital imaging by addressing a primary limitation of conventional photography: specular reflection, or glare. Glare resulting from light reflecting off the tooth surface hinders accurate color selection by blocking visualization of subsurface color and often causing an overestimation of white opacities when using flash photography(figure 5) (20).

The core technical principle of CP photography involves the use of two polarizing filters: one placed over the light source (typically the flash) and one placed over the camera lens, crossed at 90 degrees to each other (figure 6). This configuration effectively eliminates the excess light reflecting directly back to the camera sensor, resulting in glare-free images(20).

By removing this superficial reflection, CP photography facilitates the unobstructed visualization of deep, intrinsic color and subsurface dentin and enamel characteristics(20). This mechanism is particularly beneficial in complex clinical scenarios, such as assessing enamel defects and managing the challenge of varying enamel thickness, by removing the "frosty appearance and other distractions"(20). Therefore, the physical principle of cross-polarization provides a direct technological solution for correcting the most significant quantitative variable in conventional digital shade capture, resulting in images that facilitate more accurate color interpretation (figure 7) (20).



Figure 5: Ring flash(16).



Figure 6: A twin flash using two polarizing filters(21).

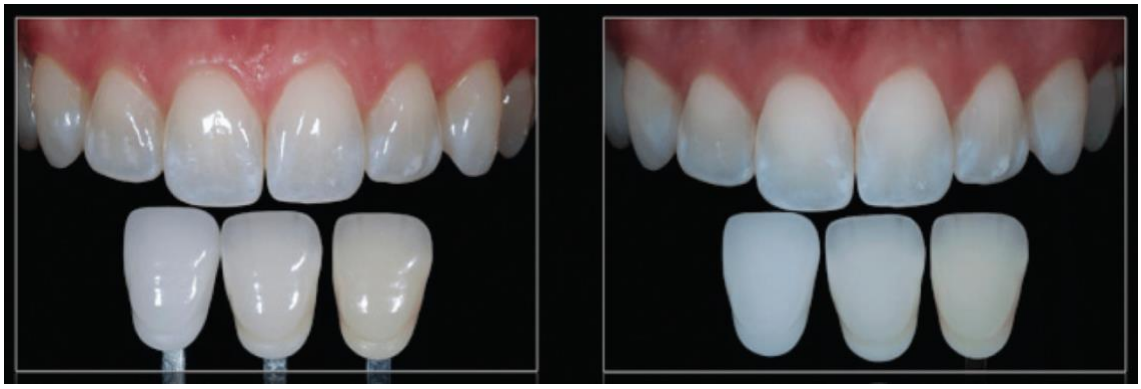


Figure 7: Comparison of dental shade matching, with and without using cross-polarized photography(20)**.**

1.7. Digital and Polarized Photography in Dentistry

Methods for selecting instrumental shade have significantly diversified, now including spectrophotometers, digital cameras, cross-polarizing filters, and integrated smartphone applications(22). Comparative studies confirm that digital photography typically results in diminished color discrepancies and fewer inaccurate shade matches compared to traditional visual techniques employing shade tabs(6).

Cross-polarized photography has become a dependable technique owing to its objective glare-elimination capabilities. Research comparing CP photography to specialized instrumental devices has produced exceptionally positive outcomes. Researchers have determined that CP photography is a "dependable method for conducting color evaluations" in comparison to a spectrophotometer. Subsequent comparisons revealed "no significant difference" in shade assessment values between CP photography and a colorimeter(20).

This method holds a distinctive role as a practical intermediate solution. It preserves the exceptional visual communication attributes of digital photography while integrating the standardization and objectivity essential for quantitative color assessment. Evidence indicates that CP photography is a dependable and economical substitute for colorimeters (figure 8) and spectrophotometers(20). Due to the significant financial burden and inter-device reliability concerns linked to dedicated spectrophotometers(22), it is imperative to validate the high accuracy of CP photography to offer clinicians an accessible, standardized, and objective alternative to subjective visual matching.



Figure 8: Vita Easyshade® V, Bad Säckingen, Germany(22).

1.8. Factors Influencing Shade Matching Accuracy

Accuracy in dental shade matching, whether visual or instrumental, is influences by a complex interaction of factors that must be carefully controlled in standardized research protocols.

Extrinsic and environmental factors encompass variables such as illumination. Diverse illuminants, including dental unit lamps and daylight, can affect measurements, and certain spectrophotometric instruments have demonstrated significant variations under different lighting conditions(23). Background interference is crucial, necessitating a neutral grey or white environment to avert perceptual bias(8). The accurate placement of the measuring probe is essential for instrumental devices. Errors in probe placement, such as displacing the tip more than 1mm from the surface, can substantially affect the results by disturbing the controlled light field in accordance with the Inverse Square Law(11).

Intrinsic and Material Factors pertain to the tooth and the restorative material utilized. The hydration status of teeth must be preserved, as excessive drying can significantly elevate the perceived light(11). Moreover, when juxtaposing measurements with shade guide standards, it is essential to recognize that the optical properties, including the thickness and opacity of the ceramic or composite materials utilized in the fabrication of the guides, introduce variability(5).

Operator and methodological factors pertain to human interaction and calibration. While instrumental methods diminish subjectivity, the precise acquisition of color data through digital photography necessitates exceptional skill and rigorous compliance with protocols, including White Balance calibration, which has been demonstrated to significantly enhance visual color matching when standardized(9). The efficacy of objective instruments, such as cross-polarized photography, depends not only on the device's functionality (e.g., glare management) but also on the thorough eradication of human and environmental variables via rigorous methodological control(16).

1.9. Problem statement

Although precise shade matching is crucial for aesthetic success and patient satisfaction, traditional visual techniques are inherently subjective and susceptible to significant error rates. Although specialized instruments, especially spectrophotometers, offer objective color measurements, their extensive clinical implementation is significantly hindered by substantial acquisition costs and reported problems with inter-device reliability and consistency.

There is a critical need to rigorously validate the accuracy and reliability of cost-effective cross-polarized digital photography as a standardized alternative to expensive spectrophotometry, thereby providing a clinically viable, objective protocol to reduce aesthetic failure in restorative dentistry.

2. OBJECTIVE

Evaluate whether the use of photographs taken with polarization improves the accuracy of color matching compared to the ring flash.

H1: The use of polarized photographs increases the percentage of correct results in color matching compared to the ring flash.

H0: There are no differences in the precision of material selection between the two methods.

3. MATERIAL AND METHODS

3.1. Study design

The study employed an in vitro observational, design. This approach focuses on comparing the accuracy of shade identification across three distinct photographic techniques, conventional ring flash versus cross-polarized photography versus diffuser flash photography when assessed by human observers under standardized, controlled conditions. No clinical data or patient involvement was required for the experimental procedures.

3.2. Sample size

The study sample comprised two distinct sets of elements: the testing objects and the human observers.

- **Testing Objects (Shade Tabs)**: A limited selection of 8 shade tabs from the **Vita Classical (VC) Shade Guide** was used, specifically including the shades A1, A3, B1, B3, C1, C3, D2 and D3.

- **Observers (Subjects)**: The study recruited a pool of **15 students** currently enrolled in the prosthodontic post-graduate. These individuals served as the evaluators for the comparative shade matching task.

3.3. Inclusion and exclusion criteria

The criteria for participation were focused on the observers involved in the subjective assessment:

- **Inclusion Criteria**: Participation was strictly limited to students actively enrolled in the prosthodontic post-graduate.

- **Exclusion Criteria**: The study excluded any individuals who were not current in the prosthodontic post-graduate.

3.4. Material

- Vita classic shade guide (VC).
- Polarization filter branded Polaris.
- Ring flash branded Nissin digital MF18 Macro.
- DSLR camera Canon EOS 600 D.
- Camera Lens Canon Macro 100mm.
- MacBook Pro.
- Black dental image contrast board.
- Data sheet.

3.5. Intervention

The intervention involved a comparative shade matching task based on two different photographic capture methodologies:

Preparation of Testing Material:

- The selected Vita Classical shade tabs were placed individually against a **black background** to standardize the environmental reference and minimize potential visual bias or glare effects. (Figure 10)

- An **DSLR camera** was used to capture standardized photographs of each shade tab. Configurated at 1/125, F32, ISO 100 and focal point at 0,49 meter for non-polarized ring flash. For cross- polarized, the only value that was changed was F32 to F13. (Figure 11)



Figure 10: Black dental image contrast board.



Figure 11: DSLR camera configuration.

Creation of Photographic Stimuli:

- **Condition A (Conventional Control):** Photographs were taken using a **standard ring flash attachment**, *without* any polarizing filter applied to the lens or flash (figure 5).

- **Condition B (Test Intervention):** Photographs were taken with the camera equipped with a **specialized polarization filter** on the Lens and **standard ring flash attachment** (Figure 12).



Figure 5: Ring flash(16).



Figure 12: Polaris filter mounted on the ring flash.

Observer Procedure:

- All photographs were organized in a numbered digital folder in PowerPoint for controlled and **personalized presentation** to each student. Each student was presented with **three randomly selected pairs** of shades from the eight available.

- Each student observer was assigned the task of comparing and selecting the most accurate color from a series of images displayed on a laptop screen while **holding the Vita guide**. The observer was presented with two images of the same shade tab: one taken **without a filter (A)** and one with the **polarized filter (B)**. To ensure consistent lighting, the **laptop was connected to the charger**.

- The order of comparison (A first or B first) was **randomized** for each observer and shade tab to eliminate potential sequence bias.

- Between each shade, a **black screen** was shown **for 3-4 seconds** to prevent color fatigue.

3.6. Method of data collection

Data collection was conducted immediately following the observer procedure:

- For each comparison task performed by the student observer, the resulting choice was recorded in a dedicated **data sheet**.

- The primary metric for data recording was a binary assessment: whether the observer's shade choice was **correct or incorrect**.

3.7. Ethical issues

This study was classified as an *in vitro* investigation utilizing shade guides as the sole testing material, with no invasive or clinical procedures performed on human patients. Consequently, the requirement for formal ethics committee approval specific to *in vivo* research was not applicable. All student observers provided informed consent prior to participation, and the anonymity and confidentiality of their individual response data were maintained throughout the study.

4. RESULTS

4.1. Sample characterization

The study was conducted with a sample of 15 observers who were post-graduates in prosthodontics. Each student evaluated a randomized selection of three shade tabs under two distinct lighting conditions, resulting in a total of 90 individual observations (15 observers × 6 shade tabs).

The shades utilized in the master pool were: A1, A3, B1, B3, C1, C3, D2, and D3.

4.2. Descriptive analysis of accuracy

The performance of the observers was quantified by determining the percentage of correct matches for each method (table 1) (Figure 13).

Metric	Standard (Ring flash)	Experimental (cross-polarized)
Mean	17,60%	41,80%
Standard deviation (SD)	24,5	29,2
Standard error (SEM)	6,3	7,5

Table 1: Descriptive table of the mean, standard deviation, and standard error of the two methods used for the experiment

- **Mean:** The accuracy of standard ring flash and cross-polarized methods was determined by calculating the answers of each method.
- **Standard Deviation (SD):** Utilized to characterize the dispersion of the results. A higher standard deviation (SD) indicates greater inter-observer variability in shade selection.
- **Standard Error of the Mean (SEM):** Calculated as SEM $= \frac{SD}{\sqrt{n}}$ (where n=15). This parameter was selected for the graphical representation as it provides a more precise estimation of the population mean by accounting for the sample size.

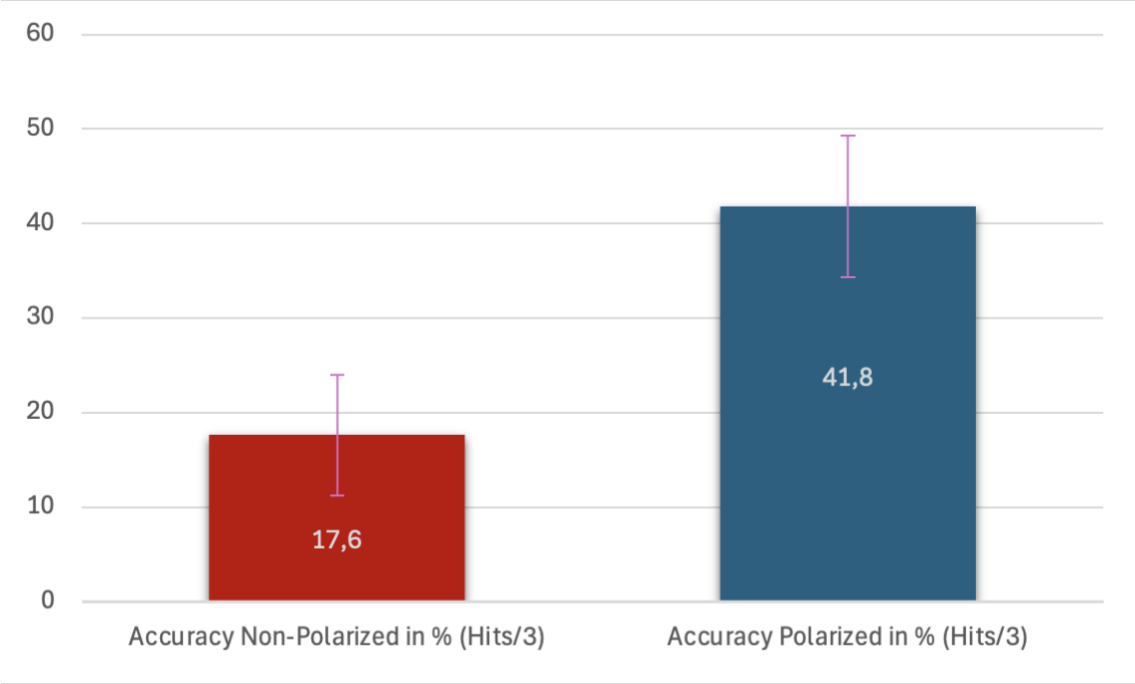


Figure 13: Histogram depicting the outcomes of the experimental procedure.

4.3. Observational Control and Fatigue Mitigation

To ensure the integrity of the results and minimize chromatic adaptation, a « reset » protocol was strictly enforced.

- A solid black slide was displayed for 3 seconds between every image.
- Observers were instructed to fixate on this neutral screen to reset retinal cone cell sensitivity.
- This protocol successfully prevented afterimage interference, ensuring each observation was independent of the previous one.

4.4. Statistical analysis

To validate the hypothesis, a Paired Student's T-test was performed to compare the accuracy scores of the same 15 observers across the two photographic methods.

- Degrees of Freedom (df): 14
- T-statistic (t): 3,5555
- Significance Level (p-value): 0,0032

The calculated p-value was less than the alpha level of 0,05.

4.5. Resolution of Hypotheses

Based on the statistical findings:

1. Null Hypothesis (H0): Rejected.
2. Alternative Hypothesis (H1): Confirmed.

The data demonstrates that polarized photography significantly enhances the accuracy of dental shade matching by eliminating specular reflections (glare) that typically obscure the true hue and saturation of the material under standard ring flash conditions.

5. DISCUSSION

5.1. Primary Hypothesis and Statistical Significance

The empirical results derived from this investigation provide conclusive evidence supporting the efficacy of cross-polarized (CP) photography as a superior tool for dental shade matching compared to conventional ring flash methodologies. The primary objective was to evaluate whether the elimination of specular reflection via polarization filters would result in a statistically significant improvement in shade matching accuracy among post-graduate prosthodontic students. The findings, characterized by a *p*-value of 0.0032 and a *t*-statistic of 3.5555, necessitate the rejection of the null hypothesis (*H0*) and the acceptance of the alternative hypothesis (*H1*). This low *p*-value indicates that the probability of the observed improvement occurring by chance is less than 0.32%, reinforcing the robustness of the data. In the context of clinical practice, these results suggest that the standard ring flash introduces significant optical distortions that compromise the objective determination of tooth color(17). The rejection of *H0* confirms that polarized photography provides a more accurate representation of the material's true hue and saturation, which is essential for achieving biomimetic harmony(20).

The observed statistical significance is deeply rooted in the mitigation of "optical noise" that typically plagues traditional flash photography. When light from a ring flash strikes the hydrated, convex surface of a tooth, it generates high-intensity specular reflections or "hot spots"(20). These reflections effectively block the observer's ability to perceive the light that has penetrated the enamel and reflected off the underlying dentin(17). By contrast, the cross-polarization technique utilized in this study—employing a *Nissin* digital MF18 macro ring flash with a *Polaris* filter—allows only the depolarized, scattered light to reach the camera's sensor. The *t*-statistic of 3.5555 reflects the consistency of this benefit across the 15 observers and the 90 individual observations. Such a high degree of statistical reliability suggests that the

CP protocol is not only effective but also repeatable, providing a dependable foundation for objective shade selection(24).

5.2. Optical Physics of Cross-Polarization and Glare Mitigation

The fundamental mechanism that explains the superior performance of the polarized group lies in the physics of light-matter interaction, specifically the distinction between specular and diffuse reflection(21). Natural teeth are translucent structures with complex internal architectures where light undergoes both superficial Fresnel reflection and volumetric scattering(17). In the non-polarized control group, the superficial glare carries no information about the tooth's intrinsic color, as it merely reflects the spectral composition of the light source(17). This glare often causes an overestimation of the "Value" (lightness) and can mask the "Chroma" (saturation) and "Hue"(12). The results of this study show that by removing this superficial interference, observers were able to focus on the light that had undergone multiple scattering events within the material, providing a more truthful assessment of color coordinates(17).

Furthermore, the transition from an aperture of *F32* in the ring flash group to *F13* in the polarized group highlights the subtractive physical properties of polarizing filters. Polarization filters absorb a significant portion of incident light, typically requiring a compensatory change in exposure settings(17). The researchers' decision to adjust the aperture to *F13* for the polarized intervention was critical to maintain equivalent exposure levels and ensure observers were not biased by differences in overall image brightness. This adjustment ensures that decisions were made based on the quality of the color information rather than the quantity of light(21). The fact that accuracy increased despite the reduction in depth of field underscores that color clarity is a more critical variable than edge-to-edge sharpness in dental matching(17). The ability of the *Polaris* filter to provide a near-to-zero light interference environment allowed for the visualization of subsurface characteristics that are otherwise "lost" in standard documentation(17).

The physical principle of cross-polarization also addresses the challenge of Brewster's Angle and the curvature of the dental arch(21). Specular reflection is most intense when the angle of incidence matches the angle of reflection, a condition frequently met in the convex anatomy of maxillary central incisors(17). Standard ring flashes, which encircle the lens, are particularly prone to creating these reflections at the center of the tooth(17). By crossing the planes of

polarization at 90 degrees, the filters effectively cancel out any light that maintains its initial polarization state—specifically the light reflected directly from the surface(21). This leaves only the depolarized light, which has been "color-coded" by its journey through dental tissues(17) (Table 2).

Optical Feature	Conventional Ring Flash	Cross-Polarized Photography	Impact on Shade Selection
Surface Reflection	High (Specular Glare)	Near-Zero	Glare masks internal hue/chroma.
Subsurface Visualization	Obscured by hot spots	Unobstructed	Essential for identifying dentin shade.
Value Perception	Overestimated due to glare	True Value (L*)	Critical for matching restoration brightness.
Chromatic Detail	Desaturated	Saturated (True Chroma)	Allows for accurate saturation mapping.
Structural Features	Surface texture only	Enamel/Dentin interface	Visualizes opalescence and halo effects.

Table 2 (Optical Features): Comparison of Optical Characteristics Between Conventional Ring Flash and Cross-Polarized Photography and Their Impact on Dental Shade Selection(17,20,21).

5.3. Comparison with Traditional Visual Shade Selection

The traditional approach to shade selection, relying on subjective visual assessment under uncontrolled lighting, is fraught with inaccuracies due to eye fatigue and environmental interference(9). Previous studies have shown that visual shade matching accuracy can be as low as 27%, and even experienced clinicians struggle with repeatability(25). The *p*-value of 0.0032 in this study suggests that digital intervention significantly bridges the gap between human limitation and clinical requirements(26). While visual methods are often influenced by the clinician's mood, age, and gender, the polarized digital images provided a stable platform for all 15 observers(9). This transition from a 3D physical comparison to a 2D digital analysis appears to reduce the cognitive burden on the clinician, leading to more consistent results(25).

In the hierarchy of shade-taking instruments, the spectrophotometer—such as *the Vita Easyshade V(22)*—is considered the "gold standard" due to its ability to measure spectral reflectance objectively(15). Studies confirm that spectrophotometers can improve color matching accuracy by 33% compared to visual techniques, achieving objective matches in up to 93.3% of cases(15). However, these devices are expensive and limited by "edge-loss"

errors where light escapes the measurement probe(18). The high correlation ($r > 0.96$) reported between standardized photography and spectrophotometry suggests that CP photography can serve as a viable, cost-effective alternative(18). While the spectrophotometer provides a numeric shade, CP photography provides a detailed "map" of the tooth's aesthetics, including translucency and opalescence(9). The current results reinforce that CP photography is a reliable solution that combines instrumental objectivity with visual communication(18)(Table 3).

Reliability Metric	Spectrophotometer	Cross-Polarized Photography	Intraoral Scanner
Intra-instrument Reliability (κ)	0.928 – 0.949	0.810 – 0.832	0.748 – 0.765
Agreement with Gold Standard (κ)	1.000 (Reference)	0.736 (Substantial)	0.607 (Moderate)
Clinical Acceptability ($\Delta E_{00} \leq 1.8$)	High	Moderate/High	Low/Moderate

Table 3 (Reliability Metrics): Reliability and Clinical Accuracy of Spectrophotometer, Cross-Polarized Photography, and Intraoral Scanner in Dental Shade Determination(14).

The performance of the post-graduate students in the CP group highlights the role of assisted human perception. While a spectrophotometer might provide the "truth" in terms of *CIELAB* coordinates, the dentist must still translate those into a material selection(9). CP photography allows the clinician to perform this translation with more confidence by removing white specular noise that might make an A3 tab look lighter(20). The findings of this study, using 8 specifics *Vita Classical* shades, demonstrate that CP photography is particularly effective in discriminating between shades within the same Hue group where Value and Chroma are the differentiating factors(9,20).

5.4. Influence of Clinical Experience and Observer Training

The sample of 15 prosthodontic post-graduate students represents a group with a higher-than-average baseline for shade matching. Interestingly, literature such as the study by Saygılı et al. (2024 found that postgraduate students sometimes achieved better results with *non-polarized* photographs, suggesting that experts may develop a specific intuition for interpreting standard reflections(24). However, the current study contradicts this, showing a clear preference for polarization among post-graduate observers. This discrepancy might be

explained by the standardization protocol used here, specifically the black background and the retinal reset period. For a post-graduate student, the removal of glare likely simplifies the visual task from interpretation to matching(24,27). This suggests that technology can enhance even the skills of advanced practitioners, providing a safety net against chromatic fatigue(25,26).

In contrast, undergraduate students typically show significantly lower accuracy in shade matching, often failing to reach the clinical acceptability threshold of $\Delta E_{00} \leq 1.80$(24). For these less experienced observers, CP photography acts as a crucial educational aid(24). Studies have shown that while experts can sometimes "see through" the glare, novices are often misled by it(24). The *p*=0.0032 result suggests that for post-graduates, the CP technique provides a level of precision that their clinical experience alone could not achieve. This highlights the importance of incorporating CP photography into post-graduate curricula as a standard method for aesthetic verification(24). By providing a glare-free ground truth, the technology allows students to calibrate their eyes against a more accurate reference(24,27).

5.5. Psychological and Physiological Factors

A critical component of the methodology in this study was the implementation of a 3-second black screen "reset" between each shade observation. This protocol is designed to address the physiological phenomenon of chromatic adaptation or retinal fatigue(26). When the eye fixates on a specific color—particularly the yellow and orange hues prevalent in dental shades—the photopigments in the cone cells become temporarily depleted(28). This results in a reduced sensitivity to those colors and the formation of negative after-images(28,29). Without a reset period, an observer's selection for a second shade tab could be biased by their perception of the first(28). The p-value of 0.0032. suggests that by neutralizing the visual field with a black screen, the researchers ensured that each of the 90 observations was independent and unbiased.

The use of a black background for the testing material also played a vital role in contrast sensitivity. The perceived brightness and hue of an object are significantly influenced by its surroundings(26). A neutral grey or black environment prevents "simultaneous contrast" bias, where a bright background might make a tooth appear darker(26,28). In this study, the black background provided a null reference point, ensuring that students were assessing absolute color values rather than relative values(30). This methodological rigor isolated the variable of polarization from environmental lighting distractions(15).

5.6. Clinical Implications for Restorative and Prosthetic Dentistry

The successful validation of the CP method in this study has direct implications for the selection of restorative materials. CP photography allows the clinician to see the CIELAB coordinates of the natural tooth and match them to a custom library of composite or ceramic shades(17). This digital protocol helps in achieving more predictable outcomes by finding the closest mathematical combination of enamel and dentin shades(21). This is particularly critical for the restoration of single maxillary central incisors where an exact match to the contralateral tooth is required(17).

For direct composite restorations, the hydration of the tooth is a critical variable. Dehydrated teeth appear significantly lighter and opaquer(17). Polarization helps clinicians visualize subsurface characteristics even when the tooth is moist by removing the glare of the moisture film(17,26). When translated to the clinic, this means CP photography can provide a more accurate record of the pre-operative shade even under rubber dam isolation(21). The precision afforded by CP photography reduces the frequency of aesthetic failures and the need for remakes(21).

5.7. Future Directions: Artificial Intelligence and Augmented Reality

The evolution of dental shade matching is increasingly moving toward the integration of Artificial Intelligence (AI)(31). AI algorithms can analyze thousands of tooth color data points and predict the best match based on individual patient characteristics(31). For these algorithms to function effectively, they require high-quality input data like cross-polarized photographs, which provide glare-free ground truth images(31,32). Recent studies have shown that AI-based digital smile designs (AI-DSD) can increase the proportion of clinically acceptable matches from 70% to 85%(9,31).

Furthermore, the emergence of Augmented Reality (AR) could allow for real-time shade matching(17,18). AR glasses equipped with polarizing filters could provide a live color-map of the tooth overlaid on the field of vision(33). Until such technologies are widely available, the protocol validated in this investigation remains the most reliable and accessible bridge to the digital future of aesthetic dentistry(14,18).

6. CONCLUSIONS

The study confirms that using polarized photographs significantly improves the accuracy of dental shade matching when compared to a standard ring flash. The results prove that the elimination of specular reflections and glare allows for a much better visualization of the true hue and saturation of the material. This means that cross-polarization is a superior and more reliable method for choosing the correct shade, helping us achieve the biomimetic harmony that is so important in modern dentistry.

7. SUSTAINABILITY

Economic sustainability is achieved by providing a cost-effective alternative to expensive spectrophotometers, reducing the financial barrier for clinicians to access objective diagnostic tools. By significantly improving shade matching accuracy ($p=0.0032$), this protocol minimizes the frequency of restoration remakes. Reducing remakes directly lowers laboratory costs and chair-side time, enhancing the overall economic efficiency of the dental practice.

From an environmental perspective, increasing the first-pass success rate of aesthetic restorations reduces the waste of clinical and laboratory materials, such as ceramic powders, composite resins, and single-use infection control shields.

Socially, the high accuracy of CP photography ensures superior aesthetic outcomes, which is vital for patient psychological well-being and satisfaction. Furthermore, as a reliable educational aid, it fosters more equitable access to high-quality dental care by assisting less experienced practitioners in achieving expert-level results.

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9. ANNEXES