Comparative Shade Measurement Analysis Between

Visual Assessment, Intraoral Scanner and Vita EasyShade

A Thesis

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Master of Science in Dental Research

By

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ABSTRACT

Aim & Hypothesis:

This research aimed to perform a comparative analysis of shade measurement methods in dentistry, focusing on the accuracy of a digital scanning system (Trios 4) in comparison with traditional visual determination with Vita Classical and Vita 3D Master shade guides, using a handheld spectrophotometer (Vita EasyShade) as the reference standard. The null hypothesis was that there would be no difference in the shade matching outcomes between the methods.

Materials & Methods:

In a controlled clinical setting, 25 teeth were assessed for color matching using the Vita EasyShade device to establish reference values. The same teeth were then measured with the Trios 4 scanner. A diverse group of twenty examiners, including ten dental students and ten experienced dentists, utilized Vita Classical and Vita 3D Master shade guides to determine the shade that best matched each tooth. The ΔE values were calculated and compared with the thresholds of acceptability and perceptibility for color match precision.

Results:

When applying the more stringent acceptability/perceptibility threshold of 1.8, a mere 14.6% of 714 observations were in agreement with the Vita Easyshade measurements. Notably, the success rate of matches varied slightly across different groups, with the lowest being the Vita Classical and 3D Master guide indications by the Trios 4 scanner at 11.8%, and the highest being the student group using Vita Classical and 3D Master at 15.3%. These differences, however, did not reach statistical significance ($p = 0.994$). The analysis conducted at the threshold of 3.6 demonstrated an overall agreement rate of 42.6%, with individual group performance ranging from 38.4% to 64.0%, still maintaining statistical non-significance ($p = 0.135$).

Conclusions:

In the study of shade matching efficacy, the comparative analysis between digital assessment using the Trios 4 scanner and conventional visual evaluation with Vita Classical and Vita3D Master shade guides did not show statistically significant differences. The anticipated enhancement in consistency and reliability with digital methods, as per prior expectations, was not substantiated with empirical evidence within the parameters of this study. It is particularly noteworthy that when a decision threshold of 1.8 was used, the data did not demonstrate a definitive trend in favor of the digital approach. These findings imply that current advancements in digital shade determination technology have not yet reached a level of development that conclusively surpasses traditional methods in the practice of aesthetic dentistry. As such, this research underscores the essentiality of ongoing development in digital dental technologies and presents a tempered perspective on the immediate integration of such methods. Further inquiries are warranted to establish the specific conditions under which digital methods might indeed exhibit significant improvements, thereby justifying a methodological shift in the field.

Keywords:

Dental Aesthetics, Shade Matching, Digital Dentistry, Intraoral Scanner, Spectrophotometry, Visual Assessment, Color Analysis, Trios 4, Vita Classical, Vita 3D Master, ΔE, Shade assessment

DEDICATION

To my parents, whose boundless love and unwavering support have been my sanctuary. From our home in Thailand to my academic pursuits across the seas in the States, you have been my guiding stars. With every Video call that stretched across continents, every parcel that brought a piece of home to my doorstep, and every word of encouragement that bridged the distance, you fortified my resolve. Your sacrifices, made without a second thought, allowed me to chase my dreams with a heart full of courage and a spirit ready to soar. This thesis is not merely a reflection of my own endeavors; it is a mosaic of the principles and wisdom you have woven into the fabric of my character. I extend my heartfelt thanks for your constant love, encouragement, and unwavering belief in me, even in moments when self-doubt whispered. The confidence and direction you gifted me are the most cherished treasures, guiding every step of my academic voyage. With a heart brimming with appreciation and affection, I devote this accomplishment to both of you.

To my dear brothers and sisters, your videos of laughter and growth from the little ones—have been a balm to my soul. Your visits were the physical manifestation of our unbreakable bond, a reminder that family is a compass that always leads you home, no matter how far you roam.

And to my friends, the ensemble cast in this adventure, you've painted my life with the vibrant colors of joy. Your spirit and camaraderie never failed to lift my spirits, turning even the most grueling days into opportunities for laughter and warmth.

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I am indebted to each of the examiners who participated in the research process. Their commitment and professionalism played an integral role in the collection and analysis of crucial data.

The support of my fellow graduate students was a source of motivation and camaraderie that made the laboratory not just a place of work, but a space of shared aspirations and collective endeavor. To my friends and family, your unwavering belief in my abilities and your boundless emotional support provided me with strength during moments of doubt and fatigue. Your encouragement was the wind beneath my wings.

This thesis is not only a reflection of my work but also a celebration of the collaborative effort of all the aforementioned individuals and groups. To everyone who contributed, I extend my sincerest thanks.

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I- Introduction

Esthetics mandates many aspects of people's lives nowadays. This also has an impact in the field of dentistry, where obtaining the best esthetic results is of paramount importance in certain specialties. For many patients, restoring dental esthetics is critical when considering dental treatment. A main objective of the restorative dentist should be to integrate restorative materials with the teeth, providing a natural-looking appearance acceptable for the patient and in which the dental restorations cannot be noticeable. [1, 2] Therefore, one of the most fundamental aspects in restorative dentistry, especially in the esthetic zone, is the tooth shade matching/measurement.

In the early 1900s, Professor Albert H. Munsell created the Munsell color system that describes each color as a point within the three-dimensional Munsell color space.[3] The system attributed Munsell Hue (H), Munsell Chroma (C), and Munsell Value (V) independently, and are expressed in the form of H V/C, which is known as the Munsell notation. Munsell Hue (H) is the term used to represent the color tone in the spectrum which divided into five primary groups: red, yellow, green, blue, and purple, as well as five intermediate hues that exist between neighboring primary colors. Munsell Chroma (C) measures the degree of color intensity, saturation, reflectance, or strength. Munsell Value (V) represents the lightness and darkness of a color, determined vertically along from black (value 0) at the bottom to white (value 10) at the top. [3, 4]

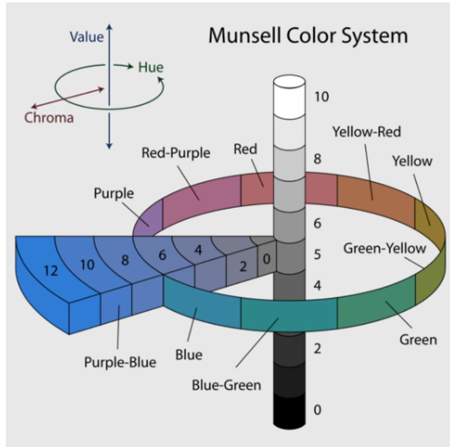

Figure 1: The Munsell Color System - A three-dimensional representation of color dimensions including Hue, Value, and Chroma. [5]

This color notation, albeit useful for many fields, is limited within the dental profession. In dentistry, the brightness of a restorative material can be increased by decreasing chroma or increasing surface reflectiveness of an object. On the other hand, decreasing in object's value represents more light being absorbed or scattered and less light being reflected from the object. [5] Moreover, degree of translucency, ranging from transparent to opaque, can affect the natural appearance of human teeth and shift the apparent color described by Munsell. The higher the translucency, the lower the value of a crown as less light reflects to the eye. [5]

Another color measurement system is the RGB model which is used in displaying images on electronic devices such as TV, computer or image scanner. The name of the model is derived from red, green and blue, which are the three primary colors. It is an additive color model which combined the three colors in various ways to give a wide range of colors. Colors are created in this paradigm by combining components, with white containing all colors and black containing none.[6]

One the other hand, color printers, paint and photographs utilized a subtractive color model, the CMYK color model. The four ink plates used in certain color printing are referred to as CMYK: cyan, magenta, yellow, and key (black). The model works by subtracting the colors red, green and blue from the background, usually white color. For example, cyan can be created by absorbing red from the white light and reflecting/transmitting green and blue. Unfortunately, these color measurement systems are not applicable to clinical dentistry. [6]

Currently the measurement system that can be used in our profession refers to the accuracy and acceptability of the color differences, namely the value ΔE, which is computed from the CIELAB value. In 1931, the Commission Internationale de l'Eclairage (CIE, International Commission on Illumination) created the CIELAB color order system[7] It is based on the color standardization of light sources and observers and is commonly used in color research. The system is a three-dimensional space that encompasses the complete spectrum of human color perception. It uses three coordinates to represent color: L* for perceived lightness of the color, a* for its position between red and green (where negative values indicate green and positive values indicate red), and b* for its position between yellow and blue (where negative values indicate blue and positive values indicate yellow). [3]

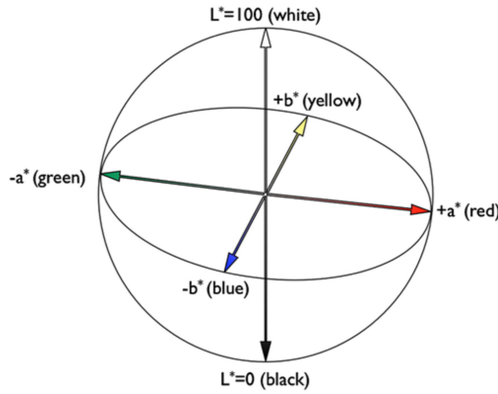

Figure 2: The CIELAB Color Space - A graphical representation illustrating the three axes of color dimensions: lightness (L*), red-green axis (a*), and blue-yellow axis (b*), where L* = 100 represents white and L* = 0 represents black. [9]

Given two colors in CIELAB color space, the CIE76 color difference formula is defined as:

$$\Delta E_{ab}^{*} = \sqrt{(L_2^{*} - L_1^{*})^2 + (a_2^{*} - a_1^{*})^2 + (b_2^{*} - b_1^{*})^2}.$$

For the CIELAB metric, the greater value of the **ΔE** indicates a larger difference between 2 colors expressed in numeric values. In dentistry, the **ΔE** can be used to express the difference between 2 dental colors based on determined thresholds of acceptability and thresholds of perceptibility. The acceptability threshold (AT) is the degree of color difference that is clinically acceptable for an esthetic outcome, whereas the perceptibility threshold (PT) expresses the magnitude of perceivable color difference by human eyes.[8] Some studies have shown that the threshold of acceptability is higher than the threshold of perceptibility[9]. Under controlled conditions, the ΔE values range from 1 to 2 to perceive a color difference by the human eye, whereas the ΔE values for acceptability threshold range from 2.48-4.48. [8, 10]

Restorations in the esthetic zone require competence in determining the tooth shade to meet the patient's esthetic concerns. One study reported that there are more than 80% of patients with anterior restorations that were unsatisfied with the color compared to their adjacent teeth. [11] The esthetics depend on the form of the tooth, texture, surface and the color. [12] Contemporary visual clinical techniques of shade selection can provide acceptable results to most patients. However, the techniques are very subjective and can be affected by conditions of lights, the dentist's personal experience, judgment in shade matching and angle of view. [13]

Visual shade selection methods are the most commonly used techniques for tooth color determination. They usually entail the comparison of a shade guide with the patient's tooth. The conventional visual technique is simple and very cost-effective for both patients and dental practitioners. [1] It allows the dental practitioner to confirm an agreement upon color satisfaction with the patient. There are numerous commercial shade guide systems available on the market. The first systemic shade guide introduced by Clark, tooth color indicator, consisted of 60 different shade tabs. Since then shade guide systems have developed throughout the years. In mid 1950s, the VITA Classical shade guide (VC, Vita Zahnfabrik, Bad Sackingen, Germany) was introduced to the market and is still a widely used shade guide in dentistry.[1] There are 16 color tabs with distinctive shades based on Vita Chart. The color tabs were grouped into four groups (A-to-D) increasing in chroma. The VITA Classical (VC) shade guide was a benchmark for tooth shade selection for decades. However, there were a significant degree of complaints in color range, color distribution and user-friendliness reported. The most critical concern includes absence of a rational and sufficient distribution in the portion of color space occupied by human teeth. [14] In 1985, the majority of undergraduate and graduate professors involved in color acknowledged a need for the creation of a new and systematic shade guide. [15]

The Toothguide 3D-Master (TG, Vita Zahnfabrik, Bad Sackingen, Germany) was the next evolution of dental shade guides in the late 1980s. TG uses the established color perception principles of hue, lightness, and chroma and number (lightness) – letter (hue) – number (chroma) markers more precisely than VC, which was created experimentally. Six distinct degrees of lightness, ranging from 0 (the lightest) to 5 (the darkest), were created to generate six distinct groupings of tabs. Each group has three chroma levels, ranging from one (the least chromatic) to three (most chromatic), except two chroma levels in group 1. In groups 2, 3, and 4, the two distinct hues L (less red) and R (more red) are connected with intermediate chroma values (1.5 and 2.5). [16]

A study has shown that fabrication of ceramic crowns with the Vita Toothguide 3D Master (TG) shade has a better color matching to the adjacent teeth than the Vita Classical guide (VC).[17] As compared to VC, it was found that TG had superior performance in matching natural teeth due to its wider color range and more uniform color distribution. [10, 18] Moreover, TG showed a significant smaller ΔE between natural teeth and the matching tab. [19]

The key strength of direct visual methods in shade selection lies in fostering mutual color match confirmation between the patient and the practitioner. This method stands out for its ease of use and minimal costs, making it a popular choice in clinical settings. Despite its prevalence, as indicated by sources[4,5], the process is inherently subjective, hinging on the variable criteria employed during assessment. The human eye, while sensitive to minuscule color differences, is not immune to error. The reliability of color perception can be affected by an array of personal factors such as the observer's age, gender, level of expertise, inherent color vision capability, and potential visual fatigue. Additionally, external conditions such as the quality and intensity of lighting, as well as the environment where the color matching takes place, also play a significant role. [20] The observer's sex has often been proposed as a factor affecting the repeatability of tooth shade selection. Haddad et al. demonstrated that women are better in shade determination than males. [21] However, in a study by Miranda et al., the opposite results were reported. [22]

When using the visual shade selection method, the quantity and quality of the light source is critical in obtaining the optimal tooth color match with a shade tab. The wavelength of visible light is between 380 to 780 nm. The ambient light should be balanced with the full spectrum of visible wavelength. If the light source is not balanced and does not contain all the visible wavelengths, the missing light energy at the wavelength in the visible spectrum, that would otherwise have been reflected or transmitted to the observer, will not be observed. As a result, the color of the tooth or the shade tab would be altered.[23, 24] During visual shade selection, the amount of light (intensity) should be diffuse, allowing observers to perceive color properly and pleasantly. In the dental operatory, adequate ambient illumination provides dental practitioners with visual comfort, particularly in terms of contrast. The recommended lighting intensity for tooth shade determination is between 200 to 300 fc, with a minimum of 150 fc. Fortunately, it has been determined that the intensity of dental ambient operatory lighting is not critical for color matching; no significant differences in correct color matching were observed when light intensity was varied from 75 to 300 fc.[24]

Daylight was considered to be the best light source for tooth color determination, but it is no longer recommended. The daylight has ranges of color temperature depending on the sun. It varies from 1000 K during the sunset to more than 20000 K in the blue sky. Moreover, daylight's spectral energy distribution fluctuates from a higher proportion intensity in the blue wavelengths while the sky is blue to a lower relative intensity at red-orange wavelengths during sunset. The relative intensity of daylight varies during the day due to cloud cover. [25]

Technological advancements have allowed a better accuracy in measuring tooth shade and thus improving the efficacy of shade matching during esthetic procedures.[9] The main advantage of dental shade-matching instruments is the ability to decrease subjectivity and provide better communication between the dentist and laboratory. It also increases the overall accuracy of the shade matching because it can be done in addition to visual shade selection. There are numerous types of dental shade-matching instruments available in the market, including colorimeters, spectrophotometers, digital cameras with an imaging system, and intraoral scanners. [1]

Colorimeters measure the tristimulus method of colorimetry and with three filtration sensors to the same sensitivity or color matching: red, green and blue. The instrument measures the amount of light reflection of an object. One disadvantage is that the quality of the filters can affect the accuracy of the colorimeters. Colorimeters express colors as international standard numerical values and are easily understood. An imaging colorimeter (ShadeVision; X-Rite, Grandville, MI) can provide a complete tooth image by using three separate area of databases:

cervical, middle and incisal third. [3] However, complex color analysis is not suitable with colorimeters as it can only obtain numerical color data in the specific color spaces.

The spectrophotometer is considered to be the most accurate and useful instrument for shade matching in dentistry, especially with surface color. [26] A spectrophotometer consists of a light source, a dispersing light, a measuring optical system, a detector and a system to transform the light into a signal that can be analyzed. A prism in the spectrophotometer disperses white light from a tungsten-filament bulb into a spectrum of wavelength bands between 5 and 20 nm. For each wavelength in the visible spectrum, the quantity of light reflected from a specimen is measured. [26] Spectrophotometer data must then be processed and converted into a format that dental practitioners can understand and communicate. The readings are usually compared to dental shade guides and translated to shade tab equivalents.

Vita EasyShade Compact (Vita Zahnfabrik, Bad Sackingen, Germany) was developed to be a fast, cordless, portable and reliable spectrophotometer for natural teeth and ceramic restorations. Due to the LED technology on the spectrophotometer, the result will not be unaffected by ambient circumstances and will provide objective and reliable measurements. In compliance with the American Dental Association, measurements from Vita EasyShade are established as standard shade systems Vita Classical A1-D4 and Vita 3D-Master system as well as an indication of the VitaBlocs shades and bleached index. The spectrophotometer consists of different measurement modes including tooth single mode, tooth area mode, verification of restoration color and shade tab mode. A study has reported the Vita EasyShade compact to have a significant higher repeatability and accuracy compared to conventional visual shade determination. [27] The Vita

Easyshade compact was estimated to have 92.6% and 96.4% accuracy and repeatability, respectively. [28]

Spectrophotometers have a 33% increase in accuracy when compared to the conventional visual shade selection method. Moreover, in a study comparing crowns fabricated using conventional shade-matching and a spectrophotometer, crowns fabricated using a spectrophotometer had a significantly higher shade matching and lower rate of patient dissatisfaction in terms of color mismatch. [29] Inter-rater agreement between observers between visual and spectrophotometric shade analysis were 26.6% and 83.3% respectively. [16]

Recently, digital technologies, such as an intraoral scanner (IOS) and 3D printing, have been introduced in dentistry to improve clinical success. Initially, intraoral scanners were designed to produce instantaneous digital dental impressions. The new generations of digital intraoral scanners, such as the 3Shape TRIOS, provided new features like a built-in shade determination function. The device consists of a high-definition camera and LED light source that provides measurements according to the VITA shade guide. [30]

The 3Shape Trios intraoral scanner and Vita Easyshade were compared in a study of 107 patients, where the shade measurement was determined. Results showed 43% accuracy of the visual assessment, 76.6% accuracy for Vita Easyshade, and 78.3% accuracy for 3Shape Trios 3. [31] Moussaoui et al. compared different methods of shade determination. The study suggested that the 3Shape TRIOS intraoral scanner was recommended as an alternative method to the conventional visual shade selection method. [32] Moreover, Rutkunas et al. showed 53.3% accuracy from 3Shape TRIOS intraoral scanner with 27.5% accuracy of 3D-Master shade guide compared to the VitaEasyshade. However, they found that the results of shade determination from the TRIOS scanner do not match with the results from spectrophotometers. Therefore, it is recommended to have it as an additional method. [33]

Studies have shown that instrumental methods were more accurate and reliable than the visual method. Therefore, color measuring devices are recommended to enhance the accuracy of tooth shade determination, fabrication, interpretation of tooth and restorations within the oral cavity.

II- SIGNIFICANCE

Although numerous studies have been conducted investigating and comparing the reliability and accuracy of tooth shade selection methods, there is limited information available in regards to comparing visual assessment and the ability of the newer versions of intraoral scanners to detect tooth shade. In 2019, Rutkunas et al. proposed a study using Spectroshade, a comprehensive tooth surface measuring spectrophotometer, as a reference device in their in vivo investigation. Spectroshade was recognized as a reliable and accurate instrument. However, this was designed for in vitro experiments and was able to compare only one instrument, SPEC (VITA Easyshade Advance 5.0), to the manufacturer's shade. [36]

In addition, an in vitro study was designed to use "true shade" assessment. The benefit of utilizing the manufacturer's shade as a control group is that "accuracy" may be defined as the color's trueness. Specifically, Mehl et al. were concerned with the usage of the term "accuracy" in numerous in vivo research studies since they considered the genuine colors of natural teeth were unknown. As a result, they preferred to use "relative accuracy" in their investigation.[37]

Therefore, the shade measurement function of a digital scanning system and visual determination (Vita Classical shade guide) compared to a handheld spectrophotometer has not been investigated.

III- AIM AND HYPOTHESIS

The aim of this study was to evaluate the shade measurement function of a digital scanning system and visual determination (Vita Classical and Vita 3D master shade guides) compared to a handheld spectrophotometer (Vita EasyShade).

The null hypothesis was that there would be no difference in the shade matching outcomes between the methods.

IV- MATERIALS AND METHODS

I. Study design

This study was an in vitro experimental study. The overview of the study design is shown in Figure 3.

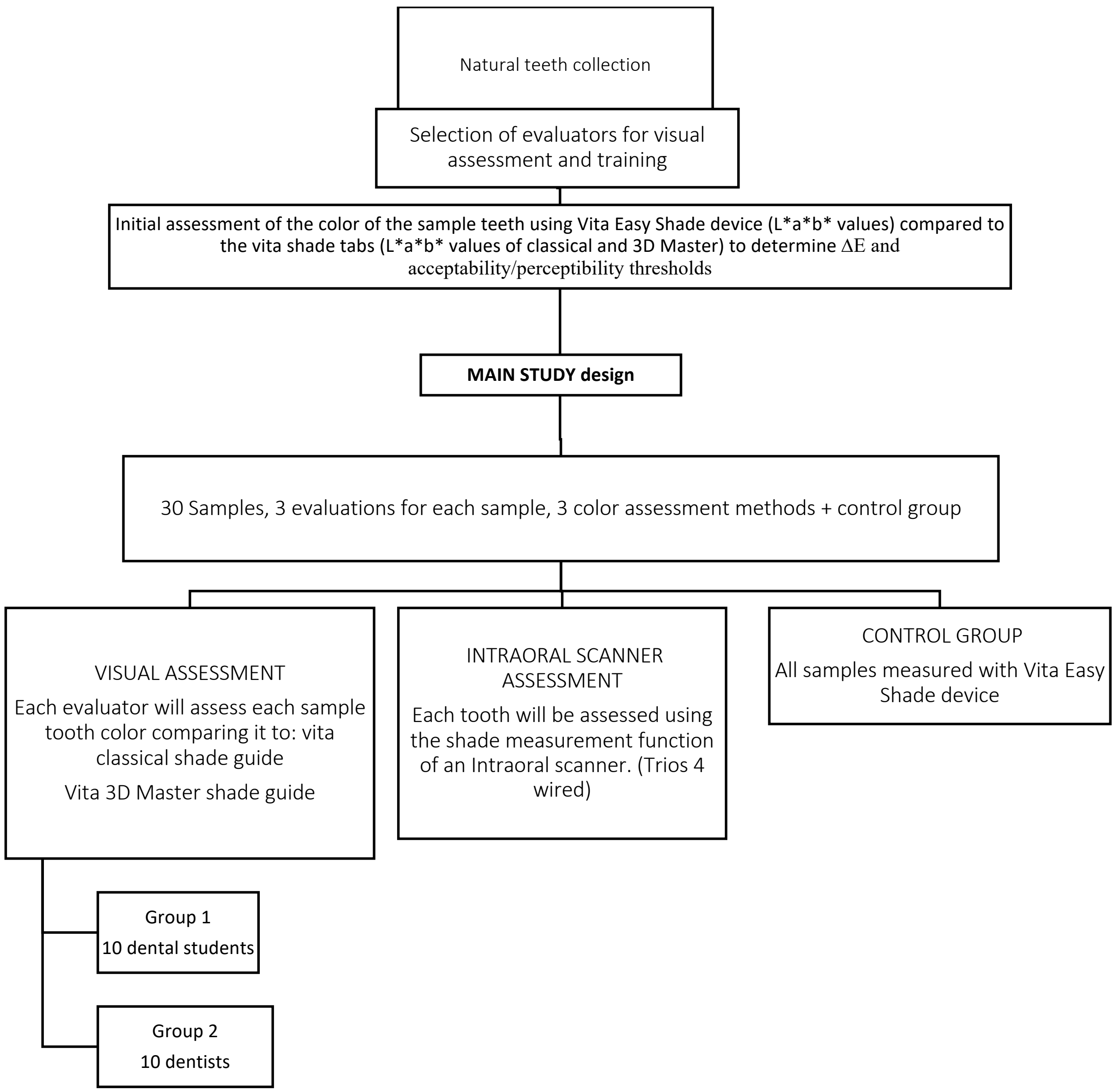

Figure 3 Overview of the study design

II. *Sample preparation*

Thirty anterior intact extracted teeth were chosen. Teeth were not bleached or disinfected with any solution that may have altered their shade. There were no restorations or severe fractures/craze marks on the teeth. Teeth were collected from private practices in the United States, with the patient's consent, disinfected in 2% Chlorhexidine solution, and then preserved in 0.4% Sodium Azide solution until the color/shade evaluations were performed.

III. Initial assessment of the color of the sample teeth (Control group)

To determine whether a natural tooth shade was comparable to a given shade tab, we measured the ΔE value between them. For this assessment, each shade tab and sample tooth were measured using the Vita Easyshade device. Each sample tooth was measured 3 times and the mean values were considered. L* c* h values were obtained for each measurement. Each shade tab from both the Vita Classical and Vita 3D Master shade guides was measured with the Easyshade device using the same methodology. After all the mean readings had been recorded in a spreadsheet, the readings were analyzed to calculate ΔE_{00}. This is a more current version of analyzing color differences and it is the one recommended to determine dental color differences, since it accounts for 5 extra corrections that are specifically important in dental color research. Once the L*C*h coordinates had been obtained, ΔE_{00} was calculated using the following formula:

$$\Delta E_{00}^{*} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C} \frac{\Delta H'}{k_H S_H}}$$

The CIE dE2000 (ΔE_{00}) formula takes into account several factors to better align with human visual perception. These factors include differences in lightness (L*), chroma (C*), and hue (h). The formula also incorporates corrections for the specific sensitivities of the human eye to different colors, addressing the non-uniformity of color perception.

This formula results in a value between 0 and 100 and it represents the difference between the shades in this designated set of color coordinates. The field of color science employs a practical system for interpreting color differences by means of visual benchmarks, notably the perceptibility threshold (PT) and acceptability threshold (AT) at a 50:50 ratio. The 50:50 PT is defined by a situation where a color difference between two samples is noticed by 50% of the observing individuals, with the other 50% unable to detect any difference. Correspondingly, a 50:50 AT is characterized by an instance where half of the observers believe a color mismatch in dental prosthetics warrants correction, while the other half assesses the discrepancy to be negligible or within an acceptable range.[44]

For the assessment of color difference in this study, the color difference thresholds were determined as acceptability thresholds (50:50 AT). If the ΔE value was higher than the threshold, the difference in color was considered unacceptable. If the ΔE value was lower than the threshold, the difference was considered acceptable.

According to a study by Paravina et al [41], a 50:50% perceptibility threshold (PT) and a 50:50% acceptability threshold (AT) are critical for distinguishing between acceptable matches. The use of either PT or AT depends on how strict the color differences are evaluated. For this study, we considered the lower and higher spectrums of 50:50% AT (1.8 and 3.6 respectively). These thresholds provided a framework for our analyses, allowing for separate evaluations of data that fell within the defined ranges of acceptable thresholds. [41] We considered that AT define what is applicable clinically, instead of PT which are very strict. These thresholds were applied to the match/no match analysis described earlier.

At the end of the data collection, the shade of the sample teeth could match one or multiple shade guide tabs depending on the thresholds considered. If multiple shade tabs matched the color of a sample tooth, these tabs were grouped to facilitate statistical analysis and determine the match/no match of shade for each tooth and the visual color assessment.

IV. *Selection of examiners*

The examiners for visual assessment were separated into two categories. Group 1 consisted of 10 examiners who were third- and fourth-year dental students from the Tufts University School of Dental Medicine, Boston, MA; five women and five males between the ages of 20 and 30. Group 2 consisted of 10 licensed dentists, five women and five men, who were dentists with at least five years of expertise in restorative dentistry from the Boston, MA area of the United States.

V. *Setting and Calibration*

a) Examiners

All shade selection procedures were carried out by examiners who were trained by a specialist in shade matching. Instructions were given on how to measure and determine/record the shade of each sample with both shade guides (Vita Classical and Vita 3DMaster). Examiners were handed the sample teeth and shade guides by an assistant. All visual assessments were carried out in the same room with standardized D65 artificial daylight.

b) Spectrophotometer

The spectrophotometer (Vita EasyShade) was calibrated every time before the shade selection procedure according to the manufacturer's recommendation to assess the initial shade of each sample tooth from the control group.

c) Intraoral scanner

A calibrated TRIOS intraoral scanner (3Shape, Copenhagen, Denmark) was used for the intraoral scanner color assessment of the sample teeth. The software was upgraded to version 1.3.2.0 of TRIOS software to ensure the latest technology of this device was used. Before any shade measurement, calibration was performed prior to scanning without the dental unit's light source, according to the manufacturer's recommendation. Natural (sample) teeth were mounted on a dentoform using modeling clay to simulate an arch of natural dentition exposing just the coronal part of the tooth.

Figure 4: Simulation of Natural Dentition Using a Dentoform

d) Shade guides

An unaltered Vita Classical and Vita 3D Master shade guide (Vita Zahnfabrik, Bad Sackingen, Germany) was used. Just the center (middle-third) of each shade tabs was measured. This area is the one usually utilized for shade taking and it is the one that has middle chroma, middle value and the hue corresponding to each designation. The incisal and cervical thirds were coated with matte black acrylic paint to avoid confusion with the visual assessment part and to ensure proper reading of the devices. The shade color numbers were also covered with black tape.

Figure 5: Shade Tabs from VITA Classical and VITA 3D-Master Systems

VI. *Shade selection assessment*

a. Method 1: Visual assessment

Examiners were divided into two groups: 10 dental students and 10 experienced dentists. Each participant evaluated all the extracted teeth (only in the middle third of the tooth) and gave their rating based on the "best match" compared to the Vita Classical shade guide and Vita 3D Master separately. They were advised that no shade tab might match perfectly, so they would have to find the one that they thought was the best match. All the examiners performed the shade selection using the visual assessment methods described, comparing the natural tooth shade to the closest shade tab of the Vita Classical shade guide and Vita 3D Master separately under D65 artificial daylight. Teeth were always stored in Sodium Azide solution and were taken out for a brief moment each time for the shade comparison to avoid the teeth getting dehydrated.

b. Method 2: Intraoral scan assessment

Every sample tooth was scanned using a TRIOS 4 scanner by one trained operator. 3 scans per tooth were made and results recorded. Teeth were mounted with pink/red modelling clay on typodonts to make sure scanning was seamless and similar to a dental arch. Then, using the TRIOS software, tooth color was determined by the device. However, the TRIOS 4 software does not provide CIE l* a b* values; it provides results in the format of the Vita Classical or 3D Master shade guide, so a conversion table was used to calculate a match between those readings and the control group, based on the initial color assessment described previously for the shade tabs. Based on the matching shade tabs assigned to each sample tooth, the TRIOS 4 readings were compared to those matching tabs and were assigned the match/no match score, similar to the visual assessment results.

VII. *Sample size calculation*

Power calculations were conducted using nQuery Advisor v. 9.1.1.0 (Statistical Solutions Ltd., Cork, Ireland) to assess the power of the study to detect a difference between the groups in terms of the percentage of samples matching the Vita Easyshade device. Regarding the effect size, the anticipated percentage of matching samples was based on the findings of Igiel et al. [38] for the Trios groups and the findings of Della Bona et al. [39] for the other groups, resulting in an effect size of $\Delta^2 = 0.13$. Furthermore, the power calculations accounted for the presence of correlated data via the methodology of Killip et al. [40] Based on Killip et al., the intracluster correlation coefficient was assumed to be $\rho = 0.01$ or $\rho = 0.02$, and a separate power calculation was performed for each value of ρ. Both calculations demonstrated that the obtained sample size was adequate to obtain 99% power to detect a difference between the groups in conjunction with a Type I error rate of $\alpha = 0.05$. Additionally, sensitivity analyses were undertaken in which the value of ρ was conservatively assumed to be 0.10 or 0.20. Even under these conservative assumptions, the obtained sample size was still sufficient to obtain greater than 80% power to detect a difference between the groups in conjunction with a Type I error rate of $\alpha = 0.05$.

VIII. *Statistical Analysis*

Results were analyzed in a binary "match/no match" format based on the initial assessment of shade of the sample teeth and after the threshold of acceptability was established. Separate analyses were conducted for the 1.8 and 3.6 AT thresholds. Descriptive statistics were calculated, and the findings were also displayed graphically via side-by-side boxplots. Statistical significance was evaluated using a mixed-effects model to account for the presence of correlated data. The significance level was set at $\alpha = 0.05$. SAS 9.4 (SAS Institute Inc., Cary, NC, USA) was used in the analysis.

V– RESULTS

Threshold of acceptability/perceptibility at 1.8

Applying a 1.8 threshold, 17 sample teeth had at least one match either with the Vita Classical or Vita 3DMaster shade guide. Among the 714 observations from all six groups combined, 104 (14.6%) matched the Vita Easyshade device. Table 1 shows the percentage matching the device for each group separately. This percentage ranged from 11.8% (Vita Classical and 3D Master guide provided by the Trios 4 scanner) to 15.3% (students using Vita Classical and 3D Master). However, the difference between groups was not statistically significant (p = 0.994).

Group	N (%) Matching Vita Easyshade	p
Faculty / Vita Classical (N = 170)	23 (13.5%)	0.994
Faculty / Vita 3D Master (N = 170)	25 (14.7%)	
Students / Vita Classical (N = 170)	26 (15.3%)	
Students / Vita 3D Master (N = 170)	26 (15.3%)	
Trios / Vita Classical (N = 17)	2 (11.8%)	
Trios / Vita 3D Master (N = 17)	2 (11.8%)	

Table 1: Comparison of Shade Matching Accuracy Between Vita Classical, Vita 3D Master, and Trios Scanner Against Easyshade Spectrophotometer - Threshold of acceptability/perceptibility at 1.8

Figure 6 displays side-by-side boxplots illustrating the distribution of the percentage matching Vita Easyshade for four of the six groups. The “Faculty / Vita Classical” boxplot represents the distribution of this percentage across faculty members when using the Vita Classical shade guide; the “Faculty / Vita 3D Master” boxplot shows the distribution for faculty members using the Vita 3D Master shade guide. The “Student / Vita Classical” and “Student / Vita 3D Master” boxplots demonstrate the distributions for students using each respective shade guide. Faculty using the Vita Classical shade guide exhibited a median matching percentage of 12%, with the middle 50%

of their matches falling between 12% and 18%. The faculty's use of the Vita 3D Master shade guide showed a higher median matching percentage of 15%, with the middle 50% of matches ranging from 6% to 25%. No outliers were detected in this group. Students using the Vita Classical shade guide also demonstrated a median match percentage of 15%, with the middle 50% of their matches ranging from 12% to 19% with no outliers detected. The Vita 3D Master shade guide, when used by students, also revealed a median matching percentage of 15%, with the middle 50% of their matches ranging from 11% to 21%. No outliers were detected for this group. Note that boxplots displaying the variability across practitioners could not be created for the Trios groups since only one practitioner used the Trios scanner.

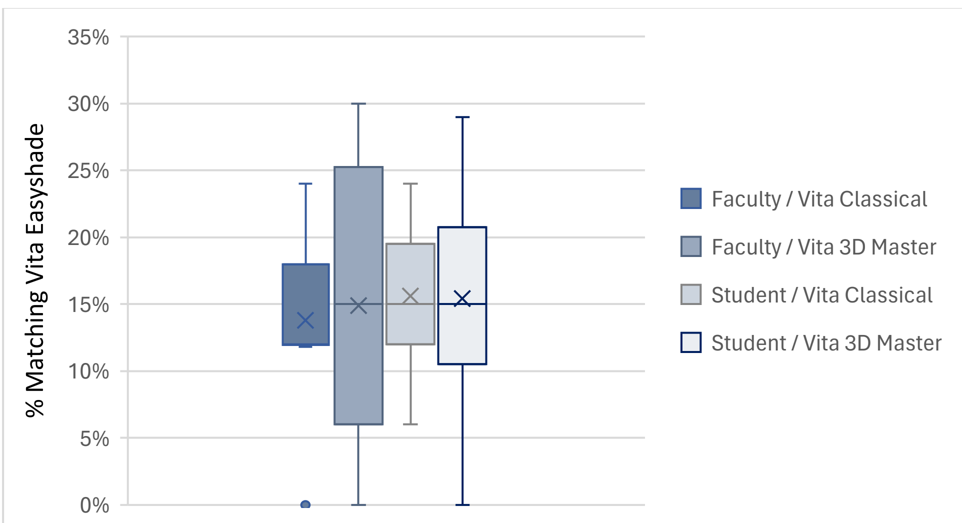

Figure 6 : The distribution of shade matching percentages between faculty and students using the Vita Classical and Vita 3D Master Shade guides compared with the Easyshade Spectrophotometer - Threshold of acceptability/perceptibility at 1.8

Threshold of acceptability/perceptibility at 3.6

Applying a 3.6 threshold, 25 sample teeth had at least one match either with the Vita Classical or Vita 3DMaster shade guide. Among the 1050 observations from all six groups combined, 447 (42.6%) matched the Vita Easyshade device. Table 2 shows the percentage matching the device for each group separately. This percentage ranged from 38.4% (students using Vita 3D Master) to 64.0% (Vita 3D Master guide provided by the Trios 4 scanner). The difference between groups was not statistically significant (p = 0.135).

Group	N (%) Matching Vita Easyshade	p
Faculty / Vita Classical (N = 250)	107 (42.8%)	0.135
Faculty / Vita 3D Master (N = 250)	100 (40.0%)	
Students / Vita Classical (N = 250)	114 (45.6%)	
Students / Vita 3D Master (N = 250)	96 (38.4%)	
Trios / Vita Classical (N = 25)	14 (56.0%)	
Trios / Vita 3D Master (N = 25)	16 (64.0%)	

Table 2: Comparison of Shade Matching Accuracy Between Vita Classical, Vita 3D Master, and Trios Scanner Against Easyshade Spectrophotometer – Threshold of acceptability/perceptibility at 3.6

Figure 7 presents analogous information to Figure 4, but defining the threshold of acceptability/perceptibility at 3.6. Faculty using the Vita Classical shade guide exhibited a median matching percentage at 44%, with the middle 50% of their matches falling between 36% and 49%. The faculty's use of the Vita 3D Master shade guide showed a similar 25th percentile but a reduced median of 42%. Students using the Vita Classical shade guide demonstrated a slightly higher median match percentage near 46%, albeit with a broader spread of data, indicating a more variable match rate. The Vita 3D Master shade guide, when used by students, revealed the lowest median matching percentage of 38%, with the widest range of data, extending from as low as 8% to as high as 60%, highlighting a considerable inconsistency in matching success within this group.

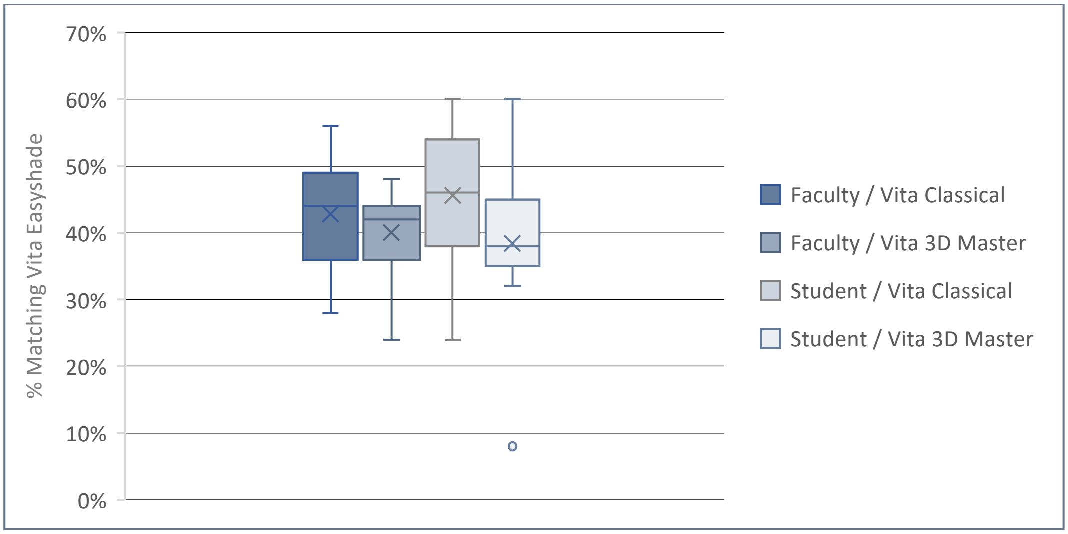

Figure 7: The distribution of shade matching percentages between faculty and students using the Vita Classical and Vita 3D Master Shade guides compared with the Easyshade Spectrophotometer- Threshold of acceptability/perceptibility at 3.6

VIII – DISCUSSION

This study initiated a comprehensive in vitro comparison of shade measurement analysis between visual assessment, intraoral scanner and the Vita EasyShade device. In the realm of dental restorations, the accuracy of shade matching plays a crucial role in ensuring aesthetic success and thereby significantly influencing patient satisfaction. The quantitative metric employed for this assessment was the ΔE value, which quantifies the deviation in color match; a lower ΔE value indicates a closer match and thus, a more successful outcome in shade matching.

The pursuit to achieve a shade match unveiled a significant challenge with the tools currently available to dental professionals. Only a small fraction of matches (14.6%) fell within the defined acceptable range of the ΔE threshold of 1.8, highlighting the substantial limitations in both visual and instrumental shade matching techniques. It also highlights the high variability of tooth shades that present in a clinical scenario, since only a fraction (17 out of 30) of sample teeth found a match within the 2 shade guides utilized in this study, which represent one of the most commonly used in clinical practice. This was also a consistent observation across various groups, which underscores a pervasive challenge that transcends the experience level of the practitioners and the sophistication of the tools utilized. The uniform outcomes across different experiences and technologies suggest a fundamental barrier in surpassing subjective color perception limitations.

Further analysis at the higher ΔE threshold of 3.6 revealed that 42.6% of observations matched the EasyShade device, indicating a greater leniency in perceived accuracy but still showcasing considerable room for improvement. This finding suggests that while some tools may perform adequately under less stringent criteria, there exists a significant discrepancy in achieving optimal shade matches that meet the highest standards of aesthetic dentistry.

From our study, the statistical analysis revealed no significant differences in the performance of all the shade measuring methods using both established thresholds. These findings show that we failed to reject our null hypothesis. These findings suggest that the precision of the digital devices used in this study may approximate that of traditional visual assessment methods under the specified experimental conditions.

Further contextualization is provided through a comparative literature review. In their study titled "In vivo study for tooth colour determination—visual versus digital," Brandt et al. explored similar methodologies in a cohort of 107 patients. Their findings indicated accuracy rates of 43% for visual assessments, 76.6% for Vita Easyshade, and 78.3% for the 3Shape Trios 3.(31)These results suggest a potential advantage of digital methods over traditional visual techniques in larger or differing experimental setups. The alignment of our study with these findings confirms the variability in the performance of digital devices and supports the premise that their efficacy may be dependent on specific clinical and environmental factors. It is, however, important to note that this study design used the Vita Easyshade device as the control group, since it was the most reliable way of assessing a match of the shade tabs to the natural teeth. Other studies have used the Vita Easyshade device as an experimental group, finding that it usually outperforms visual assessment methods. (30, 31)

Additionally, the research by Moussaoui et al., which supported the 3Shape TRIOS intraoral scanner as a feasible alternative to traditional visual shade selection, corroborated the growing inclination towards digital methods in dental practice. [32] This endorsement advocates for the integration of digital technologies in clinical settings to potentially enhance the accuracy of shade matching. However, only 3 articles could be included in the review, which highlights the potential risk of generalizing a statement obtained from such a small dataset and the lack of reliable data on the subject.

One of the most striking observations is the wide range of outcomes exhibited by the students when using the Vita 3D Master shade guide. The data demonstrated a particularly wide spread of accuracy, suggesting a variability in proficiency that may be attributable to the inherent complexity of using the Vita 3D Master system or to the students' level of experience. This variability underscores the challenges faced by less experienced practitioners in achieving accurate shade matches, even when utilizing advanced tools designed to facilitate this process. As highlighted by Güven et al., the process of visual shade matching poses significant challenges in prosthetic dentistry, especially for students who require thorough training to overcome these obstacles. [42]

The presence of an outlier at the 8% match rate within the student group using the Vita 3D Master shade guide is particularly noteworthy. This deviation suggests that at least one student encountered significant difficulties with shade matching, highlighting the limitations of the Vita 3D Master when used by those without adequate training. This instance serves as a clear indicator of the broader challenge faced by novice practitioners, raising awareness of the urgent need for proper training in such a basic clinical skill as shade matching of teeth. According to the study by Jebaraj, the effectiveness of digital shade matching tools like the Vita 3D Master is heavily dependent on the operator's experience and training. As such, integrating comprehensive training modules specifically tailored to digital shade matching into dental curricula could substantially improve the proficiency of future dentists, ensuring that they are better equipped to utilize these tools effectively. [43]

The necessity for advancements in dental material science and technology aimed at improving shade matching accuracy becomes evident through these findings. There is a clear indication for the potential benefits of incorporating more objective measures into the shade selection process. Moreover, the results advocate for a reevaluation of educational approaches to better equip future dentists for the complexities of aesthetic dentistry, suggesting a shift towards methodologies that minimize human subjectivity and enhance reproducibility.

Future research should pivot towards exploiting artificial intelligence and machine learning to refine shade match predictions. The development of standardized shade guides, calibrated against objective colorimetric standards, represents a promising direction. Investigating environmental and operational factors that influence shade selection in clinical practice could lead to optimized protocols for shade matching, ultimately enhancing the aesthetic outcomes of dental restorations and elevating patient satisfaction.

In the field of dental aesthetics, the precision of shade matching is paramount, and AI stands at the vanguard of enhancing this intricate process. By harnessing the prowess of advanced color analysis algorithms, AI transcends the limitations of human perception, offering a consistency in shade determination previously unattainable. It systematically learns from extensive datasets, capturing the myriad nuances of tooth coloration, thereby refining the accuracy of its predictions. Furthermore, AI's objective approach mitigates the inherent subjectivity of manual shade matching, promising a uniform standard across varying clinical settings.

The integration of AI with cutting-edge imaging technologies could facilitate real-time, intraoperative color assessments, streamlining the restoration workflow. AI's predictive modeling capabilities are particularly groundbreaking, enabling the anticipation of final restorative outcomes by considering factors such as tooth translucency and underlying color. This foresight is crucial in customizing patient-specific restorations that harmonize with the natural dentition.

Moreover, AI's ability to adjust for environmental influences, such as lighting conditions, ensures that shade selection remains consistent and true to life, independent of extraneous variables. As AI systems continue to evolve through machine learning, their ever-improving analytical precision heralds a new era of color matching that continually refines itself with each application.

This technological evolution also enhances patient-dentist communication, allowing for more engaged and informed discussions. By providing patients with visual simulations of potential outcomes, AI aids in setting realistic expectations, thereby elevating patient satisfaction. The culmination of these advancements underscores a transformative impact on dental restorations, driving the field towards an unprecedented level of customizability and accuracy in aesthetic dentistry.

The study's examination of the Trios 4 Scanner, Vita Classical, and Vita 3D Master shade guides, in comparison to the spectrophotometer EasyShade, offers critical insights into the operational principles, advantages, and limitations of these tools. Our study found that the Trios 4 Scanner's performance in shade matching did not exhibit a significantly better outcome compared to traditional methods. This observation was consistent despite the scanner's use of advanced digital imaging and analysis. It is important to note that our results are based on trials conducted with a single user of the Trios4 device, which could imply that user experience and the technical environment might play a less pronounced role in its effectiveness than previously thought. The Vita Classical and Vita 3D Master shade guides, while beneficial for their ease of use, worldwide acceptability and accessibility, face limitations in their ability to capture the full range of tooth colors, often leading to subjective mismatches. This study only considered the middle third of each shade tab, trying to simplify the assessment of the color and to make the shade matching more objective.

The spectrophotometer EasyShade, serving as a benchmark for accuracy, underscores the value of objective, quantifiable color measurements in achieving precise shade matches. This comparison illuminates the path for optimizing existing tools and developing new technologies that incorporate both digital accuracy and user-friendly interfaces.

Shade matching is profoundly influenced by psychological and visual factors, including the variability in human color perception, the impact of lighting conditions, and the phenomenon of color constancy. These elements can significantly affect the accuracy of shade selection, emphasizing the need for standardized lighting environments and training programs that enhance practitioners' awareness and understanding of these factors. Addressing these aspects in tool development and clinical practice can mitigate the subjective errors inherent in visual shade matching and lead to more consistent and satisfactory outcomes.

The findings of this study hold significant implications for dental education and training, highlighting the necessity for curriculum enhancements that focus on the challenges of shade matching. Proposing specific changes, such as integrating modules on the use of digital tools and the principles of color theory, can better prepare students for the intricacies of aesthetic dentistry. Moreover, professional development programs should incorporate hands-on training with advanced shade matching technologies, fostering a deeper understanding and proficiency among current practitioners.

This study paves the way for future research in dental shade matching, suggesting avenues such as the exploration of artificial intelligence in predictive shade matching, the impact of new materials on shade stability, and longitudinal studies assessing the durability of shade matches. Interdisciplinary research, combining insights from materials science, optical engineering, and psychology, can yield innovative solutions that address the current limitations and enhance the efficacy of shade matching tools.

Based on the study's findings, practical recommendations for dental practitioners include the adoption of standardized protocols for shade matching, the consideration of patient-specific factors in tool selection, and the continuous education on advancements in shade matching technologies. These guidelines aim to improve the accuracy of shade matches, enhance patient communication, and ultimately, elevate the quality of dental restorations.

While our study found no significant differences in shade matching accuracy among the Trios Intraoral scanner and visual assessment compared to the Vita EasyShade device, it is crucial to consider the specific aspects of our methodology that may have influenced these results. One notable limitation is the area of the tooth from which the shade was measured. Our analysis was confined to the middle third of the tooth, a region that does not account for the potential translucency observed in other parts of the tooth. This uniform approach may have masked subtle variations in shade that could significantly impact the overall effectiveness of different shade matching tools, particularly in clinical settings where such nuances are crucial for achieving aesthetically pleasing results.

Our finding aligns with emerging trends in dental technology, where digital tools are becoming as reliable as conventional methods. However, historical data indicate variability in the performance of these tools. According to Hampé-Kautz et al., earlier versions of intraoral scanners were less reliable than spectrophotometers and traditional visual methods, often failing to meet clinical accuracy thresholds. This historical perspective contrasts with our findings, suggesting significant advancements in intraoral scanner technology[45]

Moreover, the skills and potential biases of the dental students selected to perform shade matching may have impacted the outcomes. These students, possibly more adept or better trained in aesthetic judgment than typical dental professionals, could have skewed the accuracy of our comparisons, potentially not reflecting the general capabilities within the dental community.

The sample size and diversity of the subjects and teeth, including variations in age, tooth health, and inherent color, might also limit the generalizability of our results. A more extensive and diverse sample could provide insights that are more reflective of the broader population. Furthermore, the subjective nature of color perception, which varies significantly among individuals due to physiological differences and personal interpretation, introduces an element of unreliability that affects both visual and digital shade matching methods. Acknowledging these limitations is crucial as they highlight areas for improvement in future studies, suggesting a need for more comprehensive participant profiling, vision impairment screening and a holistic approach to tooth color assessment.

The accuracy of shade matching directly impacts patient satisfaction and the aesthetic success of dental restorations. This study highlights the importance of accurate shade determination in meeting patient expectations and enhancing the overall treatment experience. Effective communication, informed consent processes, and the incorporation of patient feedback in the shade selection process are essential components in achieving optimal aesthetic outcomes.

IX – CONCLUSION

The investigation into the comparative effectiveness of dental shade matching tools, specifically between the Trios 4 Scanner and traditional methods utilizing the Vita Classical and Vita 3D Master shade guides, compared to the EasyShade spectrophotometer, has afforded substantial insights into the nuances required to optimize aesthetic outcomes in dental restorations. Using ΔE values as a quantitative metric, this study methodically evaluated the limitations and strengths inherent in both visual and instrumental shade matching techniques, paving the way for a nuanced and updated understanding of digital versus traditional methodologies.

Contrary to our working hypothesis, which anticipated a significant discrepancy in shade matching accuracy between the Trios (TR) scanner and the conventional visual assessment using the Vita Classical shade guide, our findings revealed no significant differences. This outcome did not support the hypothesis that digital methods would demonstrate superior precision compared to visual techniques, thereby indicating an equivalency in performance that merits further exploration based on the variables aforementioned.

This study's conclusions are instrumental in advocating for an evolution in dental shade matching processes. While the current literature and preliminary data suggested potential superiority of digital tools in achieving greater accuracy and consistency, the evidence obtained from our study design indicates that these digital devices, as of now, perform on par with established visual methods. This revelation underscores an essential continuity in technology development and optimization, especially in digital shade matching applications.

Furthermore, the implications of this research extend beyond mere technological comparison, influencing educational strategies within dental curricula. It highlights the critical importance of integrating comprehensive training on digital tools and advanced color theory, thus preparing future dental professionals for a technologically advanced practice environment. Additionally, our exploration into the psychological and environmental influences on shade matching emphasizes the necessity for a holistic approach to clinical practice, tool development, and patient interaction.

Prospectively, the integration of emerging technologies such as artificial intelligence and the development of more refined, standardized shade guides promise to revolutionize the field. These innovations are poised to minimize subjectivity in shade matching, potentially enhancing both the accuracy and the efficiency of dental aesthetic treatments, thereby increasing patient satisfaction.

In conclusion, our research contributes significantly to the ongoing discourse in dental aesthetics, reinforcing the pivotal role of digital technologies in the evolution of shade matching precision. Although our study did not substantiate the expected superiority of digital tools over traditional methods, it provides a foundational platform for future interdisciplinary research. Such endeavors should aim at not only refining existing technologies but also at continuously improving educational methodologies and clinical practices. As we move forward, the intersection of technological innovation, academic inquiry, and clinical application is expected to yield substantial advancements, setting a progressive course for future breakthroughs in the domain of dental shade matching.

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APPENDIX

Appendix A. Tables

Table 1: Comparison of Shade Matching Accuracy Between Vita Classical, Vita 3D Master, and Trios Scanner Against Easyshade Spectrophotometer - Threshold of acceptability/perceptibility at 1.8

Group	N (%) Matching Vita Easyshade	p
Faculty / Vita Classical (N = 170)	23 (13.5%)	0.994
Faculty / Vita 3D Master (N = 170)	25 (14.7%)	
Students / Vita Classical (N = 170)	26 (15.3%)	
Students / Vita 3D Master (N = 170)	26 (15.3%)	
Trios / Vita Classical (N = 17)	2 (11.8%)	
Trios / Vita 3D Master (N = 17)	2 (11.8%)	

Table 2: Comparison of Shade Matching Accuracy Between Vita Classical, Vita 3D Master, and Trios Scanner Against Easyshade Spectrophotometer – Threshold of acceptability/perceptibility at 3.6

Group	N (%) Matching Vita Easyshade	p
Faculty / Vita Classical (N = 250)	107 (42.8%)	0.135
Faculty / Vita 3D Master (N = 250)	100 (40.0%)	
Students / Vita Classical (N = 250)	114 (45.6%)	
Students / Vita 3D Master (N = 250)	96 (38.4%)	
Trios / Vita Classical (N = 25)	14 (56.0%)	
Trios / Vita 3D Master (N = 25)	16 (64.0%)	

Appendix B. Figures

Figure 1: The Munsell Color System - A three-dimensional representation of color dimensions including Hue, Value, and Chroma.

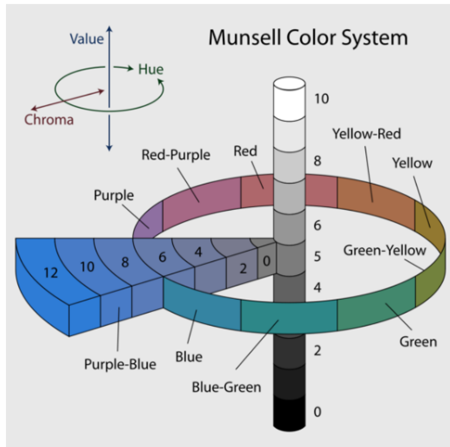

Figure 2: The CIELAB Color Space - A graphical representation illustrating the three axes of color dimensions: lightness (L*), red-green axis (a*), and blue-yellow axis (b*), where L* = 100 represents white and L* = 0 represents black.

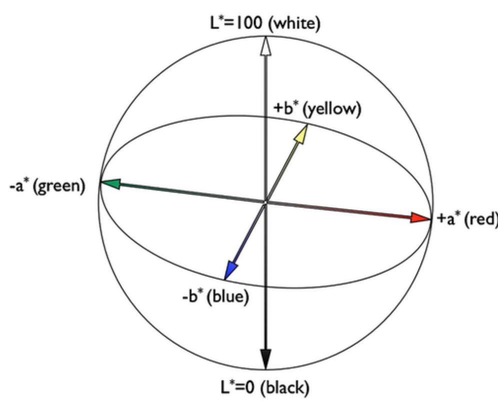

Figure 3 Overview of the study

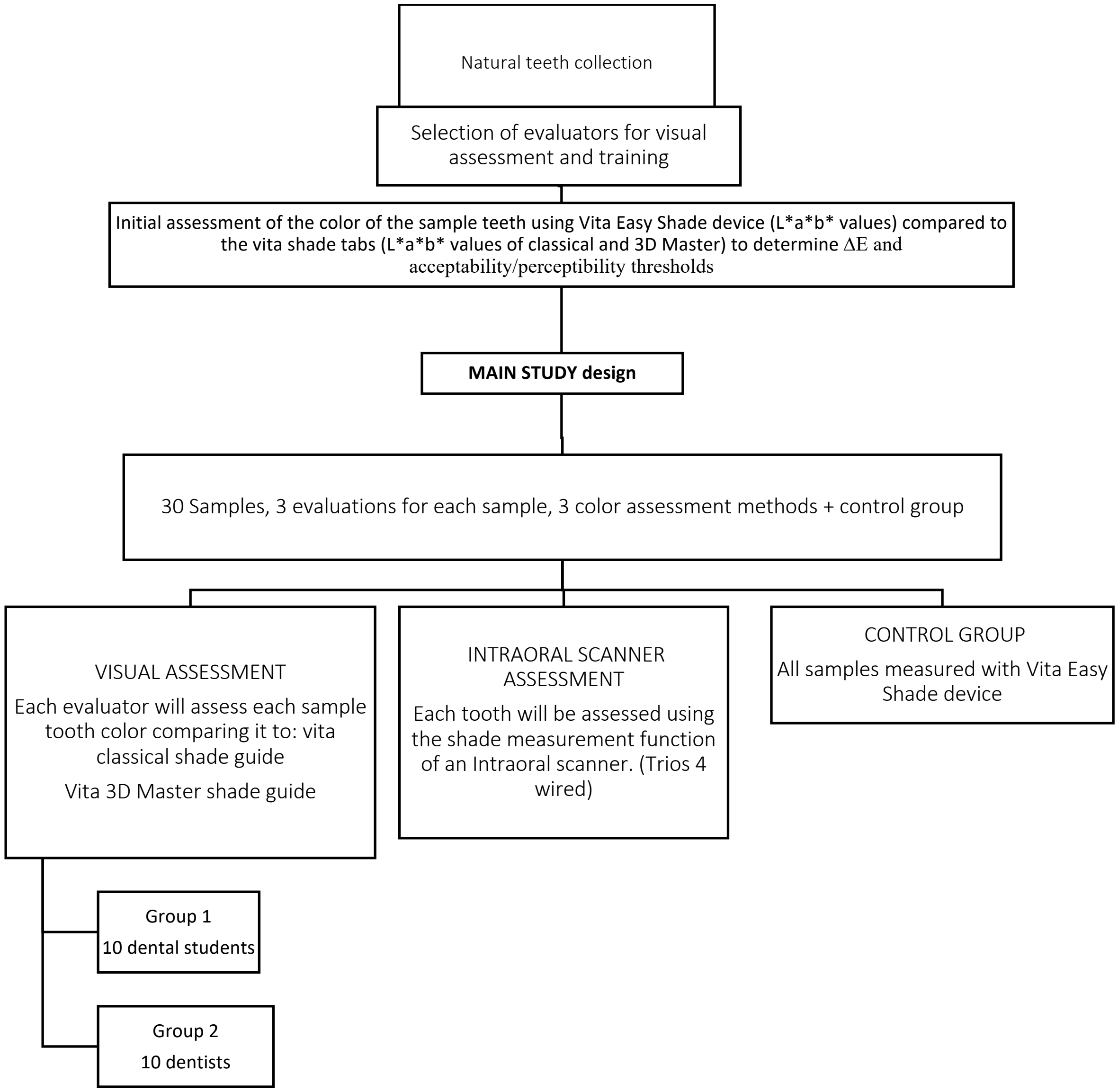

Figure 4: Simulation of Natural Dentition Using a Dentoform

Figure 5: Shade Tabs from VITA Classical and VITA 3D-Master Systems

Figure 6 : The distribution of shade matching percentages between faculty and students using the Vita Classical and Vita 3D Master Shade guides compared with the Easyshade Spectrophotometer - Threshold of acceptability/perceptibility at 1.8

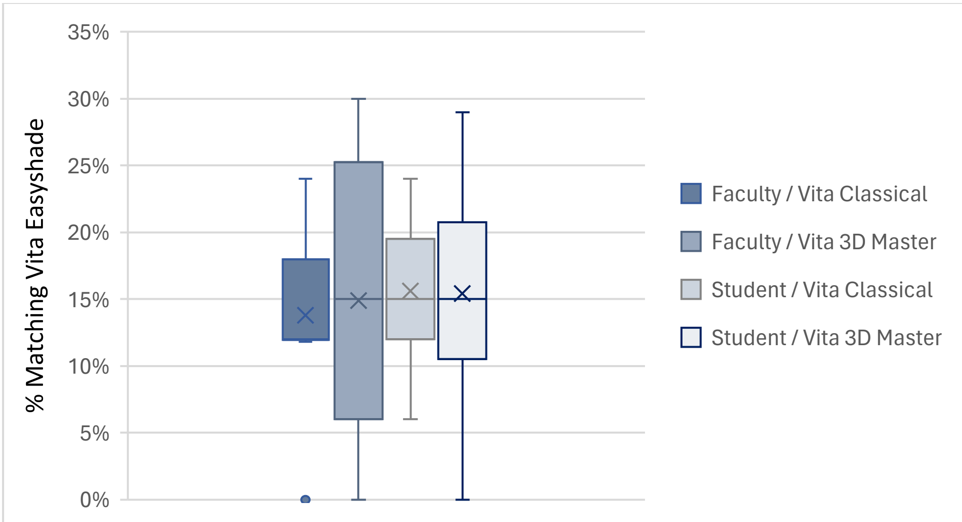

Figure 7: The distribution of shade matching percentages between faculty and students using the Vita Classical and Vita 3D Master Shade guides compared with the Easyshade Spectrophotometer- Threshold of acceptability/perceptibility at 3.6