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Advancing Visual-Instrumental Agreement in Dental Colorimetry: Development and Validation of Novel Assessment Methodologies

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"Blessed is the one who finds wisdom, and the one who gets understanding, for the gain from her is better than gain from silver and her profit better than gold. She is more precious than jewels, and nothing you desire can compare with her"

Proverbs 3:13-15

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Dedication

This dissertation is dedicated to the memory of Jaap ten Bosch, Emeritus Professor of Dental Physics at Groening University in the Netherlands. As my first mentor, he ignited my passion for understanding the physics of light and colour, and his encouragement to pursue academic advancement has shaped my career path. His legacy continues through the work of those he inspired.

Abstract

Background: Colour matching in dentistry remains a significant challenge despite technological advances in measurement devices and materials. Traditional approaches to evaluating colour differences in dentistry have relied on various mathematical formulae and measurement devices, yet the correlation between instrumental measurements and visual perception has been inadequately addressed. Furthermore, the fundamental question of natural tooth colour variability and the capability of current shade guides to represent this variation has remained largely unexplored across significant populations.

Aim: This research aimed to develop and validate new methodologies for evaluating visual-instrumental agreement in dental colorimetry while assessing the performance of contemporary measurement technologies and exploring the limitations of current shade matching systems. Additionally, the study sought to quantify the actual number of natural tooth colours and evaluate the impact of illuminant metamerism on modern dental materials.

Methods: The research employed multiple complementary approaches across six interconnected studies. A large-scale multicentre study involving 154 expert observers from 16 sites across 5 countries evaluated visual-instrumental agreement of six colour measurement devices. Cardinality analysis was performed on 8,153 in-vivo CIELAB measurements of natural teeth to determine the number of unique tooth colours. The performance of various colour difference equations (ΔE^*_{ab}, ΔE_{00}, ΔE_{94}, and CAM16-UCS) was assessed using the standardised residual sum of squares (*STRESS*) index. A novel Visual Instrument Agreement Scale (*VIAS*) was developed and validated through comparative analysis of four intraoral scanners and traditional spectrophotometry. Illuminant metamerism was evaluated using spectral reflectance measurements from natural teeth and zirconia restorations under ten different illuminants.

Results: The research revealed 1,173 unique natural tooth colours, with current shade guides showing significant coverage errors (CE 4.1 ΔE^*_{ab} for Vita Classical, 3.3 ΔE^*_{ab} for 3D-Master). The optimised ΔE^*_{ab} formula demonstrated superior visual-instrumental agreement (mean VIAS 76%) compared to more complex colour difference metrics. Intraoral scanners showed unexpectedly high performance in shade matching, with the Carestream CS3700 achieving 82% visual-instrumental agreement, significantly outperforming traditional spectrophotometry (57%). Illuminant metamerism effects between natural teeth and zirconia restorations were found to be clinically insignificant (Milm = 0.3 (±0.2) for layered, Milm = 0.5 (±0.4) for monolithic restorations).

Conclusions: This investigation has established new methodological frameworks for evaluating colour matching in dentistry while challenging traditional assumptions about measurement devices and colour difference metrics. The development of *VIAS* provides a scientifically grounded approach for assessing visual-instrumental agreement, while the quantification of natural tooth colours highlights the limitations of current shade matching systems. These findings have significant implications for clinical practice and future technological developments in dental colorimetry, suggesting the need for digital solutions to address the limitations of physical shade guides and supporting the adoption of intraoral scanners for shade selection.

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Chapter 1 Introduction

1.0 Background and motivation

In restorative dentistry, the aesthetic outcome is of considerable importance to patients, as it forms the basis of their initial and lasting impression of the quality achieved. The accuracy of the shade match between the restoration and natural dentition plays a central role in this perception, directly influencing the clinician's reputation. Poor shade matching is a common concern, and even technically excellent restorations can be critically judged due to noticeable colour discrepancies, which patients often associate with a lower standard of care (Hall, 1991).

Consistent shade matching remains a fundamental challenge in restorative dentistry (Joiner and Luo, 2017). Complications arising from colour mismatches between natural dentition and dental restorations are frequently reported in clinical practice (Corcodel et al., 2011; McCracken et al., 2019; Lawson et al., 2021; Alnusayri et al., 2022; Morsy and Holiel, 2023). While these mismatches do not compromise the functional performance of restorations, provided essential clinical criteria such as marginal fit, occlusion, and contact points are met, they can become highly problematic in the Aesthetic Zone (Matthews et al., 1978; Bergen, 1985). Located in the anterior part of the mouth, this region is particularly sensitive to any disharmony in appearance, making the perceived quality of the shade match a critical factor.

In specialised dental laboratories, single central incisor shade matching cases are common (Stankiewicz & Wilson, 2000), and experience has shown that the economic impact of colour-related complications often exceeds that of complete losses from structural failures, which can range between 0.2% for metal-ceramic and 1.45% annually for zirconia restorations (Sailer et al., 2018). This is particularly relevant, as central incisors have been shown to have the greatest influence on perceived dental attractiveness compared to other teeth (Ruan et al., 2025). Consequently, even minor shade mismatches in these teeth can be highly conspicuous, leading to costly remakes and adjustments. This observation is further substantiated by quantitative research, with one estimate of the financial burden of colour mismatch-related complications at approximately $16,000 annually per laboratory (Corcodel et al., 2011).

The essential skills and experience required for accurate colour matching are neither taught in dental school nor typically acquired through clinical practice. Limited training and a lack of understanding of the procedures involved, remain prevalent (Preston & Bergen, 1980). Instead, dental restorations such as crowns, bridges, and veneers are typically fabricated by dental technicians through a labour-intensive and artisanal process. Layers of glass ceramic with varying thicknesses, translucencies, and chromaticities are meticulously applied using a Kolinsky brush and a wet ceramic slurry, then fired at high temperatures (750–950ºC) to achieve vitrification (Yamamoto, 1985; McLean, 1991; Naylor & King, 1992; Hein & Geller, 2011). The final colour of the restoration becomes apparent only after firing (Riley et al., 1985; Hein et al., 2014), requiring technicians to rely on their expertise to select the appropriate materials in advance.

This process presents unique challenges, as dental technicians must navigate extensive ceramic kits containing hundreds of shades. It is akin to the work of a colourist in the print industry, who must select the right primaries to mix and match a target colour using skill, experience, and visual assessment (Wyszecki & Stiles, 1982). Success in both fields demand refined colour perception skills and the ability to discern subtle variations in appearance. Nevertheless, achieving a perfect shade match clinically remains fraught with uncertainty.

Aesthetic failure is among the top three reasons for restoration rejection, with rejection rates varying significantly among practitioners, ranging from 0% to 42% (McCracken et al., 2019). Notably, 15% of these rejections were attributed to colour mismatch. The economic burden of these rejections is primarily borne by dental technicians who work behind the scenes in dentistry and are largely unnoticed by the public (Ismail & Al-Moghrabi, 2023). Corrective measures can range from minor shade adjustments to complete re-fabrication of restorations. McCracken et al. also observed substantial heterogeneity, where a majority of remakes originated from a smaller subset of practitioners, while others reported none. This suggests a subjective bias, further complicating the process of achieving consistent aesthetic outcomes. These rejections not only strain dental laboratories but also impact dental practices, requiring additional chair time, increasing costs, and causing frustration for both dentists and patients (Corcodel et al., 2011).

Since its inception in the late 1950s, instrumental colour measurement in dentistry initially remained primarily confined to research, limited by instrument designs that were simply too impractical for clinical use. Initial efforts to translate these advancements into practical applications emerged in the 1980s ultimately failed, however. The late 1990s saw renewed commercialisation efforts, leading to a surge of product launches in the early 2000s. However, these products, hindered by practical limitations and a lack of user acceptance, failed to resolve the shade matching challenge and quickly faded into obscurity without achieving widespread clinical adoption. Instrumental colour measurement then reverted to being predominantly a research tool, while clinical shade matching continued to be addressed through conventional methods like visual shade assessment. This period can be characterised as a *Colour Measurement Winter*, reflecting a phase where technological solutions were sidelined due to practical limitations and insufficient clinical integration. Nevertheless, published research utilising dental colorimetry surged but primarily due to growing interest across academia. The focus of such research was largely theoretical and did not fulfil the original goal of aiding shade matching in dentistry.

A turning point came in 2016 when dental technicians drove instrumental colour measurement innovation yet again. The earlier measurement systems focused on dentists' shade selection needs, overlooking the technicians who actually fabricate dental restorations. The key catalyst for this renewed interest was the advent and widespread adoption of digital dental photography, which provided an accessible and practical means of implementing dental colorimetry using relatively basic equipment (Bengel & Chu, 2004). Interest in colour measurement experienced a resurgence, offering practical benefits to assist dental technicians more effectively ending a period of dormancy (Hein & Zangl, 2016; Hein et al., 2017; Hein et al., 2021; Awdaljan et al., 2024).

Despite recent innovations, successful shade matching remains, primarily, a practical skill of the dental technician; one that cannot be fully replaced by present technology (Raigrodski, 2008). Even with advancements in technology and improved methodologies, achieving a perfect shade match remains challenging, with mismatches still occurring, albeit less frequently than in the pre-instrumental era (Ratzmann et al., 2020). As will be shown, the reasons for these complications are multifaceted, encompassing differences in visual perception, limitations of instrumental shade measurement and colour difference computation as well as inadequate dental shade guide coverage. In addition, differences in optical properties between dental hard tissues and materials, as well as constraints on available space to create lifelike restorations with the illusion of depth, further complicate the process of achieving an accurate shade match.

2.0 Aims and Objectives

This thesis acknowledges the complexity of shade matching challenges in dentistry and does not claim to provide comprehensive solutions. Instead, it seeks to elucidate critical factors influencing the shade matching process, focusing on the interplay between human visual perception and instrumental measurement techniques. By addressing fundamental misconceptions in the dental literature regarding colorimetric accuracy and precision, this work introduces methodologies firmly rooted in the principles of colour science. These methodologies aim to bridge the gap between theoretical colour science and clinical practice, providing dental researchers with scientific tools for evaluating the performance of shade measurement devices and advancing restorative dentistry.

3.0 The history of dental colorimetry

The field of dental colorimetry has experienced an exponential increase in published research over the last few decades (Chu et al., 2010). Hundreds of studies have either utilised, or are related to, dental colorimetry. This section does not attempt to provide an exhaustive review of the entire literature but rather focuses on the most significant advancements that have shaped the field.

3.1 The invention of spectrophotometry

In the 1920s, Arthur Cobb Hardy (1895–1977), a physicist at MIT, developed the first recording spectrophotometer (Hardy, 1938). The first commercial version, produced by General Electric, became operational in early 1933. Though costly and complex, with only around 100 units produced, this instrument revolutionised industrial colour measurement. Prior to its invention, spectral transmission and reflection measurements relied on visual instruments, making observations laborious and often impractical due to low light conditions. Hardy's spectrophotometer enabled the rapid recording of spectral reflection curves across the visible spectrum within minutes, allowing industries to objectively assess key properties such as the spectral absorption of dyes and pigments. A major breakthrough in its design was the use of an optical attenuator, a system of polarising prisms, to balance reflected light from the sample against a reference white. This minimised reliance on the less reliable photoelectric cells of the time, which were instead used as null detectors (Wright, 1978).

Beyond his instrumental contributions, Hardy played a pivotal role in advancing colour measurement with the publication of the Handbook of Colorimetry in 1936. This was the first major text on colorimetry following the establishment of the 1931 CIE colour specification system, providing essential charts and tables that facilitated the widespread adoption of the CIE system for colour standardisation and industrial applications (Hardy, 1936).

3.2 The 1931 CIE Standard Observer

The quantification of human colour perception was crucial for standardising colour measurement across various industries, prompting extensive research efforts. The 1931 CIE standard observer was developed based on pioneering experimental studies carried out independently by two British researchers. At the National Physical Laboratory in Teddington, John Guild employed a trichromatic colorimeter with a tungsten lamp and coloured filters, while W. David Wright, at Imperial College London, used monochromatic light bands separated by a prismatic system (Wright, 1969). Despite differences in their methodologies, the results from both studies demonstrated an agreeable level of consistency. The Commission Internationale de l'Eclairage (CIE) combined the Wright and Guild data to establish the 2° colour-matching functions, marking a significant advancement by providing the first globally recognised scientific framework for colorimetry. The '2°' specification refers to the visual angle used in the experiments, selected to confine light stimulation to the fovea, the central retinal region densely populated with cone photoreceptors (CIE, 2004). These colour matching functions became a cornerstone of modern colorimetry, facilitating objective colour specification and measurement practices that continue to be used today. Their relevance extends to dentistry, where Technical Report ISO/TR 28642 (ISO, 2016) explicitly recommends the use of the 2° 1931 standard observer, as defined in ISO 11664-1, for the measurement of teeth and dental restorations.

3.3 Paul Kubelka and Franz Munk

In 1931, two German physicists, Paul Kubelka and Franz Munk, published their seminal work on the optics of paint layers (Kubelka & Munk, 1931), introducing what would later become known as the Kubelka-Munk theory (Kubelka, 1954). Their research aimed to provide a theoretical framework for understanding how light interacts with scattering and absorbing layers, such as paints and coatings. The fundamental equations derived in their work describe the distribution of light within a material and allow for the quantification of its optical behaviour. The Kubelka-Munk model is particularly useful in describing the relationship between the absorption and scattering properties of a material and its overall reflectance. Although originally intended for use in the paint and coatings industry, the model was later applied to a variety of fields, including the analysis of dental materials (Judd, et al., 1937; Spitzer and Bosch, 1975; Cook & McAree, 1985; Molenaar et al., 1999). The theory's relevance to dental colorimetry lies in its ability to mathematically describe the optical properties of dental hard tissues (Li, R. et al., 2012; Pop-Ciutrila et al., 2015) and restorative materials (Miyagawa & Powers, 1983; Pop-Ciutrila et al., 2021; Duveiller et al., 2023), making it an important tool for dental researchers (Ragain & Johnston, 2001).

3.4 The invention of tristimulus colorimetry

While spectrophotometry provided a scientific method for colour measurement, its high cost and technical complexity limited its practicality for industry. Businesses needed efficient tools for two main purposes: estimating colour differences for quality control and predicting mixing recipes, both of which were slow and tedious when relying on spectral data. Using the electro-mechanical calculating devices of the 1940s, Park and Stearns (Park & Stearns, 1944) solved the problem of colour match prediction, but the process took about 40 hours, making it impractical. While colour-difference calculations from CIE XYZ colour space were faster, requiring about 15 minutes, this was still too slow for routine quality control. The issue stemmed from CIE XYZ not being a uniform colour space, meaning perceptual differences were not equidistant (Judd, 1933; MacAdam, 1942).

Richard S. Hunter (1909–1991) developed the first tristimulus colorimeter in 1948, addressing critical industrial limitations in colour measurement and quality control (Hunter, 1958). Recognising the practical challenges arising from the lack of perceptual uniformity in the CIE CIE XYZ colour space, which made predicting perceived colour differences difficult, Hunter developed his own Hunter colour space. It was designed to enhance perceptual uniformity and offer a more practical framework for industrial colour measurement. His innovation incorporated an analogue device within the tristimulus colorimeter to facilitate direct conversion of measurements into this more perceptually uniform space, reducing the computational burden associated with CIE XYZ transformations (McLaren & Perry, 1979). While not a true uniform colour space, this development marked the beginning of a decades-long effort to refine colour difference models and create a perceptually uniform colour space, driven by their industrial significance (Judd & Wyszecki, 1963).

3.5 Early developments in dental colorimetry

From the outset of aesthetic dentistry during the 1930s, the importance of creating restorations that satisfy visual inspection from a reasonable distance was recognised. Equally recognised, however, was the frequent discouragement experienced when clinical results failed to meet these expectations, despite meticulous attention to detail and the application of painstaking, time-consuming procedures (Vehe, 1934). Historically, shade guides served as the primary tool for the purpose of visual shade selection, yet their designs were largely empirical rather than based on a systematic colour order (**Figure 1**).

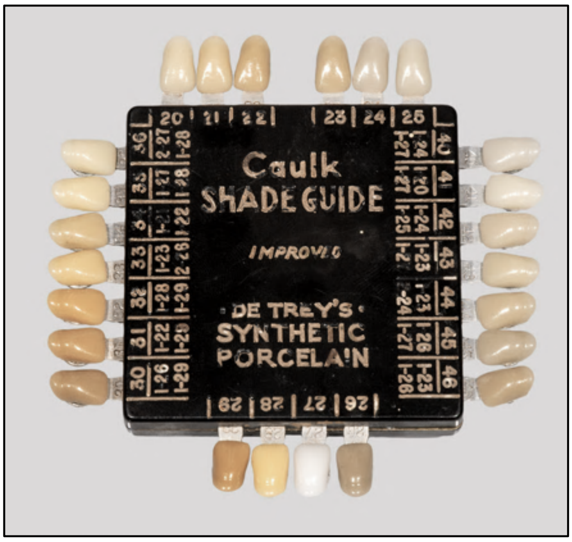

Figure 1. De Trey's Caulk Shade Guide for Synthetic Porcelain (1925) exemplifies the typical shade guides of its era. While the arrangement of the shade tabs followed a discernible ordering system, their selection was largely empirical (Source: Sascha Hein).

Edwin Bruce Clark (Clark, 1933) visually assessed over 6,000 natural teeth to establish their hue, chroma, and value range using Munsell Notation, producing a shade guide with 60 samples. Despite its innovation, his Tooth Color Indicator garnered little enthusiasm at the time

(Sproull, 2009b), as the Second World War understandably shifted priorities away from advancements in aesthetic dentistry.

Judd et al. (Judd et al., 1937) were the first to apply Kubelka-Munk theory (Kubelka & Munk, 1931) to analyse the optical properties of dental silicate cements, used as a filling material for cavities. Their work focused on understanding the relationship between reflectance, thickness, scattering, and absorption properties of these materials. This early application of the Kubelka-Munk theory to dental materials marked a significant milestone in dental research, setting the foundation for later studies in the optical behaviours of restorative materials.

3.6 Dental colorimetry in the 1950s

The topic of shade matching regained attention in the 1950s, but the same fundamental obstacles persisted (Gill, 1950). A notable breakthrough came in 1956 with the introduction of the Vita Lumin Vacuum shade guide—the first dental shade guide based on a systematic arrangement. While it relied on clinical experience rather than strict scientific criteria, it was quickly adopted by clinicians (Vichi et al., 2011). Its modern counterpart, the Vita Classical shade guide was introduced in 1982 and remains the most widely used shade guide today (Paravina et al., 2009). A pivotal scientific milestone for dental colorimetry emerged from Japan in 1958 with "On the Colour of Teeth (Particularly, A Colorimetric Study of Dentin)" by Haga, Ukiya, and Hashimoto (Haga et al., 1958). This groundbreaking collaboration, conducted under the guidance of Professor Katsue Kitamura (Department of Prosthetic Dentistry) and Professor Masakuni Kanai (Department of Physics) at Tokyo Dental College, represents the first documented use of spectrophotometry on human teeth (**Figure 2**).

Figure 2. Colour swatches (sRGB) representing first spectrophotometrically measured tooth colours by Haga et al. in 1958. Extracted tooth samples were selected to capture natural variations in tooth colour (Source: Sascha Hein).

By combining dental expertise with sophisticated physics instrumentation, they produced the first ever recorded spectrophotometric measurements of tooth colour. Their methodology was remarkably advanced, employing spectrophotometry with 45º/0° illumination geometry and CIE colorimetric analysis, techniques that remain standard practice today. Most significantly, they went beyond mere colour measurement to investigate the optical mechanisms underlying tooth appearance. Through their interdisciplinary approach, they described how the enamel surface reflection creates a white, opaque appearance while deeper reflections are influenced by dentin, a phenomenon that would be rediscovered and termed the Double Layer Effect decades later (O'Brien, 1985). Their work demonstrated that tooth colour is not a simple surface property but rather the result of complex interactions between enamel and dentin layers. This understanding was decades ahead of its time and sadly overlooked, most likely due to language barriers as the work was originally published in Japanese.

Stübel (1911) discovered that teeth naturally fluoresce under ultraviolet radiation using a Woods Glas filter and an arc lamp, utilising the Hallwachs effect. The selective absorption and fluorescence of visible light was later termed the Lumin Effect (Wikipedia, 2025). In 1956, artificial teeth were shaded to mimic this behaviour under artificial light, which led to the introduction of the Vita Lumin Vacuum denture teeth. A corresponding shade guide was subsequently developed in the form of the Lumin Vacuum shade guide **(Figure 3)**.

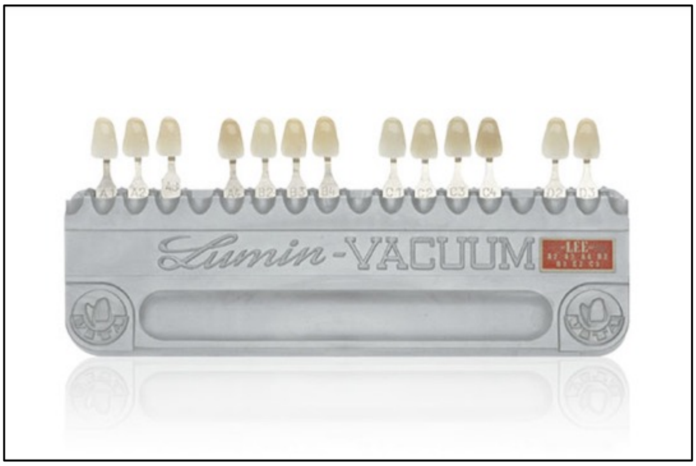

Figure 3. Introduced in 1956, the Vita Lumin Vacuum Shade Guide went on to become the most widely used shade guide over the ensuing decades (Source: Vita Zahnfabrik).

3.7 Early instrumentation of the 1960s

The 1960s saw significant advancements in colour science (Wyszecki & Stiles, 1967; Wright, 1969), particularly in spectrophotometry (McCamy, 1966; Billmeyer, 1969) with the introduction of the Beckmann Model DB dual beam spectrophotometer (**Figure 4**).

Figure 4. Beckman Model DB dual-beam spectrophotometer, introduced in the 1960s, represented a significant advancement in spectrophotometry. Successor models like ACTA CII and CIII, were widely used in dental research and remained in use well into the 1990s (Source: Science History Institute).

In 1966 Atkins and Billmeyer (Atkins & Billmeyer, 1966) observed a peculiar phenomenon that led to measurement errors in translucent materials – they termed it Edge Loss. It is observed in translucent materials, where subsurface bulk scattering causes incident light to reemerge beyond the intended detection area, resulting in flux loss. As light enters the material, it undergoes multiple scattering events before escaping, with some of the scattered light emerging outside the boundaries of the aperture or sample holder. This effect leads to measurement errors in spectrophotometry, as the lost light is not accounted for in the detector's response and is especially problematic in samples like dental hard tissues and tooth-coloured materials. Recognising the widespread implications of this issue, the US National Bureau of Standards later dedicated an entire technical report to the phenomenon, renaming it the Translucent Blurring Effect. This report detailed both the theoretical underpinnings and experimental approaches to quantify and mitigate flux loss, emphasizing its importance in precision spectrophotometry (Hsia, 1976). Unfortunately, edge loss has remained a persistent challenge in dental colorimetry throughout its history (Borsboom & Ten Bosch, 1982; Cook and McAree, 1985; van der Burgt et al., 1985; van der Burgt et al., 1990; Bolt et al., 1994; ten Bosch & Coops, 1995; Gevaux et al., 2020). The 1960s also saw further efforts to improve visual shade assessment, leading to the development of a shade guide comprising 125 samples, created from printed Munsell paper tabs based on spectrophotometric measurements of extracted teeth (Hayashi, 1967). However, a limitation of this shade guide was that it reflected the colour space of a Japanese population. Nevertheless, Toshio Hayashi had demonstrated the potential of spectrophotometry, inspiring others to follow his path. In October 1968, renowned colour scientist Henry Hemmendinger invited Robert Sproull to his laboratory in Easton, Pennsylvania, where he demonstrated a spectrophotometric measurement of an extracted human tooth, initiating a collaboration in which Hemmendinger went on to analyse hundreds of natural teeth and shade guides for Sproull, as well as many other researchers and manufacturers (Sproull, 2009). Meanwhile a prototype contact colorimeter with an optical fibre for easier clinical access underwent initial trials in Japan using extracted teeth in Japan (Ishikawa et al., 1969).

3.8 First advances in dental colorimetry during the 1970s

The decade that followed was marked by the beginning of colour measurement in dentistry with numerous investigations (Ishikawa et al., 1969; Sproull, 1973b; Tsuchiya, 1973; Grajower et al., 1976; Dennison et al., 1978). At first, such measurements were restricted to using extracted human teeth or tooth-coloured samples, due to the size and design of the spectrophotometers available at the time. Sproull published a series of articles (Sproull, 1973a; Sproull, 1973b; Sproull, 1974) highlighting the three-dimensional nature of colour and its relationship to natural tooth colour. These studies offered both theoretical insights and practical recommendations for improving shade matching procedures. One of the critical issues identified was the inadequacy of contemporary shade guides in capturing the complexity of natural tooth appearance.

During the 1970s, efforts to understand the optical properties of dental hard tissues which contribute significantly to tooth appearance (O'Brien, 1985) gained momentum. A pivotal study by Spitzer and ten Bosch (Spitzer & Bosch, 1975) marked the first application of the Kubelka-Munk theory to dental hard tissues, specifically enamel. Their research utilised an integrating sphere to measure the reflectance and transmittance of thin enamel slabs across a wide wavelength range, enabling the calculation of absorption and scattering coefficients. This groundbreaking approach provided an essential framework for future research into the optical behaviour of teeth, influencing subsequent developments in dental colorimetry and restorative materials.

In his contributions, Sproull also discussed the effect of illuminant metamerism between natural teeth and artificial restorations, dramatically referring to it as a Monster capable of destroying an otherwise perfect shade match when viewed under lighting conditions different from those under which the original visual shade selection occurred – a claim that will be challenged later in the thesis. Nevertheless, this idea was perpetuated over subsequent decades (McLean, 1979; Yamamoto, 1985; Barghi et al., 1985) and became widely accepted within the field of aesthetic dentistry (Fondriest, 2003). It eventually found its way into contemporary textbooks (Sakaguchi & Powers, 2012; Chu et al., 2017) and it is taught in pre- and post-graduate programs (Oliveira, 2022) despite lacking scientific validation (Hang et al., 1993; Lee & Powers, 2005) and although doubts were soon expressed regarding the role of illuminant metamerism in dentistry (O'Brien, 1985).

By the mid-1970s, the need for a perceptually uniform colour spaces for applications in business and industry had become evident. Judd and Wyszecki (1975) highlighted its commercial and scientific importance, noting that it would simplify colour specification, improve tolerance setting, and aid in the creation of reference standards. However, previous attempts had failed due to their reliance on non-uniform colour spaces, which did not align with human perception. In response, the CIE introduced the ΔE_{ab} formula in 1976, based on the CIELAB colour space, marking a significant advancement in the quantification of colour differences (CIE, 1977).

3.9 The birth of modern dental colorimetry: the 1980s

The 1980s were an exciting era that saw significant progress in dental colorimetry with many innovations that would shape its future. The first successful attempt to measure tooth colour in vivo was conducted by MacEntee and Lakowski (Macentee & Lakowski, 1981), who employed a spectroradiometer due to the previously encountered technical challenges of adapting a spectrophotometer for intraoral use. A spectroradiometer, originally designed to measure the radiance of light sources, is equipped with a camera lens that allows measurements to be taken from a distance without the need for direct contact with the tooth surface. This approach was important in overcoming two major challenges associated with tooth colour measurement: the curved, irregular surface of teeth, and edge loss which was later found to exhibit wavelength dependence, thus contributing to inaccuracies in chromaticity and saturation (Bolt et al., 1994). The spectroradiometer effectively mitigated these issues, providing more reliable and consistent colour measurement. This advantage is a key reason why spectroradiometers are still regarded by many researchers as the Gold Standard for colour measurement in dental research (Lim et al., 2010; Akl et al., 2022; Pop-Ciutrila et al., 2021). MacEntee and Lakowski also included the measurements of extracted human teeth, revealing discrepancies in colorimetric data between their measurements and those reported by other investigators. They attributed these differences to factors such as variations in instrumentation, surface measurement limitations, and the technical challenges posed by the irregular surfaces of teeth. The variability in measured tooth colours between identically labelled devices (e.g., spectrophotometers) will be explored in greater detail later in this thesis. In Japan, Takahiro Ishizaki (1989) also employed a spectroradiometer for in vivo tooth colour measurement. Notably, Ishizaki observed distinct dips in the spectral reflectance factors of the region closest to the gums and deduced that these dips corresponded to absorption bands typical of oxygenated haemoglobin (Schmitt, 1986) from the surrounding soft tissue. While groundbreaking, the use of a spectroradiometer was highly technical and impractical for routine clinical application, prompting researchers to explore alternative methods. One such approach was the development of a dedicated contact, fibreoptic tristimulus colorimeter (Bangtson & Goodkind, 1982; Goodkind et al., 1985; O'Brien, 1985; Goodkind & Schwabacher, 1987). The Chromascan system revived earlier efforts by Ishikawa (Ishikawa et al., 1969). It functioned as a tristimulus colorimeter, utilizing a tungsten-halogen lamp and a fibre-optic probe to illuminate the tooth surface (**Figure 5**).

Figure 5. Chromascan was the first commercially available contact tristimulus colorimeter for use in dentistry. It provided digital readouts of RGB values (Source: www.ebay.com).

A rotating colour filter wheel sequentially separated the reflected light into red, green, and blue components, which were detected by a photosensitive diode and processed via a dual-slope integrator digital voltmeter (Roll, 1974). Chromascan provided digital readouts in the form of RGB values, which researchers sought to convert into CIE XYZ colour space through a rigorous assessment of its colorimetric accuracy (Bangtson & Goodkind, 1982). This was conducted using a set of 12 colour standards, measured by Hemmendinger with a General

Electric Recording Spectrophotometer for reference. Additionally, the study included tooth-coloured metal-ceramic discs to evaluate the system's performance on dental materials. The results revealed significant variability in Chromascan's measurements, with inaccuracies influenced by factors such as porcelain thickness, surface texture, and firing cycles, ultimately limiting its reliability for precise shade matching. Although short-lived, the Chromascan system highlighted the challenges of reliable colour measurement and marked a fundamental step in the evolution of contact-based clinical colour measurement systems, as will be shown later.

During the 1970s and 1980s, dental researchers assessed the coverage of shade guides over the natural tooth colour gamut using the Munsell colour system. This involved mapping measured tooth colours onto Munsell hue-chroma and value-chroma diagrams to estimate the proportion of the natural gamut covered by existing shade guides. Coverage was determined separately for each attribute, hue, chroma, and value, and these estimates were multiplied to approximate the three-dimensional coverage of the shade guide within the full colour space (Preston & Bergen, 1980). While this method provided a structured way to assess shade guide coverage, it had several inherent limitations. The key issue was that the calculation assumed the colour space was a simple rectangular prism, where hue, chroma, and value dimensions were independent and evenly distributed. In reality, the natural tooth colour gamut is irregularly shaped, meaning that multiplying independent coverage percentages led to an overestimation of the actual space occupied (Miller, 1987; Hall, 1992). Additionally, this approach did not account for lack of perceptual uniformity, as colour differences within the Munsell system were estimated visually rather than computed using a dedicated colour difference metric. Attempts were made to introduce a CIELAB-inspired colour difference equation for Munsell Notation (O'Brien et al., 1990) which was too complicated and never saw widespread adoption. As a result, the accuracy of coverage estimations remained approximate, and the practical limitations of shade guides in achieving comprehensive colour representation were likely underestimated (Lemire & Burk, 1975). Nevertheless, the Munsell colour order system was widely regarded as the gold standard by dental researchers during this period (Sproull, 1973c; Lemire & Burk, 1975), valued for its logical organisation based on the principles of hue, chroma, and value (Jorgenson & Goodkind, 1979).

The absence of a practically useful colour difference metric lead to a significant milestone in 1987 with the adoption of the CIELAB system (McLaren, 1976; CIE, 1977) following a proposal by Wozniak (Wozniak, 1987) which was subsequently ratified by the American Dental

Association (O'Brien et al., 1989). Shortly before this, Seghi et al (1986) had utilised the CIELAB colour space to analyse colour differences between porcelain systems, marking the first application of the ΔE_{ab} formula in dental colorimetry. The transition from Munsell Notation to the CIELAB system was swift (Rosenstiel & Johnston, 1988; White & O'Brien, 1989; O'Brien et al., 1991b) although parallel data reporting continued until the early 1990s (O'Brien et al., 1989; O'Brien et al., 1990; O'Brien et al., 1991a). The advantages of the CIELAB system over Munsell Notation became evident when O'Brien et al. (1991a) applied the ΔE_{ab} colour difference formula to assess the coverage error of two shade guides against a population of extracted teeth. Although the study aimed to bridge CIELAB and Munsell Notation, the latter soon became obsolete as CIELAB was widely adopted as the new standard in dental colorimetry (Goldstein & Schmitt, 1993).

The 1980s also marked a transformative period in dental research, with the Department of Dental Materials at the University of Michigan School of Dentistry playing a pivotal role. Established with funding from the National Institute of Dental Research, the department accepted PhD students through its affiliation with the Department of Materials Engineering. The interdisciplinary Dental Materials and Mechanical Engineering PhD program attracted applicants with backgrounds from a wide range of fields such as metallurgy, chemistry and chemical engineering. The department's faculty brought together a diverse range of expertise: Kamal Asgar, with a PhD in chemical engineering focusing on metallurgy; William O'Brien, a metallurgist; John M. Powers, with a background in chemistry; and Bob Craig, a chemical engineer who served as the department chair. Their combined expertise fostered an interdisciplinary collaboration between graduate students and dental students, enabling groundbreaking research that spanned multiple disciplines. This led to early exploration of the Kubelka-Munk Theory for potential applications in dentistry. Brodbelt et al. (Brodbelt et al., 1981) investigated the translucency of human dental enamel by measuring its total transmittance at wavelengths from 400 to 700 nm, evaluating the effects of dehydration and rehydration on its optical properties to provide insights relevant to shade matching, a topic that is still of interest today (Burki et al., 2013; Suliman et al., 2019; Ruiz-López et al., 2021). Attempts were made to influence the colour of dental porcelains with mixing recipes to simplify the shade matching process (Johnston & O'Brien, 1982). Kubelka-Munk theory was also used to estimate the masking power of dental porcelains (Woolsey et al., 1984) and to predict the colour of restorative materials of varying thicknesses over different backgrounds (Miyagawa & Powers, 1983). O'Brien et al (O'Brien, 1985) analysed various optical phenomena affecting the appearance of dental porcelain restorations. This included chromatic adaptation, changes in translucency, and the Double Layer Effect which refers to the way the colour of a tooth or dental restoration is influenced by the interaction between the translucent outer enamel (or body porcelain) and the inner dentin (or opaque porcelain). As the thickness of the translucent layer increases, the observed colour shifts towards that of the translucent material. Fraunhofer diffraction patterns were observed originating from human enamel, resulting from the periodic arrangement of hydroxyapatite prisms that act as slits (O'Brien, 1988). A study by Cook and McAree from the Australian Dental Standards Laboratory (Cook and McAree, 1985) aimed to investigate the applicability of the Kubelka-Munk theory to predict the optical properties of dental restorative materials, including composite resins and ceramics, and to compare these with the optical properties of human enamel and dentine by analysing their scattering and absorption coefficients and they noticed edge loss. Detailed analysis of the optical properties of dental hard tissues in the 1980s revealed a fundamental flaw in both the Munsell Notation and the CIELAB system: treating the complexity of tooth colour appearance as equivalent to solid colours commonly used in the print, paint, and textile industries.

The increasing adoption of spectrophotometry and the CIELAB system in dental research led to a growing awareness of the subjective nature of colour perception and the need to correlate measured colour differences with visual thresholds, as had been established earlier in other industries, such as paint and textiles (Kuehni & Marcus, 1979; Wyszecki & Stiles, 1982). This shift saw the introduction of the terms 50/50% perceptibility (PT) and acceptability (AT) thresholds into the dental literature. Johnston & Kao (1989) initially suggested that a colour difference of 1 ΔE^*_{ab} would be ideal for acceptability but concluded that 3.3 ΔE^*_{ab} would serve as a more suitable AT value under realistic clinical conditions. This estimate closely aligned with the findings of Ruyter et al. (1987), who proposed 3.7 ΔE^*_{ab} as an appropriate AT value.

4.0 A new shade guide and advanced analysis of optical properties: The 1990s

The term Coverage Error (CE) was first introduced in dental colorimetry by O’Brien et al. (1991a) to quantify how well a shade guide represents the range of natural tooth colours. Defined as the average minimum colour difference between each measured tooth and its closest shade match, this metric provided a systematic approach to evaluating shade guide performance. The study found that the Bioform and Vita Lumin shade guides had a coverage error of 3.0 ΔE^*_{ab} respectively, while combining both shade guides reduced the coverage error to 2.6 ΔE^*_{ab}, demonstrating that a broader selection of shades improves accuracy. These findings highlighted the limitations of individual shade guides and established CE as a valuable tool for assessing shade guide effectiveness, laying the groundwork for future research. This growing awareness of the need for a more comprehensive approach to shade selection set the stage for a significant transformation in shade guide design in the early 1990s, driven by the contributions of Dr Neil Rex Hall (**Figure 6**), an Australian dental practitioner from Hornsby, New South Wales (Hall, 1991; Hall and Kafalias, 1991).

Figure 6. The inventor of the Vita 3D Master shade guide, Dr Neil Rex Hall of Hornsby, New South Wales, Australia (Source: Australian Prosthodontic Journal).

Hall's meticulous investigation, which went largely unnoticed at the time, identified key limitations of conventional shade guides, emphasizing their lack of scientific organization and incomplete representation of natural tooth colour. He astutely observed persistent challenges in clinical shade matching, many of which remain relevant today. Hall's initial proposal (Hall, 1984) built upon the foundational concepts of Clark (1933), Hayashi (1967), and Sproull (1973), advancing the idea of a colorimetrically structured shade guide. While still referencing the Munsell system, his approach was expressed within the CIELAB colour space, reflecting a shift toward perceptually uniform colour measurement. Hall (1993) filed a patent detailing a structured arrangement of shade tabs aimed at improving the efficiency and accuracy of shade selection. Rather than introducing an entirely new colour space or gamut, Hall's method sought to refine the existing shade guides by offering a more logical and uniform arrangement. A central premise of his work was that shade guides should not only match natural tooth colours but also correspond more closely to the optical properties of dental materials, an issue that remains a point of discussion today. His new shade order system retained the most frequently selected shades from the Vita Classical shade guide, replacing the less commonly used ones with an expanded selection intended to provide better coverage of the natural tooth colour gamut. Hall estimated that approximately 86% of the natural tooth gamut was not covered by the Vita Classical shade guide.

While Hall envisioned a streamlined and perceptually uniform system, the final commercial implementation led to an increase in the number of shade tabs from 16 to 26, diverging from the initial goal of simplification. His conceptual framework for shade arrangement, inspired in large parts by established colour scaling models described by Judd & Wyszecki (1975), involved structuring shades in three lightness levels and arranging them within each level in an equilateral triangular lattice to achieve a more uniform perceptual distribution. This systematic approach reflected an appreciation of visual scaling principles, though its practical application in dentistry required additional clinician training (Capa et al., 2011; Ristic et al., 2016; Alfouzan et al., 2017; Samra et al., 2017; Ristic et al., 2024). Despite these challenges, Hall's methodological approach marked a meaningful step forward in shade guide development, introducing a more structured system rooted in colour science. The culmination of his work materialized in the Vita 3D-Master shade guide (**Figure 7**), commercially launched by Vita Zahnfabrik (Germany) in 1998 (Glick, 1998; Vita-Zahnfabrik, 2025).

Figure 7. The first-generation 3D Master shade guide, developed by Dr Neil Hall, was launched in 1998 (Source: Vita Zahnfabrik).

While its adoption was hindered by its departure from traditional systems and the limited availability of matching restorative materials, the 3D-Master shade guide remains one of the most scientifically structured systems in contemporary dentistry.

Another remarkable contribution came from Ishikawa et al., (1992) who explored the application of a computer colour matching system for reproducing natural tooth colours in dental ceramic restorations based on the Kubelka-Munk theory. In their first study, they applied the system to the opaque layer of metal-ceramic restorations, demonstrating that precise colour reproduction is possible through systematic spectrophotometric measurements and computational modelling (Ishikawa-Nagai et al., 1992). The second study extended this approach to layered ceramic samples, incorporating dentin and enamel layers (Ishikawa-Nagai et al., 1993). A Macbeth CE-3000 integrating-sphere reflectance spectrophotometer was used to measure reflectance data from 400 to 700 nm in 20 nm intervals, allowing them to compute scattering and absorption coefficients to predict mixing recipes using Kubelka-Munk theory again. The generated formulations yielded colour differences around 1.0 ΔE^*_{ab} units between test and target samples. The major drawback of course was the reliance on an integrating-sphere reflectance spectrophotometer, which cannot be used intra-orally. This ultimately prevented the widespread adoption of this approach in the 1990s. Nonetheless, it remains a significant milestone in dental colorimetry.

Meanwhile, the quest to decode the optical properties of human teeth continued in Europe throughout the 1990s. At the University of Groningen in the Netherlands, a team of trained physicist under the leadership of Jaap ten Bosch, began applying more rigorous methodologies than previously (Zijp, 2001). They included advanced Kubelka-Munk models (Molenaar et al., 1999) and eventually the computationally heavy and complex Radiative Transfer Equation (RTE) (Chandrasekhar, 1950) to analyse the optical properties of dental hard tissues. Their work contributed to a growing subfield of optical physics that would later be known as Biophotonics, the study of light interactions with biological tissues, which has since become integral to medical imaging and diagnostic applications (Daghigh Ahmadi et al., 2022). The primary research focus of the Dutch team during this period was the application of optical properties for caries detection, an area that capitalized on advancements in non-invasive diagnostic techniques (Brinkman et al., 1988; van de Rijke et al., 1991; Vaarkamp et al., 1997; Vaarkamp et al., 1995; Verdonschot et al., 1999). The study of optical properties played a significant role in understanding the visual appearance of teeth. The scattering coefficient was found to influence the perceived brightness and opacity of a tooth, while absorption determined its hue and saturation (ten Bosch & Coops, 1995). Fluorescence, on the other hand, was widely believed to provide teeth with a vital appearance under sunlight (Monsénégo et al., 1993). This assumption, based largely on expert opinion, became entrenched in aesthetic dentistry literature and textbooks without rigorous scientific validation (Lee., 2015), similar to the earlier misconceptions surrounding illuminant metamerism. However, the natural fluorescence of teeth did play a significant role in the development of quantified light-induced fluorescence (QLF) technology (Angmar-Månsson & ten Bosch, 2001) for caries detection, which led to several clinical diagnostic products (Gimenez et al., 2013).

Instrumental colour measurement in dentistry entered a new era in 1997 with the introduction of the Shofu Shade Eye-Ex (Yamamoto, 1998). It was a contact, fibreoptic tristimulus colorimeter developed through a collaborative effort between Minolta Co., Ltd and Shofu Inc (Yamamoto & Scholten, 1998) (**Figure 8**).

Figure 8. The Shofu Shade Eye-Ex was a contact tristimulus colorimeter that provided both tooth shade designations as well as printouts with basic recipe formulations for the dental technician. It was sold between 1998 and 2002 when it was superseded by the updated ShadeEye NCC system (Source: Shofu inc).

The Shade Eye-Ex was based on the M-1863d Minolta prototype, originally developed in 1993, which had undergone clinical testing in various Japanese dental schools before further refinement (Yap et al., 1999). The driving force behind this innovation was Japanese Master Dental Technician Makoto Yamamoto, who was internationally renowned for his pioneering research in the field of metal ceramics (Yamamoto, 1985). The Shade Eye-Ex system aimed to bridge the gap between clinical requirements, such as ease of use and affordability, and the specific needs of dental technicians. The latter was addressed through the provision of custom mixing recipes, computed for a custom-developed metal-ceramics system (Vintage Halo, Shofu Inc. Japan).

Similar to Neil Hall's approach, the Shofu Vintage Halo MC shade guide was not intended to be radically new. Instead, it was built around the Vita Classical shades, omitting the C (greyish) and D (reddish-grey) groups while extending the more widely used A (reddish-brown) and B (reddish-yellow) groups with additional value-based and reddish hue variations (**Figure 9**).

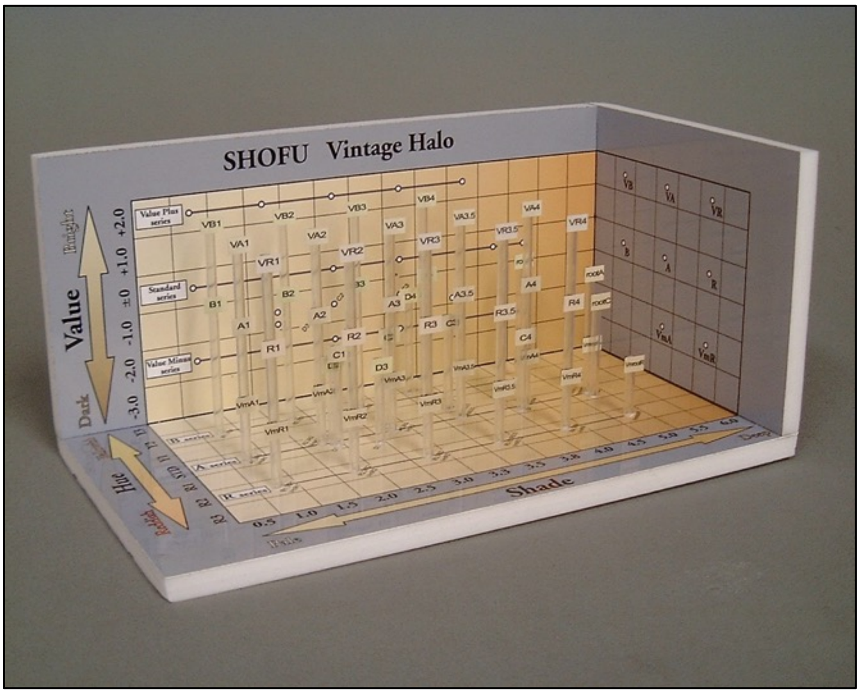

Figure 9. The Shofu Vintage NCC shade guide was extended to 54 samples to reduce the coverage error of the Vita Classical shade guide (Source: Shofu Inc).

However, the selection and grouping of these additional shades was based on a gamut analysis derived from a Japanese population study consisting of 118 volunteers with an average age of 37 years, measured using the M-1863d prototype colourimeter. Each participant had one of their maxillary centrals, laterals, and canines measured. Yamamoto acknowledged that the exclusive focus on a Japanese population was a limitation of his research, and subsequent studies have demonstrated that tooth colour varies across ethnicities (Haralur et al., 2014; Kim, 2018; Karaman et al., 2019; Ghinea et al., 2024).

Among the instrumental shade measurement systems introduced during this period, the Shade Eye-Ex was the most comprehensive, yet also the most complex. Like many before him, Yamamoto recognised the inherent limitations of shade guides. His conclusion was that reliable shade matching could only be achieved with accurate shade prescriptions through a dental ceramic system designed for this purpose as demonstrated previously. While Ishikawa et al. (1992; 1993) applied Kubelka-Munk theory for recipe prediction, Yamamoto found this approach insufficiently robust and unnecessary for metal ceramics, where the background colour was always known. Unlike modern all-ceramic restorations that use translucent framework ceramics, metal ceramic restorations featured cast metal substrates covered with opaque layers that provided complete hiding power. Instead, Yamamoto developed an extensive set of lookup tables derived from physical samples of each of the 54 Vintage Halo MC shades, allowing for straightforward interpolation between two shades (Yamamoto, 1998). However, the practical effectiveness of his shade matching system, from initial shade measurement to final restoration, was never scientifically evaluated. The complexity of Yamamoto's approach exceeded the design scope of typical dental colorimetric studies, which often involve simpler methodologies, such as tasking visual observers with matching anonymized stock shade tabs from different guides (Horn et al., 1998; Okubo et al., 1998; Yap et al., 1999). When the Shade Eye-Ex system was assessed using this type of visual comparison, a metric that fell outside its intended purpose, it did not perform well (Wee et al., 2000). In another study by Tung et al. (2002), the Shade Eye-Ex demonstrated high reliability in measuring tooth colour, with intra-examiner agreement above 95% and inter-examiner agreement above 90% for shade and value. However, its agreement with clinician-selected shades was only 55-64%, indicating that while reliable, its visual-instrumental agreement was low.

For dental practitioners, the primary concern is often whether instrumental shade measurements align with the clinician's visual perception, and whether results are expressed in terms of shade descriptions they are accustomed to (Ratzmann et al., 2020). The Shade Eye-Ex system, however, was not exactly designed to meet these criteria, but rather to offer dental technicians a comprehensive roadmap for achieving accurate shade matching in single anterior dental restorations. Few studies have evaluated instrumental shade matching systems in such a rigorous manner (Paul et al., 2004; Raigrodski et al., 2006; Da Silva et al., 2008; Xu et al., 2008; Odaira et al., 2011; Ballard et al., 2017).

Parallel to the efforts of Yamamoto and Shofu in Japan, the newly formed Canadian company Cortex Machina developed an imaging colorimeter for shade selection between 1995 and 2000 (Breton, 2025). Following its acquisition by Cynovad Inc, the ShadeScan system was commercially launched in 2001 (Hugo et al., 2005). It used a CCD camera tethered to an external computer with a video capture board while a later developed, stand-alone version, relied on CMOS digital camera technology and could capture images without a computer (Jelonek, 2025). ShadeScan could capture sRGB images of a single tooth from a defined distance using a 45º/0º illumination geometry, with a built-in guard to minimize stray light (**Figure 10**). The images were transferred via flash card to a computer running ShadeScan software for processing and shade analysis (Brewer et al., 2004).

Figure 10. The later version of the Cynovad ShadeScan system was a stand-alone imaging colorimeter incorporating CMOS digital technology. Its software generated shade maps aligned with the Vita Classical and 3D-Master shade guides, along with perceptual translucency maps. These features set a benchmark for future colour measurement systems (Source: Cynovad Inc).

The system assigned shade designations based on various commonly used shade guides, and provided a pixel-based shade map (Jeong et al., 2008) along with translucency estimations (Bayindir et al., 2012). What could be perhaps better described as “perceptual translucency” was estimated by analysing intensity variations and hue shifts, under the assumption that increasing translucency decreased intensity and shifted hue toward blue. A reference point in the most opaque region of the tooth was identified iteratively, and a translucency index was computed as the square root of the product of two sub-indices: one representing relative intensity variation (computed as the norm of the signal) and the other capturing spectral shifts based on the red/blue relative difference. A logarithmic scale was used to enhance perceptual relevance, and a median filter reduced bias, allowing for the generation of a translucency image map (Breton et al., 1999). How well this translucency estimation related to actual tooth transmittance is not known. When compared to conventional shade prescription, crowns fabricated using ShadeScan matched just as well in 40% of cases, but the conventional method performed better in 60% of cases. While ShadeScan did not improve overall shade accuracy, it significantly reduced shade selection time (Raigrodski et al., 2006). A study by Kim-Pusateri et al. (2007) contradicted this view and found that ShadeScan exhibited variability in reliability and accuracy depending on the shade guide designations used. Due to anatomical variations in natural teeth that may influence the instrument’s performance, the authors recommended visual confirmation of shade selection in clinical practice. Similar findings were reported by Dozic et al. (2007), who also observed that ShadeScan’s accuracy and precision varied depending on the experimental conditions, with reduced precision in clinical settings compared to laboratory conditions.

4.1 The 2000s: A new colour difference equation and the birth of a new industry

The new millennium began with a significant advancement in colorimetry through the development of the CIEDE2000 colour difference equation (Luo et al., 2001). From its early inception, empirical evidence had shown that CIELAB was only an approximate perceptually uniform colour space that inadequately predicted human visual responses, particularly in blue chromatic regions and near-neutral colours (McDonald, 1980; Luo & Rigg, 1986). The development process, conducted at the University of Derby's Colour & Imaging Institute, employed systematic analytical methodologies. Four comprehensive experimental datasets were accumulated, comprising thousands of assessed colour pairs across diverse surface materials. These empirical observations provided the quantitative foundation for developing novel weighting functions that demonstrated enhanced correlation with human colour discrimination capabilities. The resulting mathematical formula incorporated multiple innovative elements: integrated lightness, chroma, and hue weighting functions were complemented by an interactive term between chroma and hue differences (CIE, 2004). The formula was subsequently adopted in dental research (Lee, 2005; Paravina et al., 2005) alongside the CIELAB colour difference metric (Johnston, 2009) and specific weights for use in dentistry were recommended (Pecho et al., 2016). A study by Gómez-Polo et al. (2016) compared the CIELAB and CIEDE2000 colour difference formulas to determine which better reflects human colour perception. The results indicated that CIEDE2000 provided a better correlation with perceived colour differences, especially among women, who demonstrated greater sensitivity to colour variations than men. The early 2000s saw a significant surge in the development and commercialization of shade-matching devices, particularly between 2000 and 2005. During this period, numerous devices were introduced, yet many were discontinued within just a few years, with an average lifespan of five years or less (**Table 1**). Despite their rapid emergence, a large proportion of these instruments were never subjected to rigorous scientific evaluation, leaving their actual performance largely unverified. Established companies with expertise in colorimetry, such as X-Rite, Minolta, and Olympus, expanded into the dental market, while start-ups backed by private equity sought to capitalize on the industry's financial potential by attempting to solve a long-standing challenge: achieving reliable and accurate shade matching in dentistry. A comprehensive review of instrumental design during this period was provided by Brewer et al. (2004), highlighting two emerging design trends: contact-type instruments and non-proximity imaging instruments. The former group primarily consisted of tristimulus colorimeters, while the latter were mostly RGB imaging colorimeters using CCD image sensors.

Table 1. Tooth colour measurement instruments and shade selection devices launched until 2010.

Product name	**Launched**	**Instrument type**	**Discontinued**
Shofu Shade Eye-Ex	1997	Contact tristimulus colorimeter	2002
Dental Color Analyzer	1998	Contact tristimulus colorimeter	2002
ShadeScan	1998	RGB imaging colorimeter	2004
Ikam	2001	RGB imaging colorimeter	2003
Digital Shade Guide 4+	2001	Contact tristimulus colorimeter	2010
ShadeVision x-rite	2001	Tristimulus imaging colorimeter	2010
SpectroShade Micro	2001	Multispectral camera	Still available
Shade Eye NCC	2002	Contact tristimulus colorimeter	2009
Vita Easyshade I	2003	Contact spectrophotometer	2013
x-rite Shade-X	2005	Contact tristimulus colorimeter	2010
Crystaleye Olympus	2006	Multispectral camera	2010

The X-Rite ShadeVision device represented a unique crossover between a tristimulus colorimeter and a multispectral camera, utilizing a system of three rotating filters to capture measurements, with signals collected by a black-and-white CCD image sensor (Brewer et al., 2004) (**Figure 11**).

Figure 11. The X-Rite ShadeVision combined elements of a tristimulus colorimeter and a multispectral camera, employing three rotating filters to capture measurements. A black-and-white CCD image sensor collected the signals, enabling shade analysis. ShadeVision was available from 2001 to 2010 (Source: www.xrite.com).

Performance results for the X-Rite ShadeVision were mixed, with some studies highlighting its strengths while others pointed out significant limitations. Hugo et al. (2005) found that ShadeVision performed best among the evaluated computer-aided shade determination devices, achieving 33% agreement with human observers. Similarly, Igiel et al. (2016) reported that ShadeVision outperformed other devices in percent correct shade identifications with an average agreement of 51%. Several other studies also pointed out limitations in ShadeVision's performance. Khurana et al. (2007) found that while it demonstrated moderate repeatability, it was less repeatable than a full-tooth mapping spectrophotometer, indicating variability in its shade selection consistency. Gehrke et al. (2009) further highlighted that ShadeVision exhibited moderate reproducibility but was less consistent than other devices, often producing lighter shade readings and being significantly influenced by the differences between natural teeth and metal-ceramic crowns, which limited its reliability in clinical settings. Additional concerns were raised by Lehmann et al. (2010), who noted that while the device had excellent repeatability and relatively accurate chroma measurements, it showed significant deviations in lightness and hue, reducing its overall accuracy. Lehmann et al. (2012) reinforced this finding by demonstrating that while ShadeVision exhibited high reproducibility, its LCh° colour coordinate measurements deviated significantly from a CIE-compliant reference system, with a near-parallel but offset regression line, indicating systematic differences that limited its compliance with standardized colorimetry. Lastly, Tsiliagkou (2016) showed that while ShadeVision maintained good repeatability under standardized conditions, its performance declined significantly in freehand measurements, making it the least reliable of the three colour-matching devices studied. As ShadeVision was discontinued in 2012, studies conducted beyond that period had limited practical relevance, however.

MHT Optic Research AG and MHT S.p.A were founded in 1995 by Markus Berner, a Swiss engineer, and Carlo Gobbetti, an Italian entrepreneur (Logozzo et al., 2014). In 2001, the company launched the first true multispectral camera designed for tooth colour measurement, introducing a hybrid design that combined digital colour imaging with spectrophotometry. Before clinical shade measurement, linearization was performed using a white reference tile, and calibration verification was carried out with a second measurement of the green reference tile from the BCRA ceramic colour standards (Malkin, 1987). The device utilised a 45º/0º illumination geometry, with halogen light delivered through fibre optic strands and a built-in monochromator. The initial version required an external PC computer connected to the gun-shaped measurement head (Brewer et al., 2004). The monochromator sequentially filtered light into narrow bandwidths, illuminating the tooth in 10 nm intervals across the 400 – 700 nm range. A fibre-optic bundle transmitted this light to the measurement probe, ensuring consistent spectral distribution. Reflected light was captured by two image sensors: a black-and-white CCD sensor, which recorded intensity values at each wavelength for spectral analysis, and a colour CCD sensor, which provided a visual reference image for accurate probe positioning. The system compensated for surface glare and specular reflections using a polarizing filter system, minimising gloss artifacts and improving accuracy for translucent dental tissues (Berner, 2000). A multi-zone analysis allowed the system to detect and display spatial variations in tooth colour, distinguishing between different regions (e.g., cervical, body, incisal). Unlike earlier tristimulus-based shade measurement devices, the SpectroShade provided spectral reflectance data, significantly improving colour measurement. A commercially more successful version, the SpectroShade Mirco, featured a compact, stand-alone design with a docking station to transfer spectral data (400–700 nm in 10 nm intervals) to dedicated software (**Figure 12**).

Figure 12. MHT SpectroShade Micro was the first true multispectral camera for tooth colour measurement, combining digital colour imaging with spectrophotometry. It employed a 45º/0º illumination geometry with halogen light via fibre optics and a built-in monochromator. The associated software enabled virtual try-in's by directly comparing the restoration image to the target tooth, allowing quantification of colour differences (Source: www.spectrosupply.com).

It provided shade analysis based on the most popular contemporary shade guides, generating shade and translucency maps, a standard feature first introduced by ShadeScan. A novel addition in SpectroShade Micro was the inclusion of simple 50/50 mixing recipes to achieve intermediate shades. The device is still available in the United States where it is distributed by Spectro Supply JMC in California. In Europe, it was also sold under the proprietary name 'Shade Pilot' by Degudent, (Hanau, Germany) which was acquired by the American Dentsply

Corporation in 2001 (Jellison, 2001). Following the merger of Dentsply and Sirona into Dentsply Sirona in 2015 (Smith, 2015), MHT Optic Research AG was acquired, leading to the discontinuation of the Shade Pilot co-brand. However, the SpectroShade Micro continued to be distributed by MHT S.p.A. in Verona, Italy, until it was ultimately discontinued in 2017. While it made little impact in dental laboratories to improve shade matching (Baltzer & Kaufmann-Jinoian, 2005) several studies have evaluated the performance of SpectroShade Micro, highlighting both its strengths and limitations. Fani et al. (2007) demonstrated that SpectroShade Micro provided more accurate tooth shade measurements than visual selection in 47% of cases, indicating its potential to improve shade matching for indirect restorations. Khurana et al. (2007) found it to be the most repeatable of the tested colour-measuring devices, with narrow Bland-Altman agreement limits for CIELAB coordinates, suggesting superior measurement consistency. Similarly, Gehrke et al. (2009) reported high reproducibility, with 82% agreement between consecutive readings, confirming its greater consistency in shade selection than visual methods. Lehmann et al. (2010) further supported these findings, showing high precision and excellent repeatability, with L* and C* values closely aligning with a spectrophotometric reference system, while Chang et al. (2015) demonstrated its consistent accuracy across different hue, chroma, and value levels. Yuan et al. (2012) found that SpectroShade Micro exhibited higher accuracy than another device for in vivo shade matching, with greater consistency in clinical conditions, though some deviations in CIELAB values were observed, reinforcing the need for visual confirmation in shade selection. Igiel et al. (2016) found that SpectroShade Micro achieved 51% agreement with visual shade selection and was the only device tested to remain within the clinical acceptability threshold ($\Delta E^*_{ab} < 3.3$), reinforcing its reliability in instrumental shade selection. Tsiliagkou et al. (2016) concluded that it exhibited the highest reliability among tested devices, maintaining good repeatability and accuracy in both standardised and freehand conditions, while Akl et al., (2022) showed no clinically significant differences in CIELAB values compared to the radio-spectrometric gold standard, suggesting its suitability for dental colour research. Limitations were also identified by Gehrke et al. (2009) who noted that shade selection varied significantly between natural teeth and metal ceramic crowns, indicating that substrate type influenced its performance. Lehmann et al. (2010) reported that hue (h°) values were significantly overestimated, while Llena et al. (2011) found that inter-device agreement was weaker, particularly for lightness and chromaticity values, though overall colour differences were not statistically significant. Sarafianou et al. (2012) observed that external illuminants had a greater effect on its performance compared to other devices, raising concerns about consistency under variable lighting conditions. Furthermore, Lehmann et al. (2012) highlighted systematic deviations from a CIE-compliant reference system in LCh° coordinates, suggesting limited compliance with standardised colorimetry.

The first-generation Vita Easyshade, launched in 2003, was a contact-type filtered colorimeter that used a central light source fibre optic and multiple perimeter receiver fibres to measure reflected light at discrete spectral bands (**Figure 13**).

Figure 13. Vita Easyshade was a contact tristimulus colorimeter launched in 2003. It was designed to facilitate easy operation in a clinical setting and to provide basic shade prescriptions to the dental practitioner (Source: Vita Zahnfabrik).

It processed these signals to approximate tristimulus values, which were then matched to a database of Vita Classical and Vita 3D-Master shades (Jung et al., 1996; Brewer et al., 2004).

The Vita Easyshade is by far *the* most widely cited colour measurement device in dental literature. A PubMed search using the keyword "Vita Easyshade" yielded 417 published studies between 2004 and 2025. Its ease of access and practical usability have made it the preferred choice among dental researchers worldwide. Unfortunately, it is often used for applications where its design constraints make it unsuitable, such as in vitro analysis of the optical properties of dental materials. Despite its popularity among dental researchers, Easyshade produced mixed results across different device iterations, with decent reproducibility but notable limitations in accuracy, inter-device agreement, and performance under clinical conditions. Dozic et al. (2007), Weyhrauch et al. (2015), Igiel et al. (2017), Klotz et al. (2020, 2022) and Kutkut et al. (2024) confirmed that Easyshade demonstrated high intra-device repeatability, with intraclass correlation coefficients often exceeding 0.9. Lehmann et al. (2012), Zenthöfer et al. (2014) and Knezović et al. (2015) reported that Easyshade remained within clinically acceptable colour difference thresholds for repeated measurements, while Blum et al. (2018) and Fernández Millán et al. (2020) found that positioning guides significantly improved measurement consistency. Furthermore, Kim-Pusateri et al. (2007) and Kalantari et al. (2017)

demonstrated that Easyshade outperformed visual shade matching, reinforcing its value as an objective tool for shade selection. However, several studies highlighted accuracy and inter-device agreement issues. Lehmann et al. (2010, 2012), Llena et al. (2011), and Khashayar et al. (2012) found significant deviations in L, C, and h° values from spectrophotometric references, limiting compliance with CIE standards. Lagouvardos et al. (2009) Yuan et al. (2012), and Śmielecka et al. (2022) reported poor inter-device agreement and high colour differences, indicating that results were not interchangeable between different units. Tsiliagkou et al. (2016) observed that accuracy and repeatability declined under freehand conditions, while Della Bona et al. (2009) and Judeh & Al-Wahadni (2009) noted that lighting conditions and operator experience influenced performance. In conclusion, while Vita Easyshade appears to show a decent level of repeatability when used under controlled conditions, accuracy issues, intra-device variability, and operator sensitivity seem to limit its clinical reliability, and it should not be used without visual confirmation.

Another noteworthy device that was launched during this boom period was the Olympus Crystaleye (**Figure 14**).

Figure 14. The Olympus Crystaleye was a multispectral camera here shown with its docking station and the Application Master software for shade analysis (Source: Olympus Inc).

This was a sophisticated six band LED multispectral camera that used a 45º/0º illumination geometry with a single-use contact cap to exclude straylight. It recorded interpolated spectral reflectance factors from 400 – 700 nm for each pixel (Da Silva et al., 2008). A clinical study by Wang et al. (2009) demonstrated that metal-ceramic crowns fabricated using shade prescriptions from Crystaleye exhibited significantly better colour matching to natural teeth than crowns based on visually selected shades. Reported reproducibility varied from 0.13–0.24

ΔE^*_{ab} for shade guide measurements (Chen et al., 2010) to 0.6 ΔE^*_{ab} under clinical conditions (Odaira et al., 2011). The percent correct shade identification rate ranged from 83% to 99% for the 3D Master shade guide, while human expert observers achieved only 49% (Liu et al., 2011) Anterior full-crown restorations based on Crystaleye shade prescriptions showed an average shade match of 1.2 ΔE^*_{ab}, and ambient light conditions had little effect on measured target colours (Odaira et al., 2011). A clinical study by Witkowski et al. (2012) found that Crystaleye demonstrated high repeatability between two operators, with an interclass correlation close to unity in both dental laboratory and dental surgery settings, even under chairside examination lighting. Da Silva et al. (2008) concluded that Crystaleye significantly improved clinical shade matching compared to conventional methods, achieving a higher acceptance rate and lower colour differences. Their study supported its use as a reliable tool for enhancing tooth colour communication and reproduction in dental restorations. Overall, Crystaleye achieved favourable performance results across studies, except for an investigation by Igiel et al. (2016), which found that it had the lowest agreement rate (49%) with visual shade selection and the highest colour differences (4.5 ΔE^*_{ab}), particularly for canines and lateral incisors. Nevertheless, Crystaleye remains widely regarded as one of the best colour measurement devices ever brought to the market. However, most of the relevant research was conducted in Asia, and the system received little attention in Europe or North America, and outside of research facilities. Despite its strong technical performance, Crystaleye was not a commercial success and was discontinued in 2010.

During the rise and fall of instrumental shade measurement in dentistry, a parallel development took place: the arrival of digital dental photography (Bengel, W., 2000). Analog dental photography had been used in dentistry since at least the mid-1940s for documenting oral pathology (Greenhut, 1946) and orthodontic treatment planning (Neger, 1948). In 1952, Lester Dine invented the ring flash for dental photography (Dine, 1952), providing directional illumination ideally suited for close-up imaging of the oral cavity (Freehe, 1964). During the 1970s, colour negative film and Polaroid instant film became widely available and were used for shade communication in dentistry (Graff, 1974; Timberlake & Timberlake, 1975; Hurtgen, 1977). The use of cross-polarization to eliminate specular reflections from the tooth surface was first proposed by Wander & Gordon (1987). By the 1980s and 1990s, colour reversal film had become the standard for shade communication in dental photography (Bengel, W., 1985; Kessler, 1987; Ubassy, 1993; Magne & Belser, 2002). The introduction of consumer digital single-lens reflex (DSLR) cameras in the early 2000s immediately sparked interest in their potential for dental colorimetry.

In 2001, the ClearMatch system was launched by Clarity Dental from Salt Lake City, Utah. The system was the brainchild of Alan Morris, who held a PhD in cardio-patho physiology and worked as the director of the Electron Microscopy Laboratory at the University of Maryland (Morris Estate, 2010). Using his expertise in electronic imaging, Morris developed a method to measure tooth colour digitally, providing an alternative to traditional shade matching techniques. The ClearMatch software processed digital photographs taken in JPEG format under ambient lighting conditions, using affordable, compact cameras. The system combined visual shade assessment with digital photography: after selecting the closest visual shade match, the chosen shade tab was placed in a holder featuring two black and one white contrast strip for basic white balancing within the software (Holder, 2012). Colour calibration was achieved by using the known CIE XYZ reference values of the shade tab as a standard. Image normalisation was performed by capturing the visually selected shade tab's RGB values and computing a transformation matrix to map them to their known CIE XYZ coordinates in the reference library. This transformation was then applied to the entire image, correcting for illumination and camera response variations to improve colour measurement accuracy (Graham & Cartwright, 1989; Braunston, 2025). While the exact technical details of ClearMatch's colour calibration process are not publicly available, the system likely faced several fundamental challenges. These include the inability to account for non-linear camera sensor responses, inconsistencies in ambient lighting, and variations in colour processing across different camera brands and models. The use of basic colour transformation matrices, rather than more sophisticated colour modelling techniques, may have further constrained its accuracy. Additionally, the manual nature of the measurement process and the lack of standardised illumination geometry could have introduced variability in results. These limitations may explain why ClearMatch was never the subject of scientific evaluation in dental research. Despite its shortcomings, ClearMatch demonstrated a flexible and user-friendly approach that paved the way for similar developments in digital shade matching. With the advent of modern computational models, many of the system's original challenges could potentially be overcome today. Its legacy was carried forward by one of its associates, Dennis Braunston, who built upon the same imaging principles to develop the ShadeWave software. Launched in 2012, ShadeWave remains available today (Braunston, 2025).

In 2003 Bengel developed a standardised protocol for using digital dental photography to assess tooth colour in CIELAB colour space. The approach involved capturing RAW images with a DSLR camera equipped with a macro lens and ring flash, ensuring consistent and controlled lighting conditions. A grey reference card of known reflectance was included in the frame to enable linearisation. The RAW images were processed using Adobe Camera Raw, followed by further refinements in Adobe Lightroom. Colour correction was carried out by referencing the grey card, and image brightness was standardized. Finally, the calibrated image was analysed in Adobe Photoshop, where the CIELAB values of the tooth were extracted for colorimetric assessment (Bengel, 2003; Bengel & Chu, 2004). This method provided a more rigorous and systematic approach to dental colorimetry, overcoming many of the fundamental shortcomings associated with earlier systems like ClearMatch. Unlike ClearMatch, which relied on compact cameras and ambient lighting, Bengel's protocol utilized professional photographic equipment, which, although more specialised, was becoming increasingly accessible and affordable over the following decade.

The growing capability of instrumental colour measurement, driven by the numerous devices introduced during this period, further fuelled interest in evaluating the CE of the two most widely used shade guides: the Vita Classical, launched in 1982, and the Vita 3D Master. Various researchers reported different CE values for these shade guides (**Table 2**).

Table 2. Average CE (ΔE^*_{ab}) results from available studies between 2000 – 2010 for the Vita Classical (VC) and 3D Master (3D) shade guides.

Author	Natural Teeth (n)	CE VC	CE 3D
(Analoui et al., 2004)	150	3.1	2.7
(Paravina et al., 2007)	1064	4.1	X
(Bayindir, F. et al., 2007)	359	5.4	3.9
(Yuan, J. et al., 2007)	933	X	6.2
(Li, Q. et al., 2009)	60	6.9	3.4
(Cocking et al., 2009)	541	3.5	3.0
(Hassel et al., 2009)	313	X	5.0
(Dozic et al., 2010)	198	2.5	2.0
	Mean CE	**4.3**	**4.0**
	SD	1.6	1.3

** Note: X = not investigated*

4.2. A new colour measurement winter and its end: 2010 - 2020

A complex interplay between technological innovation, market forces, and clinical implementation in contemporary dental practice played significant and often antagonistic roles that led to disillusionment (Baltzer & Kaufmann-Jinoian, 2005) and gradual abandonment of instrumental colour measurement in restorative dentistry (Chu et al., 2010), despite its initial acclaim as a game changer (Paul et al., 2004). Another *Colour Measurement Winter* was about to descend. Between 2010 and 2020, only three colour measurement devices were launched: the Vita Easyshade Advance 4.0 (2013), the Vita Easyshade V (2015), and the Rayplicker from French start-up company Borea, based in Limoges, France.

While Vita Easyshade Advance followed the previous design as a tristimulus colorimeter, Easyshade V operates as a dual-spectrometer system capable of measuring reflected light across the 400 – 700 nm range in 10 nm intervals. The system uses high-resolution spectral sensors to improve the detection of subtle colour differences and applies compensation algorithms to correct for angular dependency, translucency effects, and surface scattering artifacts. A multi-point calibration process is designed for improving the reliability of shade matching against an expanded digital Vita shade reference database (Jung et al., 2013). Apart from these technical advancements, Vita Easyshade V introduced only incremental practical updates, without adding fundamentally new functional features (**Figure 15**).

Figure 15. The Vita Easyshade V was launched in 2015 and still is the flagship spectrophotometer of Vita today. It is a dual-spectrometer system which can measure spectral reflectance factors from 400 – 700 nm (Source: Vita Zahnfabrik).

In contrast, the Rayplicker represented a genuinely novel concept, combining the advantages of contact measurement with those of non-proximity imaging. The result was a device that appeared to be an unusual hybrid between the Vita Easyshade and the MHT SpectroShade Micro systems (**Figure 16**). This unconventional, function-driven approach aligns with a long-standing tradition of French design, where bold innovation often takes precedence over conventional aesthetics as seen in French automotive design, often noted for its quirkiness

(Cowley, 2021). The Rayplicker was designed for ease of use in clinical settings while capturing multispectral images of a single tooth, from 400–700 nm in 10 nm intervals per pixel. These images can be transferred to the Vision Software to generate shade maps based on various shade guide designations, while CIELAB values were provided for computing colour differences using the ΔE_{ab} formula.

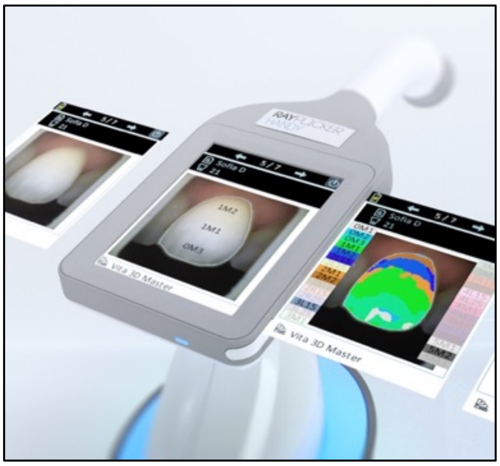

Figure 16. The Rayplicker represents an innovative hybrid between a contact-based measurement system and a non-proximity multispectral imaging spectrophotometer, combining the ease of use found in clinical contact devices with the advanced capabilities of imaging-based spectrophotometry. Its bold design reflects this dual functionality (Source: Borea).

A study by Hampé-Kautz et al. (2020) evaluated the performance of Rayplicker and found that it demonstrated close agreement with the Easyshade V, while outperforming visual shade assessment by both novice and expert practitioners. The study concluded that Rayplicker was a viable alternative to Easyshade V. This view was reinforced during a follow-up study (Hampé-Kautz et al. 2024) which assessed the clinical repeatability of Rayplicker, Easyshade V, and Easyshade Advance. Both Rayplicker and Easyshade V showed high repeatability with intra-class correlation values above 0.90. The study concluded that Vita Easyshade V and Rayplicker were reliable tools for tooth colour measurement, with superior repeatability compared to the earlier Easyshade 4 model.

Overall, the colour measurement instruments that were launched during this period, adhered to the conceptional ideas established in the previous decade. Colour measurement devices were primarily designed to meet the needs of dental practitioners, mainly by providing corresponding shade tab information. While cost constraints played a role in shaping their development, the more significant limitation was their lack of practical value, namely, their inability to improve clinical shade matching or offer features relevant to dental technicians. By 2010, instrumental colour measurement had established a foothold in university research environments, with devices like the Vita Easyshade becoming widely used by an increasing number of undergraduate and postgraduate students for research purposes. However, these instruments had virtually no impact in dental laboratories, where practical shade matching remained reliant on traditional methods. This stagnation ultimately led to another decline in the adoption of instrumental colour measurement, a second *Colour Measurement Winter*.

The turning point came with a new imaging-based approach to colour measurement, built on previous ideas but reconfigured to meet the needs of dental technicians. The increasing accessibility and affordability of DSLR cameras in both dental clinics and laboratories opened the door to a more sophisticated and practical method. The newly developed 'eLABor_aid' system as it was initially termed, built upon the Bengel Protocol, but incorporated ICC profiles obtained from an X-Rite ColorChecker Passport to characterize the DSLR camera sensor (Hein & Zangl, 2016). This approach relied on the use of RAW images, ensuring that colour measurements were free from in-camera processing alterations such as automatic white balance adjustments and tone curve applications. Sensor characterisation enabled colour measurements of the same tooth-coloured object to be directly comparable across different DSLR cameras, eliminating variations caused by differences in camera sensors and colour processing. As a result, the system provided a standardized and reproducible method, bridging the gap between digital photography and imaging colorimetry in dental laboratories (Hein et al., 2017). Empirical observations from dental laboratories had long shown that matching natural teeth with restorations such as crowns, bridges, and veneers was nearly impossible using conventional shade guides. The eLAB_prime software launched in 2019 was able to generate mixing recipes for common dental ceramic systems, requiring only a few standard shades mixed with three primary glass-ceramic stains: red, yellow, and grey (Hein et al., 2021) (**Figure 17**).

The system employs a refined RAW image processing workflow, utilising a 22-patch colour checker to compute a transformation matrix that maps sRGB values to their corresponding CIELAB values. This transformation is then applied to the entire image, converting sRGB to CIELAB and back to sRGB for precise colour rendering based on the reference CIELAB data (Westland et al., 2012). By standardizing colour representation, this method enables direct comparison of tooth colours across images taken with different cameras (Dias et al., 2023). The eLAB system has demonstrated capabilities comparable to spectrophotometric analysis for detecting tooth colour changes (Bezerra et al., 2024) and tracking variations in white spot lesions during treatment (Kashash et al., 2024).

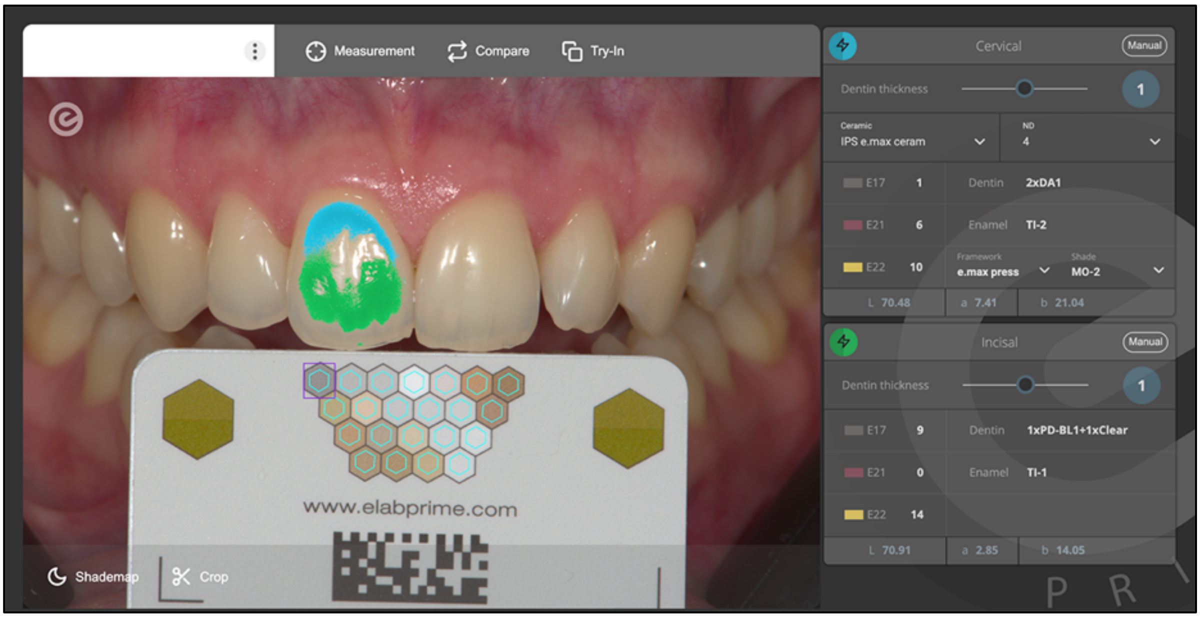

Figure 17. The eLAB_prime software was the first stand-alone software to provide individual mixing recipes, free of stock shade guides (Source: Sascha Hein).

Additionally, it has been applied in evaluating shade discrepancies among identically labelled direct composite materials from various manufacturers (Notarantonio & Seay, 2023) and assessing the effectiveness of at-home bleaching protocols (Salehi et al., 2022). The global success of the eLAB system stimulated renewed interest in instrumental shade matching, leading to the launch of several similar software systems shortly thereafter (**Table 3**).

Table 3. Colour measurement instruments and shade matching software products launched between 2010 – 2020.

Product name	**Launched**	**Instrument type**	**Discontinued**
ShadeWave	2012	Shade matching software	Present
Vita Easyshade IV	2013	Contact fibreoptic spectrophotometer	2015
Vita Easyshade V	2015	Contact fibreoptic spectrophotometer	Present
Rayplicker	2017	Imaging Spectrophotometer	Present
eLAB System	2016	Shade matching software	Present
CDSL System	2019	Shade matching software	Present
Mixceram	2019	Shade matching software	Present
Matisse	2019	Shade matching software	Present

This decade also saw the widespread adoption of intraoral scanners which, in addition to their primary function of capturing digital impressions, claimed to offer shade measurement capabilities. An early study by Mehl et al. (2017) had found that the colour differences between visual shade selections made by dentists, dental technicians, and the Trios intraoral scanner were clinically insignificant. Additionally, no significant variation was observed in the repeatability of shade assessment between the Trios intraoral scanner and other digital shade measurement systems examined in the study. Shortly after, Brand et al. (2017) concluded that the Trios intraoral scanner presented as an adequate alternative to visual shade selection. Both Liberato et al. (2019) and Reyes et al. (2019) found that the Trios intraoral scanner demonstrated superior repeatability in shade selection compared to visual methods. Liberato et al. reported a high reliability for the Trios intraoral scanner as well, while Reyes et al. quantified its repeatability at 87%, significantly higher than the 75% achieved by the visual method. But both studies confirmed that Trios provided more consistent shade selection over repeated measurements, whereas visual methods were more prone to variability. When compared to the Vita Easyshade, the Trios intraoral scanner produced statistically similar shade measurement results, suggesting that it can serve as a viable alternative to the spectrophotometer for tooth shade selection (Yılmaz et al., 2019). However, these studies remained cautious, suggesting that final shade prescriptions should still be confirmed visually.

Another significant development during this period was the establishment of the now widely accepted 50/50% perceptibility and acceptability thresholds for clinical dentistry by Paravina et al. (2015). These thresholds were defined as 1.2 ΔE^*_{ab} and 2.7 ΔE^*_{ab} and 0.8 ΔE_{00} and 1.8 ΔE_{00}, respectively, and were later adopted as an ISO standard (2016). At the same time, further research was conducted to refine estimates of the CE for the Vita Classical and 3D Master shade guides (**Table 4**).

Table 4. Average CE (ΔE^*_{ab}) results from available studies between 2010– 2020 for the Vita Classical (VC) and 3D Master (3D) shade guides.

Author	Natural Teeth (n)	CE VC	CE 3D
(Haddad et al., 2011)	2067	X	6.2
(Wang, P. et al., 2014)	236	4.2	X
(Ballard et al., 2017)	103	6.5	X
(Rao and Joshi, 2018)	700	7.2	8.4
	Mean CE	**6.0**	**7.3**
	SD	1.6	1.6

** Note: X = not investigated*

4.2. The present 2020 – 2025

The success of shade matching software, driven by the widespread adoption of digital dental photography, renewed interest in instrumental colour measurement, leading to the launch of two new devices in 2022. The Rayplicker Cobra, a compact and ergonomic upgrade to the original Rayplicker, introduced a significantly smaller, lighter, and more intuitive design, visually resembling a dental light-curing unit. This design choice, along with its pricing, indicates that the device is primarily geared toward the needs of dental practitioners rather than dental technicians. Despite being the smallest imaging spectrophotometer available for tooth colour measurement, its full potential remains underutilised, as the associated software offers similar functionalities to earlier systems like ShadeScan but lacks the ability to generate individual mixing recipes (**Figure 18**).

Figure 18. Launched in 2022, the Rayplicker Cobra is the smallest imaging spectrophotometer for tooth colour measurement currently available. Its compact and ergonomic design is tailored for ease of use in clinical settings (Source: Borea).

That same year, Swiss company Smile Line launched the Optishade (**Figure 19**), a portable imaging colorimeter with a design similar to the NIX sensor colorimeter (Schelkopf et al., 2021) capable of connecting to a smartphone. Both devices emerged in response to the challenges faced by dental practitioners in adhering to the strict dental photography protocols required for shade-matching software solutions. Meanwhile, interest in the shade measurement ability of newer generations of intraoral scanners was stimulated, and a comprehensive review was provided by Tabatabaian et al., (2024) who systematically evaluated their performance. They concluded that while intraoral scanners demonstrated acceptable precision, their accuracy remained insufficient for reliable clinical shade selection, ultimately advising against their use for this purpose. Similarly, Vitai et al. (2024) conducted a systematic review and meta-analysis, finding that while intraoral scanners exhibited high precision comparable to spectrophotometers, their trueness was significantly lower. As a result, they also recommended against relying on intraoral scanners for clinical shade matching, reinforcing the conclusion that these devices are not yet a viable alternative to dedicated spectrophotometric methods.

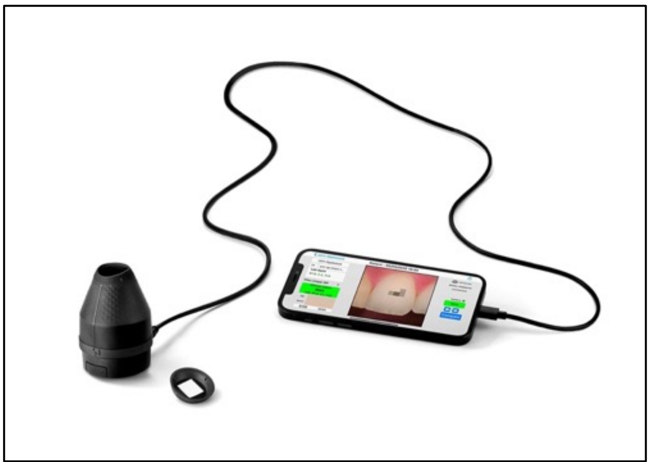

Figure 19. Smile Line Optishade is an imaging colorimeter that takes RGB images. Its integration with a smartphone app and dedicated software reflects shifting consumer preferences towards seamless digital workflows and enhanced connectivity in modern dental practice (Source: www.smileline.ch).

In recent years, two additional studies have examined the coverage error (CE) of shade guides, yielding comparable results (**Table 5**).

Table 5. Average CE (ΔE^*_{ab}) results from available studies between 2020 – 2025 for the Vita Classical (VC) and 3D Master (3D) shade guides.

Author	**Natural Teeth (n)**	**CE VC**	**CE 3D**
(Tabatabaian, F. et al., 2022)	1182	3.3	2.9
(Ruiz-López et al., 2022)	735	2.5	3.2
	Mean CE	**2.9**	**3.1**
	SD	0.6	0.2

5.0 Research Questions

The history of dental colorimetry has been shaped by an ongoing pursuit of reliable, objective, and clinically applicable methods to achieve accurate shade matching. From early visual shade assessment systems to the introduction of instrumental methods, dental researchers have utilized the Munsell system and later the CIE system of colorimetry to quantify, describe, and predict tooth colour appearance. However, persistent challenges remain unresolved. The cyclic waves of enthusiasm followed by disillusionment in instrumental colour measurement highlight the difficulty of integrating colour science into clinical dentistry in a meaningful and lasting way.

The literature reveals key historical challenges, including the subjective nature of visual shade selection, the limitations of existing shade guides in capturing the full gamut of natural tooth colours, and the significant impact of factors such as illuminant metamerism and measurement geometries. While dental colour measurement devices have demonstrated high reproducibility, conflicting reports on their accuracy persist, largely due to methodological inconsistencies in dental research. These inconsistencies stem from an overreliance on Classical Test Theory rather than established principles of colour science, leading to misleading interpretations of instrumental performance.

Despite advancements in shade matching technologies, past efforts have largely failed to establish a standardized methodology grounded in perceptual colour science. Dental researchers have frequently favoured empirical approaches with limited sample sizes, often relying on extracted teeth rather than in vivo data. The introduction of new measurement devices continues at regular intervals, yet few achieve widespread adoption, and even fewer undergo rigorous validation using methodologies aligned with best practices in colour science.

This thesis builds upon the historical context of dental colorimetry by addressing several key unresolved questions:

1. Illuminant Metamerism: Does illuminant metamerism in dentistry truly function as a disruptive ‘monster’, as characterized by Sproull in the 1970s and widely accepted in dental textbooks? A systematic evaluation using a chromatic adaptation transform will determine the actual impact of illuminant metamerism between natural teeth and zirconia restorations.
2. Instrument Accuracy: While dental research has consistently demonstrated high reproducibility for colour measurement devices, reports on their accuracy remain conflicting. Given that the methodologies applied in dentistry often do not align with colour science principles, how do we investigated devices actually compare in terms of accuracy? A multicentre study will explore this discrepancy using improved colour difference equations.

3. Gamut and Shade Guide Coverage: Dental colorimetry has been instrumental in estimating the gamut of natural tooth colours, the coverage error of commonly used shade guides (Vita Classical and Vita 3D Master), and the optimal design of new shade guides. However, past studies have varied significantly in methodology and sample size. What is the true gamut of natural tooth colours, and what would constitute the optimal arrangement of a shade guide to ensure comprehensive coverage?
4. Future Instrument Validation: Given that most colour measurement devices introduced in dentistry have had a lifespan of 5-10 years, future technological developments will continue to emerge. Can a methodology be established that is deeply rooted in colour science yet remains feasible for use within the usual scope of dental research? The Visual Instrument Agreement Scale (VIAS) is proposed as a novel approach to replacing traditional accuracy and precision measurements.
5. Clinical Trust in Instrument Readings: Clinicians often face uncertainty when interpreting shade readings from instruments such as Vita Easyshade and intraoral scanners. Classical Test Theory-based evaluation methods have produced questionable conclusions regarding their performance. Can these devices be trusted for clinical shade selection, and how does their accuracy compare when evaluated using robust statistical methodologies?
6. Visual Thresholds and Measurement Geometries: While perceptual thresholds for colour differences are well established in various industries, their application in dentistry remains ambiguous, particularly due to the non-standard illumination geometries used in tooth colour measurement. What are the expert-defined visual thresholds in dentistry, and can they be consistently applied across different devices and measurement conditions?

By addressing these fundamental questions, this thesis seeks to bridge the gap between theoretical colour science and its practical application in dentistry. The historical context underscores the need for methodologies that not only improve instrumental shade matching but also align with scientifically validated perceptual metrics. The findings presented in the subsequent chapters will contribute to the establishment of a more rigorous and reliable framework for evaluating dental colour measurement systems, with implications for both research and clinical practice.

Chapter 2: The research

2.1 The role of illuminant metamerism in dentistry

2.1.1 Introduction

Human colour perception is normally mediated by three types of cone photoreceptors in the eye, each mainly sensitive to short-, medium-, and long-wavelength radiation within the visible spectrum. Variations in the relative responses of these cones give rise to the wide range of colours perceived by the human visual system. In 1853, Grassmann stated: "Stimuli of the same colour produce identical effects in mixtures regardless of their spectral composition" (Grassmann, 1853). This principle implies that if colour A matches colour B and colour C matches colour D, then an additive mixture of A and C will match that of B and D. Consequently, spectrally distinct stimuli can appear identical in colour, a phenomenon known as illuminant metamerism (Berns et al., 2019).

Metamerism is fundamental to numerous colour reproduction technologies, including television, computer and smartphone displays, printing, and digital photography. The use of three primaries is sufficient to reproduce a gamut encompassing millions of visually discernible colours (Linhares et al., 2008). However, this flexibility presents both advantages and limitations, as metameric matches are often contingent on specific viewing conditions. Two key forms of metamerism are recognised: illuminant metamerism, where a colour match fails under different lighting conditions but remains consistent for a standard observer, and observer metamerism, where a match varies between individuals under the same illuminant (Hunt and Pointer, 2011).

To quantify metamerism, the Metamerism Index (*MI*) was introduced by the Commission Internationale de l'Éclairage (CIE), providing a colorimetric measure of metamerism based on standard observer data. In this approach, two spectrally distinct samples that appear identical under a reference illuminant, typically CIE illuminant D65 for the 2° 1931 standard observer, are assessed for colour differences under test illuminants, commonly CIE illuminants A and F2 (CIE, 1972).

A particularly striking example of such a metameric pair is illustrated in **Figure 20**, where two distinct spectral reflectance functions produce identical tristimulus values under D65 for the standard observer. The first reflectance function corresponds to the common Vita Classical A3 shade, while the second was derived through a linear combination of the same reflectance function with a scaled, orthogonal set of metameric blacks, as formulated by Wyszecki (1958) (Wyszecki, 1958). As a result, the stimuli exhibit a colour difference of exactly 0 ΔE_{00} under the reference illuminant, yet this difference increases to 10 ΔE_{00} under the test illuminant CIE LED BH1 (**Figures 21**).

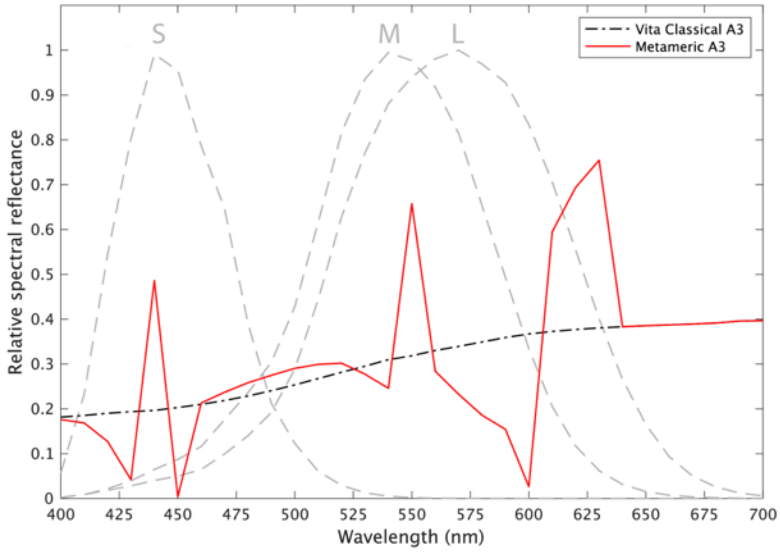

Figure 20. Spectral reflectance factors of the Vita Classical A3 shade (black dashed line) and a metameric match constructed using a scaled set of metameric blacks (red solid line). Both stimuli exhibit multiple crossover points within the LMS cone sensitivity spectra. The metameric A3 match, while theoretically valid, appears unnatural due to its lack of spectral smoothness, serving as a conceptual demonstration, only.

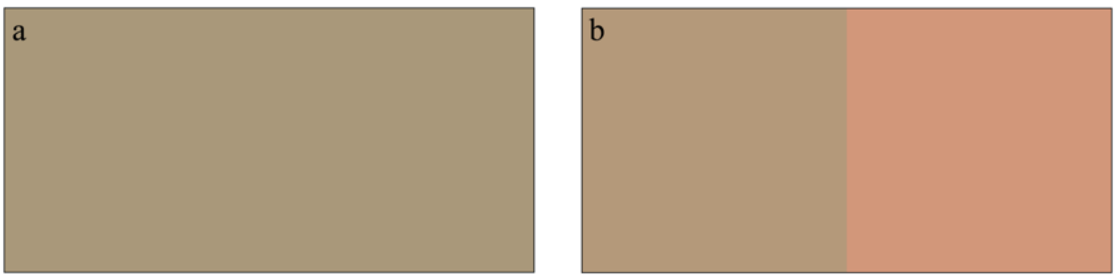

Figure 21. The stimuli exhibit colorimetric equality ($\Delta E_{00} = 0$) under the reference illuminant D65/2° (a). However, when the illuminant shifts to CIE LED BH1/2° (b), the colour difference increases significantly ($\Delta E_{00} = 10$), demonstrating illuminant metamerism.

Metamers are rare in nature (Foster et al., 2006), and in practice, spectrally different samples rarely achieve true trichromatic equality, though they may appear similar under specific lighting (Choudhury and Chatterjee, 1996; Berns et al., 2019). To address this, the ISCC Project Committee 27 proposed extending metamerism terminology to better reflect industry use (Rodrigues and Besnoy, 1980). Suggested terms included Paramerism (Kuehni, 1983), Isochromism, Parachromism, Metachromism, Orthochromism (Billmeyer, 1983), and Psychophysical Metamers (McLaren and Allan, 1990). While never formally adopted by the CIE, Kuehni's term Paramerism ultimately prevailed and is widely accepted today (Berns, 2019; Hunt & Pointer, 2011).

A good example of such paramerism is provided in **Figure 22** and it consists of the Ugra Light Indicator Strip D50 (www.ugra.ch). When measured under the reference light source with a correlated colour temperature (CCT) of 4967K (D50 simulator) for the 2º CIE standard observer, the colour difference is small (1.6 ΔE_{00}), but it increases to 8.0 ΔE_{00} when the illumination is changed to the test condition TL84 (CCT = 4022K).

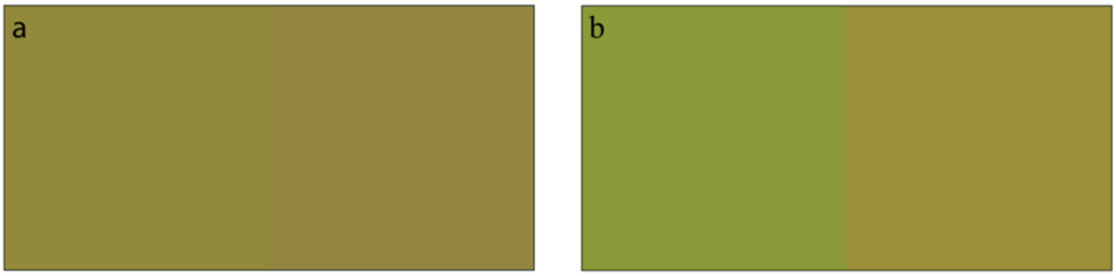

Figure 22: Parameric pair consisting of the Light Indicator Strip D50 (Ugra). When measured under the reference light source with CCT = 4967K (D50 simulator) and the 2º CIE standard observer, the colour difference is small (1.6 ΔE_{00}) (a), but it increases to 8 ΔE_{00} when the illumination is changed to the test condition TL84 (CCT = 4022K) (b)

Illuminant metamerism has long been regarded as a critical factor in restorative dentistry, particularly in the aesthetic zone, where artificial restorations must closely match natural teeth under varying lighting conditions (Matthews et al., 1978; Ahmad, 1999; Chu, S., 2002). The assumption that illuminant metamerism negatively impacts perceived colour matches has been widely accepted in dental education and practice (Fondriest, 2003; Chu, S., 2010; Sakaguchi and Powers, 2012). However, this premise has never been rigorously tested, and only a handful of studies have directly investigated its impact on dental materials and natural teeth.

Research by Hang et al. (1993) (Hang et al., 1993) compared the spectral reflectance factors of veneering ceramics and bovine dentin samples under CIE standard illuminants C and A, concluding that different materials exhibited varying degrees of colour shift, with a general reddish shift under illuminant A. However, the samples were parameric, with initial colour differences already exceeding ΔE_{ab} >2.8, making conclusions about metamerism difficult.

Lee and Powers (2005) later examined metamerism in human dentin and direct composite materials under illuminants D65, A, and F2. They introduced a modified metamerism index (mod-*MI*) that calculated the ratio of colour differences between reference and test illuminants. Their findings suggested no significant metameric effect, as the ratios for A and F2 (compared with D65) were close to unity, indicating similar colour stability under different lighting.

Duan et al. (2009) (Duan et al., 2009) conducted an in vivo study using a spectroradiometer to assess eight parameric pairs of human and denture teeth in shade A2 under illuminants D65, A, and cool white, fluorescent light. Their results showed *MI* values ranging from 0.1 to 2.2 ΔE_{ab}. Despite these findings, they recommended that multiple light sources should be used in clinical shade assessment to mitigate potential metameric mismatches.

Finally, Corcodel et al. (2010) examined natural teeth and the Vita 3D Master shade guide in an in vivo study with 37 volunteers. They used the mod-*MI*, analysing CIELAB values under D65, A, and TL84 for the 2º observer. Their findings aligned with Lee & Powers, with mod-MI_A and mod-MI_{F2} values near unity, and mod-*MI* values of 1.5. The study raised concerns about the practical significance of the mod-*MI* and echoed previous recommendations to use multiple light sources for visual shade matching.

Across these four studies, either natural teeth or bovine/human dentin samples were compared to dental materials or shade guides, yet only weak evidence was found to support the notion that illuminant metamerism is a major concern in dentistry. While colour differences were observed in some cases, most parameric pairs exhibited only minor colour shifts, and in some cases, no significant effect was found at all. The assumption that illuminant metamerism significantly affects dental shade matching remains largely unverified, and its clinical relevance may be overstated. Therefore, the aim of this research was to investigate the potential relevance of illuminant metamerism in dentistry using advanced computational methods from colour science. The study focused on two types of modern restorations commonly used in restorative dentistry: monolithic zirconia, which has gained widespread popularity in clinical practice, and polychromatic, hand-layered zirconia restorations, often considered the gold standard in aesthetic dentistry.

2.1.2 Material and Methods

Illuminant metamerism was examined between natural teeth and zirconia restorations. Three groups were analysed: natural maxillary central teeth (n=114), layered zirconia restorations (n=31), and monolithic zirconia restorations (n=75) (**Figure 23**). The restorations were selected based on commonly preferred shades from a digital dental laboratory database. Spectral reflectance factors were measured using a calibrated spectroradiometer (SpectraScan PR-670) combined with an integrating hemisphere to ensure consistent diffuse reflectance measurements. Parametric pairs were identified where the colour difference was within clinically acceptable limits ($\Delta E_{00} \leq 1.8$ under D65). The special index of metamerism (M_{ilm}) was calculated using the CIEDE2000 formula, incorporating a chromatic adaptation transform (CAT16). Ten illuminants, including conventional fluorescent (F2, F7, F11) and newer LED-based illuminants (B1-B5, BH1), were used to assess metameric effects (**Figure 24**). Descriptive statistics and a one-sample *t*-test were applied to compare M_{ilm} values against the clinical acceptability threshold ($\alpha = 0.05$).

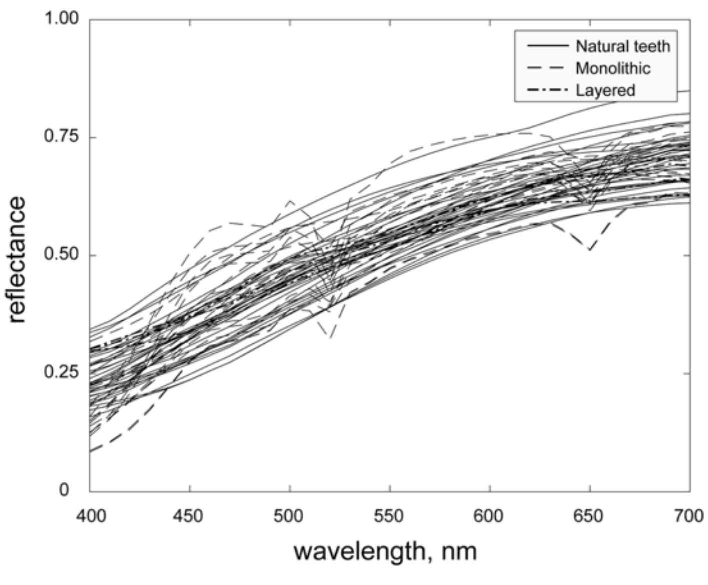

Figure 23. Spectral reflectance factors of parameric pairs comprising natural teeth with layered zirconia restorations and natural teeth with monolithic zirconia restorations. All pairs exhibited colour differences within the clinically acceptable threshold.

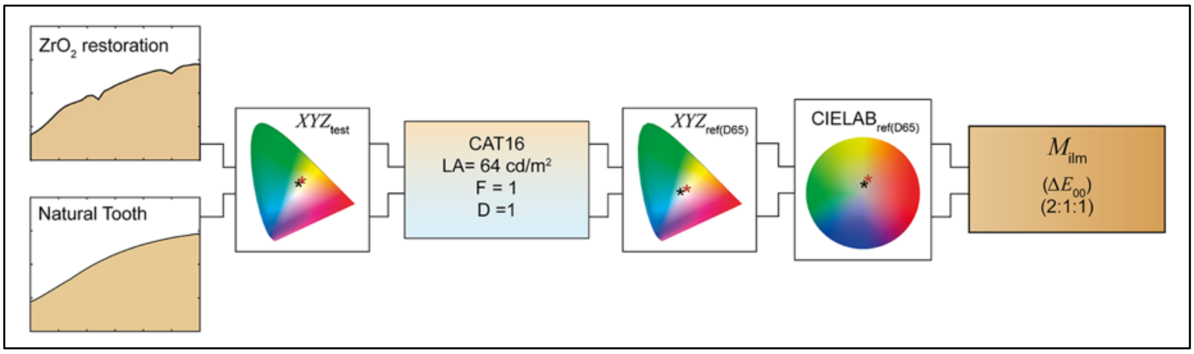

Figure 24. Flowchart illustrating the computation of M_{ilm} using the CIE 1931 standard colorimetric observer. CAT16: chromatic adaptation transform; D: degree of adaptation; ΔE_{00}: CIEDE2000 colour difference equation; *F*: average surround; L_a: luminance adaptation; M_{ilm}: special index of metamerism; XYZ: CIE trichromatic colour space.

2.1.3 Results

Layered zirconia restorations exhibited a mean M_{ilm} of 0.3 ± 0.2, while monolithic zirconia restorations had a slightly higher mean M_{ilm} of 0.5 ± 0.4. Both groups showed significantly lower metameric effects than the clinical acceptability threshold (ΔE_{00} = 1.8, P < .01) **(Figure 25)**. While most cases fell well within acceptable limits, one monolithic restoration (Amann Girrbach Zolid A3) marginally exceeded the threshold under F11 illumination (ΔE_{00} = 1.88). However, as F-type fluorescent lamps have been discontinued in favour of LED technology, this discrepancy is unlikely to have clinical significance in future applications.

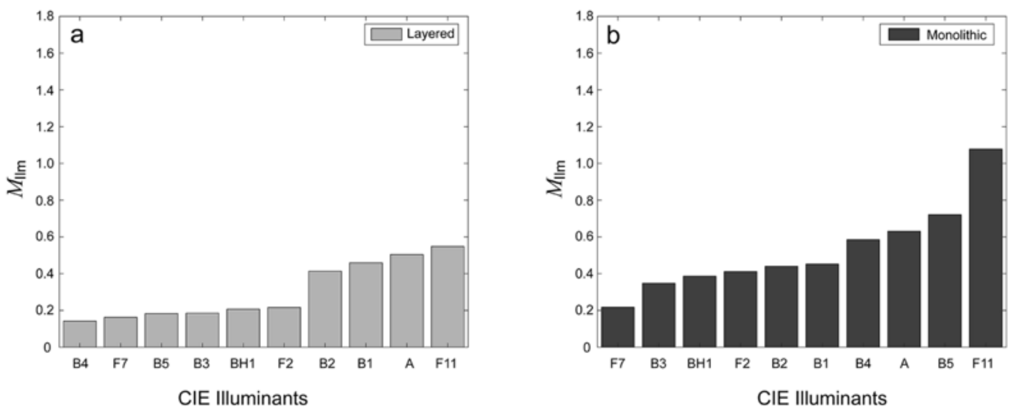

Figure 25. Mean M_{ilm} values categorized by CIE illuminant type for (a) layered zirconia restorations and (b) monolithic zirconia restorations.

2.1.4 Discussion

These results indicate that illuminant metamerism between natural teeth and zirconia restorations is minimal and within clinically acceptable limits. The mean M_{ilm} values for layered zirconia restorations (0.3 ± 0.2 ΔE_{00}) and monolithic zirconia restorations (0.5 ± 0.4 ΔE_{00}) were significantly below the clinical acceptability threshold of 1.8 ΔE_{00} ($P < .01$). These findings align with previous research indicating that modern restorative materials exhibit relatively low metameric effects compared to traditional ceramics and composites (Corcodel, et al., 2010; Paravina, et al., 2019).

Although the overall metameric effect was small, layered zirconia restorations exhibited slightly lower M_{ilm} values compared to monolithic restorations. This difference may be attributed to variations in spectral reflectance characteristics between these two restoration types. Layered zirconia restorations, which incorporate a ceramic veneering layer, tend to have smoother and more diffuse spectral reflectance curves, resembling those of natural teeth (Vichi et al., 2011). In contrast, monolithic zirconia restorations, fabricated from a single material, showed distinct spectral absorption dips at 520 nm and 650 nm. These absorption features are indicative of erbium ions (Er^{3+}), commonly used as red or pink colorants in dental zirconia, which introduce additional spectral crossover points (Fujisaki and Kawamura, 2014). However, despite these spectral variations, the overall metameric effect remained negligible.

The study also challenges a longstanding assumption in dental colour science that differences in the chemical composition of dental materials and natural teeth inherently lead to significant metamerism (McLean, 1979; Yamamoto, 1985). The findings suggest that when a zirconia restoration and a natural tooth appear as a colour match, this is largely due to their spectral similarities rather than an accidental visual match. The smooth spectral curves observed in layered zirconia restorations further support this notion, as they closely resemble the spectral characteristics of natural teeth.

A particularly noteworthy finding was that one monolithic restoration (Amann Girrbach Zolid A3) exceeded the clinical acceptability threshold under CIE illuminant F11 by 0.08 ΔE_{00} units. While this deviation is minor, it highlights the potential for metamerism under specific lighting conditions. However, F11 represents a fluorescent-type illuminant, and due to recent legislative changes in the European Union, traditional fluorescent lamps containing mercury have been phased out in favour of LED-based lighting (IEA, 2022). Given that all tested LED illuminants produced acceptable M_{ilm} values, this suggests that the global transition toward LED lighting may further reduce metameric discrepancies between natural teeth and zirconia restorations.

Another important consideration is the methodological advancements used in this study. Unlike previous studies that relied on basic colorimetric evaluations, this research employed a chromatic adaptation transform (CAT16) to improve accuracy in predicting colour appearance under different illuminants (Fairchild, 2010). A multiplicative correction factor was also incorporated to ensure that M_{ilm} values for parameric pairs accurately reflected real-world visual perception (Berns, 2019).

Despite the robust methodology and clinically relevant findings, several limitations should be acknowledged. Only A-shades from the Vita Classical shade guide were tested, as research funding did not permit the inclusion of a broader range of zirconia shades from multiple manufacturers.

It could be shown that illuminant metamerism between natural teeth and zirconia restorations is minimal and unlikely to pose significant clinical challenges. These findings support the continued use of zirconia for aesthetic restorations, as their colour stability across different lighting conditions remains within acceptable limits. The global shift toward LED-based lighting may further reduce any remaining metameric discrepancies, reinforcing the practical applicability of zirconia restorations in modern dentistry.

2.1.5 Conclusion

Illuminant metamerism between natural teeth and zirconia restorations (layered and monolithic) was found to be small and within clinically acceptable limits, except for one marginal case under F11 illumination, which is unlikely to be relevant given the phase-out of fluorescent lighting. Layered zirconia restorations exhibited slightly lower metameric effects than monolithic restorations. These findings suggest that metamerism should not be a major concern for clinicians when selecting zirconia restorations for aesthetic cases.

2.2 Bridging visual instrumental agreement

2.2.1 Introduction

Instrumental colour measurement in dentistry has received considerable attention over the past decades, with increasing appreciation for its objectivity and precision in evaluating tooth shades (Chu, et al., 2010; Joiner and Luo, 2017). However, an overreliance on instrumental methods often overlooks the crucial role of visual colour perception. A persistent challenge arises when instrumental measurements fail to align with human visual assessment, resulting in restorations that appear visually mismatched despite a small, measured colour difference. The accuracy of tooth colour difference measurement is not solely dependent on the performance of the device but is also significantly influenced by the choice of colour difference equations used for evaluation. This situation complicates the distinction between cause and effect when a measured colour difference between a restoration and a tooth does not correspond to the visual impression. Is this discrepancy due to poor device performance, or has the chosen colour difference metric failed to predict the perceived colour difference adequately—or both? Historically, the CIELAB colour space and its ΔE_{ab} equation have been widely employed in dental colorimetry (Macentee and Lakowski, 1981; Burkinshaw, 2004; Johnston, 2009) to assess device performance, particularly in terms of accuracy (Tabatabaian et al., 2021; Morsy, and Holiel, 2023). While initially developed as an approximately uniform colour space, its limitations in perceptual uniformity soon became evident (McDonald, 1980), prompting the development of more advanced colour difference equations such as CIEDE2000 (ΔE_{00}) (Luo et al., 2001) and CAM16-UCS (Li et al., 2017). These newer equations incorporate weighting factors to account for variations in hue, chroma, and lightness sensitivity; however, their effectiveness in dental applications remains debated (Pecho et al., 2016).

A fundamental question in dental colorimetry concerns the extent to which visual-instrumental agreement is influenced by the choice of colour difference equation. This study investigated the agreement of six different colour measurement devices and explored the optimisation of three colour difference equations to enhance their congruency with human visual perception. A large-scale multi-centre study was conducted, incorporating a psychophysical experiment involving expert observers, to determine the correlation between instrumental and visual assessments of colour differences.

Two null hypotheses were tested: first, that there would be no significant differences in visual-instrumental agreement among the investigated devices, and second, that optimised colour difference equations would not significantly enhance agreement compared to their conventional counterparts. By addressing these hypotheses, the study aimed to provide evidence-based recommendations for improving colour measurement in dental practice.

2.2.2 Materials and methods

A magnitude estimation (ME) technique was employed to quantify visually perceived colour differences (ΔV), enabling a direct comparison with instrumental ΔE values (Luo and Hunt, 1998). This method is widely recognised in colour science for its ability to produce reliable and consistent scaling of perceived differences (Pan and Westland, 2018).

The study involved 154 expert observers, comprising dental practitioners and technicians, all of whom passed the Ishihara test for colour deficiency. Observers were recruited from 16 different institutions, including universities, private dental laboratories, and clinical practices, ensuring a diverse dataset reflective of real-world dental settings (**Figure 26**).

To facilitate a controlled psychophysical experiment, hyper-realistic phantom models were fabricated to simulate natural teeth. Each model was constructed using microfiller-reinforced composite denture teeth in a base shade and paired with multiple interchangeable teeth to generate 26 visually scaled sample pairs (**Figure 27**). The study design ensured that observed colour differences remained within a clinically relevant range ($<5\Delta E_{ab}$) (CIE, 2004).

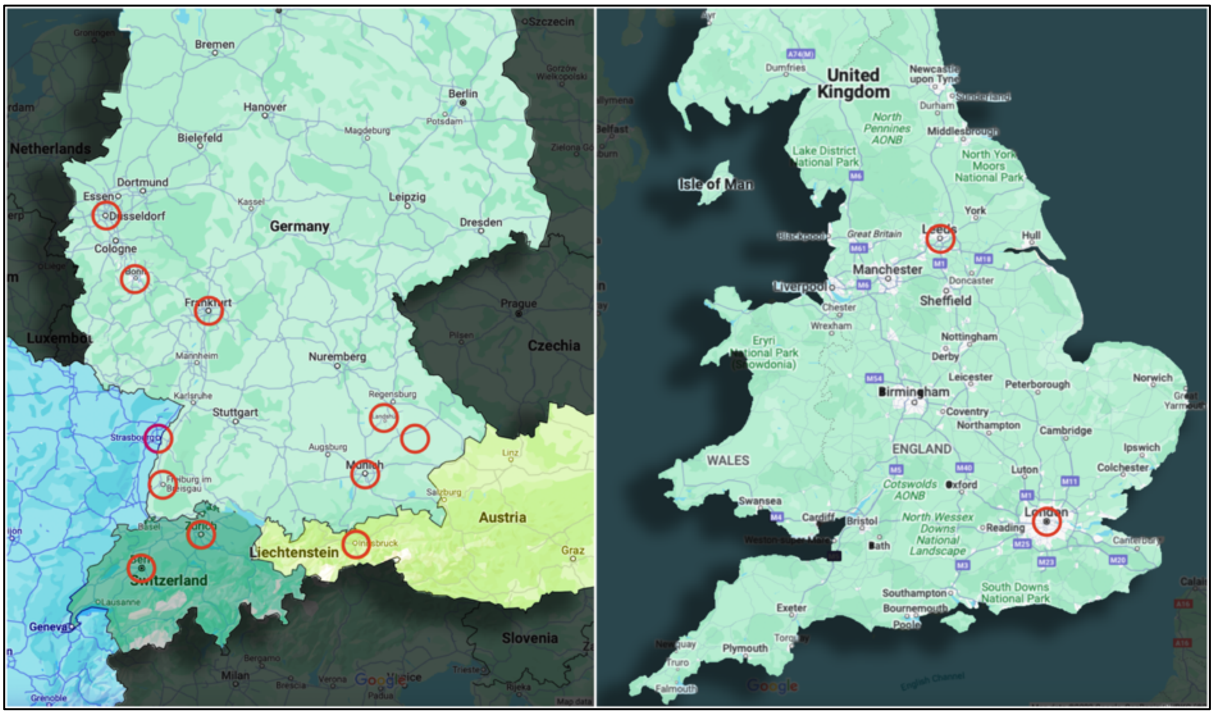

Figure 26. The study included 154 participants across 16 centres in five nations, comprising universities, private dental laboratories, and dental practices, ensuring a diverse range of professional settings.

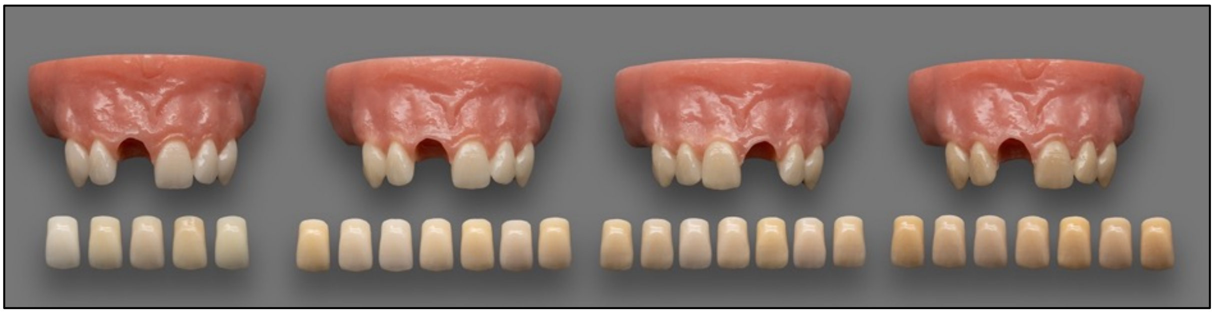

Figure 27. Hyper-realistic phantom models were fabricated in four base shades to closely resemble natural teeth, enabling a more realistic assessment of colour differences in a clinical setting.

Visual assessments were conducted under controlled lighting conditions (D65 simulation, 1000 lx) against a neutral grey background to minimise contextual colour adaptation effects (CIE, 2015) (**Figure 28**). Observers rated colour matches using a 0-100% scale, with 0% indicating the poorest match and 100% representing a perfect match. To ensure randomisation, sample presentation order was varied across observers.

Figure 28. A total of 105 dental practitioners and 49 dental technicians participated in the psychophysical experiment. Observers assessed sample pairs under controlled lighting (6500K, 1000 lx) against a Munsell N5 neutral grey background, ensuring standardised viewing conditions.

Six colour measurement devices were selected based on their relevance in clinical and research applications. These included a spectroradiometer (PR-670), a spectrophotometer (Vita Easyshade V), two multispectral cameras (SpectroShade Micro II, Rayplicker Cobra), a calibrated camera-based system (Optishade), and a digital imaging system (eLAB). Each device employed a distinct measurement approach, including different illumination geometries and sensor technologies (**Figure 29**).

Figure 29. Six colour measurement devices, including spectrophotometers, multispectral cameras, and a spectroradiometer, were selected for their relevance in clinical and research applications, each employing distinct measurement approaches.

All sample pairs were measured three times in three regions (cervical, middle, incisal) to account for potential variations across the tooth surface. Colour differences were computed using ΔE_{ab}, ΔE_{00}, and CAM16-UCS equations. The *STRESS* index was used to quantify visual-instrumental agreement (100 – *STRESS*), with lower *STRESS* values indicating better agreement (García et al., 2007). Additionally, a MATLAB-based optimisation routine was employed to adjust the weighting parameters (S_L, S_C, S_H) within each equation to enhance their performance. The *F*-statistic was used to assess whether differences in visual-instrumental agreement were statistically significant (Melgosa et al., 2011).

2.2.3 Results

The arithmetic mean of visually scaled colour differences provided the best correlation with instrumental ΔE values, supporting its use as a reference for assessing visual-instrumental agreement. Baseline *STRESS* index values for ΔE_{ab}, ΔE_{00}, and CAM16-UCS ranged from 18 to 40 across different devices, with visual-instrumental agreement varying accordingly. The highest agreement was observed with the eLAB system, which achieved an 82% visual instrumental agreement using ΔE_{ab}, whereas the SpectroShade Micro II demonstrated the lowest agreement at 60%. A comparison of the different colour difference equations revealed that ΔE_{ab} consistently outperformed ΔE_{00} and CAM16-UCS in the specific context of dental colour measurement. The mean agreement was 74% for ΔE_{ab}, 70% for ΔE_{00}, and 64% for CAM16-UCS. After optimisation, agreement improved across all equations and devices. The optimised ΔE_{ab} ($\Delta E'$) yielded an average agreement of 79%, while the optimised ΔE_{00} and CAM16-UCS equations achieved 78% and 76%, respectively. The F-statistic analysis confirmed statistically significant differences in visual-instrumental agreement across devices, leading to the rejection of the first null hypothesis. Furthermore, the optimisation of colour difference equations resulted in a significant improvement in agreement, leading to the rejection of the second null hypothesis.

2.2.4 Discussion

The findings of this study underscore the importance of selecting an appropriate colour difference equation for dental applications. While ΔE_{00} and CAM16-UCS offer improved perceptual uniformity in broader applications, ΔE_{ab} remains highly effective within the restricted gamut of natural tooth colours. The results suggest that the context in which a colour difference equation is applied should be carefully considered, as different equations may yield varying levels of agreement depending on the colour space being evaluated.

A key finding was the substantial improvement in visual-instrumental agreement following the optimisation of colour difference equations. By tailoring the S_L, S_C, and S_H parameters to each device, agreement levels were significantly enhanced, demonstrating that perceptual alignment can be improved through mathematical refinement (Huang et al., 2015). This highlights the potential for device-specific calibration to enhance the clinical accuracy of instrumental shade selection.

One limitation of this study was the restricted number of visually scaled sample pairs, dictated by the availability of systematically ordered shade tabs. Additionally, inter-observer variability remained a factor, with an average variation of 45 *STRESS* units. Despite these challenges, the methodology employed, which prioritised realistic sample pairs, offered valuable insights applicable to tooth colour measurement in clinical settings.

2.2.5 Conclusion

In conclusion, discrepancies between visual and instrumental assessments are primarily influenced by the choice of colour difference equation rather than device performance alone. By optimising colour difference equations for specific measurement devices, practitioners can significantly improve visual-instrumental agreement, ultimately enhancing the reliability of instrumental shade matching in dentistry. These findings support the need for further research into perceptually relevant colour difference metrics, refining computational models to better align with human vision and clinical needs.

2.3 The gamut of natural tooth colours

2.3.1 Introduction

Achieving accurate shade matching remains a critical challenge in restorative dentistry, particularly for single anterior restorations. Clinicians frequently encounter difficulties in this area, leading to high remake rates and patient dissatisfaction (Paravina et al., 1997; Kawaragi et al., 1990; Corcodel et al., 2011, Lawson et al., 2021; Alnusayri et al., 2022). While instrumental shade measurement methods offer improved objectivity and repeatability, visual shade selection remains the most commonly used approach in clinical practice despite its subjectivity and inconsistency (Chen et al., 2012; Tabatabaian et al., 2021, Morsy and Holiel, 2023). The Vita Classical and Vita 3D-Master shade guides are the most widely used tools for visual shade selection (Paravina et al., 2009). However, studies have shown that their coverage error (CE), the average colour difference between a natural tooth shade and the closest available shade tab, often exceeds the threshold for clinical acceptability, with reported values ranging between 2.5 and 8.4 ΔE_{ab} units (**Table 6**).

Efforts have been made to design hypothetical shade guides that either minimise CE while maintaining the same number of tabs or simplify the shade-matching process with fewer tabs (Analoui et al., 2004; Paravina et al., 2007; Cocking et al., 2010). However, these proposals have yet to be implemented in commercially available shade guides. Determining the optimal number of shades required for an ideal shade guide depends on an accurate understanding of the gamut of natural tooth colours. Cardinality, a mathematical concept that quantifies the number of distinct elements in a set (Cantor, 1879), provides a framework for estimating the number of unique, visually distinguishable natural tooth colours based on a large dataset of CIELAB measurements.

Table 6. Average CE (ΔE_{ab}) results for the Vita Classical (VC) and Vita 3D-Master (3D) shade guides from available studies.

Author	Year	Natural Teeth (n)	CE VC	CE 3D
(O'Brien et al., 1991)	1991	335	3.0	X
(Analoui et al., 2004)	2004	150	3.1	2.7
(Paravina et al., 2007)	2007	1064	4.1	X
(Bayindir et al., 2007)	2007	359	5.4	3.9
(Yuan et al., 2007)	2007	933	X	6.2
(Li et al., 2009)	2008	60	6.9	3.4
(Cocking et al., 2009)	2009	541	3.5	3.0
(Hassel et al., 2009)	2009	313	X	5.0
(Dozic et al., 2010)	2010	198	2.5	2.0
(Haddad et al., 2011)	2011	2067	X	6.2
(Wang et al., 2014)	2014	236	4.2	X
(Ballard et al., 2017)	2016	103	6.5	X
(Rao and Joshi, 2018)	2018	700	7.2	8.4
(Tabatabaian et al., 2022)	2022	1182	3.3	2.9
(Ruiz-López et al., 2022)	2022	735	2.5	3.2
		Mean CE	**4.4**	**4.2**
		SD	1.7	2.0

** Note: X = not investigated*

This study employed the eLAB system, a calibrated imaging method that uses DSLR or mirrorless cameras with cross-polarised illumination (Wander and Gordon, 1987) to eliminate specular reflections and ensure consistent colour measurement across different digital cameras (Hein and Zangl, 2016; Hein et al., 2017; Hein et al., 2021; He et al., 2020; Farah et al., 2022; Yilmaz et al., 2023). The system has been validated against spectrophotometric analysis (Bezerra et al., 2024) and used in studies assessing tooth colour changes (Kashash et al., 2024) composite materials (Notarantonio and Seay, 2023), and bleaching treatments (Salehi et al., 2022). The study aimed to estimate the number of unique natural tooth colours, identify hypothetical Super Shades that best represent this gamut, and compare their coverage error and frequency distribution against commonly used shade guides.

2.3.2 Materials and methods

This study received ethical approval under reference number 1366, complying with the EU's General Data Protection Regulation (GDPR). Data were collected over 29 months from 121,198 RAW images submitted by users of the eLAB_prime shade matching software across 98 countries. A multi-step AI-based filtering process was applied to ensure data quality, using convolutional neural networks to assess image exposure, reference card presence, and duplication detection through perceptual hashing (Vishal et al., 2006; Xudong and Wang, 2012; Li et al., 2022; Jeong et al., 2024). Object detection and semantic segmentation models excluded images containing artificial restorations (Dong et al., 2014). After visual verification by five master dental technicians, 2038 high-quality images were selected for analysis, covering 8153 untreated maxillary and mandibular anterior incisors.

Tooth colour measurements were taken from the incisal and medio-cervical regions of the labial surface, with the final CIELAB values calculated as the mean of these measurements. Colorimetric data for Vita Classical (VC) and 3D-Master (3D) shade tabs were also obtained using the eLAB system, ensuring consistency with the natural tooth colour dataset.

To determine the number of unique natural tooth colours, a convex hull approach was applied using an α-shape model (Edelsbrunner and Mücke, 1994) with $\alpha = 2\ \Delta E_{ab}$ units, balancing density and perceptibility thresholds (Paravina et al., 2015). A custom Python routine was used to quantify cardinality by representing each tooth colour as a sphere within a hexagonal close-packed model, ensuring a minimum perceptual difference of $1.2\ \Delta E_{ab}$ between distinct colours (Morovic and Morovic, 2023). This provided an estimate of the number of visually distinguishable natural tooth colours.

To establish an optimised set of super shades, the α-shape and sphere-packing approach were repeated using a sphere diameter of 2.7 ΔE_{ab}, corresponding to the threshold for clinical acceptability (Paravina et al, 2015). This determined the minimum number of shades required to effectively represent the natural tooth colour gamut while maintaining practicality for clinical application.

The CE and coverage error percentage (CEP) for VC, 3D, and the super shades were computed using the ΔE_{ab} equation in MATLAB under Illuminant D65 with the CIE 1931 standard observer (CIE, 2016). For each of the 8153 tooth colours, the closest reference shade tab was identified, and its frequency of selection was recorded. The mean CE was calculated as the average minimum ΔE_{ab} value across all sample tooth colours. The CEP was determined as the proportion of occurrences for each shade tab normalised to the total dataset, enabling a comparative analysis of shade-matching effectiveness.

2.3.3 Results

Using a perceptibility threshold of 1.2 ΔE_{ab}, 1173 unique natural tooth colours were identified (**Figure 30**). When applying the acceptability threshold of 2.7 ΔE_{ab}, 92 super shades were determined, representing the minimum number required for an ideal shade guide (**Figure 31**). Summaries of the CE and CEP results for VC, 3D, and the super shades are provided in **Table 7**. The VC and 3D shade guides exhibited CEs of 4.1 and 3.3 ΔE_{ab}, respectively, with only 1.1% and 3.0% of their shades falling within the perceptibility threshold. In contrast, the super shades achieved a significantly lower CE of 1.2 ΔE_{ab}, with 33.8% of shades within the perceptibility threshold and only 0.3% exceeding the acceptability threshold.

Figure 30. Representation of visually discernible natural tooth colours, depicted in sRGB colour space.

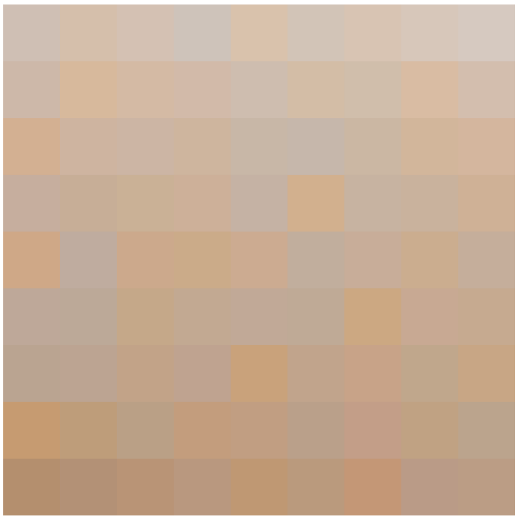

Figure 31. Representation of Super Shades needed to cover the gamut of natural tooth colours, depicted in sRGB colour space.

Table 7. CE and CEP with standard deviations (SD) for the Vita Classical (VC) and 3D-Master (3D) shade guides. CEP ≤PT refers to the percentage of natural tooth colours within the perceptibility threshold (PT, ΔE_{ab} = 1.2), while CEP >PT, ≤AT represents colours exceeding PT but remaining within the acceptability threshold (AT, ΔE_{ab} = 2.7). CEP >AT indicates colours falling outside clinically acceptable limits.

Shade Guide	CE (ΔE_{ab}) (SD)	CEP ≤PT (SD)	CEP >PT, ≤ AT (SD)	CEP >AT (SD)
VC	4.1 (1.8)	1.1 % (0.2)	24.3 % (0.4)	74.6 % (1.6)
3D	3.3 (1.4)	3.0 % (0.2)	27.8 % (0.7)	70.3 % (1.2)
Super Shades	1.2 (0.4)	33.8 % (0.2)	65.9 % (0.3)	0.3% (1.5)

2.3.4 Discussion

The present study aimed to estimate the number of distinct tooth colours based on the analysis of 8,153 in-vivo CIELAB measurements, and to determine the coverage error of the most common shade guides as well as a set of hypothetical Super Shades designed to best abridge the natural tooth colour gamut. The findings showed that the current shade guides, while widely used, have significant limitations in covering the full spectrum of natural tooth colours. In contrast, the hypothetical super shades offered a much lower coverage error, though the impracticality of a physical shade guide with 92 samples is apparent.

Historically, Clark (Clark, 1933) visually assessed over 6,000 natural teeth to establish their hue, chroma, and value range based on Munsell Colour Notation, resulting in a shade guide with 60 samples. Another shade guide developed by Hayashi (Hayashi, 1967) in 1967 consisted of 125 samples. Goodkind and Schwabacher (Goodkind and Schwabacher, 1987) measured 2,830 natural anterior teeth using a contact type colorimeter (Spectrascan), converting CIE tristimulus values to Munsell parameters for qualitative comparison with three shade guides, due to the lack of an appropriate colour difference metric.

The adoption of the CIELAB system by O'Brien et al. (1991) allowed for quantitative assessment of the CE. Subsequent studies have varied widely in their reported CEs due to differences in population sizes, age distribution, and ethnicities. Available studies reported average CEs of 4.4 ΔE_{ab} units for the VC and 4.2 ΔE_{ab} for the 3D shade guide (**Table 6**), similar to the findings of the present study.

Although a CE of 3 or 4 ΔE_{ab} may seem small, the practical limitations of the two investigated shade guides become clearer when considering the CEP. For the VC shade guide, previous studies have reported CEP values beyond AT ranging from 56% to 71% (Paravina et al., 2007; Cocking et al., 2009), with the present study indicating a higher CEP of 75%. For the 3D shade guide, reported CEP values beyond AT range from 45% to 88% (Cocking et al., 2009; Hassel et al., 2009, Rioseco and Wagner, 2021; Ruiz-López et al., 2022), compared to the present finding of 70%. It has been suggested that shade matching can be improved through dedicated training, with several studies having observers match shade tabs with concealed designations before and after training (Capa et al., 2011; Ristic et al., 2016; Samra et al., 2017; Alfouzan et al., 2017). While these efforts are commendable, the conclusions that training improves shade matching, contrast with the findings of the present study which demonstrate the significant practical challenges associated with achieving an accurate shade match.

Furthermore, a significant body of research has sought to determine the accuracy of shade measurement devices (Tabatabaian et al., 2021; Crespo et al., 2022; Morsy and Holiel, 2023; Rashid et al., 2023; Dudkiewicz et al., 2024) and, more recently, intraoral scanners (Mehl et al., 2017; Tabatabaian et al., 2022) by comparing the shade selections made by visual observers with those made by the test device (Hampé-Kautz et al., 2020; Czigola et al., 2021), or by using another device arbitrarily designated as the gold standard instead of a visual observer (AlSaleh et al., 2012; Alshiddi and Richards, 2015; Brandt et al., 2017; Klotz et al., 2020; Mahn et al., 2021). It is common practice to count how often a reference device or observer, and a test device select matching shades to draw conclusions about the test device's accuracy (Kim-Pusateri et al., 2009; Moodley et al., 2015; Mehl et al., 2017; Brandt et al., 2017; Mahn et al., 2021; Czigola et al., 2021; Klotz et al., 2020). However, in light of the findings of the present research, this approach is problematic, raising concerns about whether these discrepancies truly reflect the device's accuracy or are simply the result of the coverage error inherent in the shade guides used (Kim, 2018). Instrumental shade measurement has been praised for its accuracy and objectivity over visual shade selection (Rashid et al., 2023; Dudkiewicz et al., 2024), but given the present results, one must question the true benefit of instrumental shade measurement when its readings are ultimately expressed in terms of the same limited VC and 3D Master shades for clinical convenience.

The reported frequencies of individual shades with the lowest CEP also vary considerably. The findings of this study are generally in agreement with those of Paravina et al. (2007) and Ruiz Lopez et al. (2022) but differ from Bayindir et al. (2007) and Tabatabaian et al. (2022), who both reported that the VC shade ‘D3’ had the lowest CEP frequency. Research focusing on elderly populations consistently showed a bias towards a higher CEP frequency for darker tooth shades such as ‘A4’, ‘C4’, and ‘B4’ (Hishida, 2002; Cocking et al., 2009; Ueda et al., 2010).

In the current study, using cardinality computations estimated 1,173 unique tooth colours at a PT of 1.2 ΔE_{ab} units. For an ideal shade guide, it is estimated that 92 discrete shades are necessary when the AT is set at 2.7 ΔE_{ab} units. This finding contrasts with previous studies which suggested fewer shade tabs for acceptable coverage (Analoui et al., 2004; Cocking et al., 2010; Herrera et al., 2024). This discrepancy may be attributed to several factors, including the size and demographics of the analysed populations, the computational methods used for optimisation, the chosen colour difference equations, and the specific PT and AT values considered. Paravina et al. (2007) had shown that an optimised shade guide with 24 discrete samples resulted in a CE of 2.0 ΔE_{ab} units. Cocking et al. (2010) found that 10 shade tabs could achieve a mean CE of 3.2 ΔE_{ab} units, covering 63% of the population at an AT of 3.5 ΔE_{ab} units. Dozic et al. (2010) evaluated the CE of another hypothetical shade guide system and found that 26 shade tabs in the standard range and 33 in the expanded range were needed for optimal coverage when AT was set to $\Delta E_{ab} \leq 1.6$, based on a relatively small population of 198 natural teeth. A recent study by Herrera et al. (2024) used computational clustering to optimise shade tab distribution, concluding that 4 to 6 shades could outperform existing shade guides.

The present study's use of cardinality computation showed that a set of 92 super shades could potentially cover the gamut of natural tooth colours, with a CEP of only 0.3% outside the threshold for clinical acceptability. Interestingly, this value sits exactly in the middle between the number of unique shades suggested by Clark and Hayashi, both of whom used visual observation and the Munsell notation.

While it is clear that such a physical shade guide would be highly impractical, the insights from the present study may still prove beneficial in the near future with the rise of digital tools for shade matching (Hein et al., 2021; Awdaljan et al., 2024) and new technology like 3D printing (Espinar et al., 2022).

It is important to recognise that the results of the cardinality computation depend on specific input parameters, such as the definition of alpha-radii and the chosen visual threshold values. Consequently, the results are accurate for colour differences computed using Euclidean distance but may not hold for other colour difference equations. This is because the volume of the alpha hull, and how many spheres can be packed within it, is determined by the visual thresholds and the colour difference equation used, which in turn define the diameter of each sphere. However, even with variations in these parameters, the overall finding remains consistent: a significantly larger number of shade tabs is needed for an ideal shade guide than is currently available.

2.3.5 Conclusion

The present study comprises the largest gamut of natural tooth colours ever published. Unfortunately, the results show that the likelihood of selecting a shade that is either clinically imperceptible or at least acceptable is one in four for the VC shade guide (25%) and nearly one in three for the 3D-Master shade guide (31%). On the other hand, a physical shade guide to achieve almost complete coverage is estimated to require 92 discrete shade tabs. These findings highlight the inherent challenges when trying to select the right shade during daily clinical practice.

2.4 The visual-instrumental agreement scale (*VIAS*)

2.4.1 Introduction

The accuracy and precision of shade measurement devices have been widely discussed in dental research (Tabatabaian et al., 2021; Rashid et al., 2023). While intraoral scanners (IOS) are primarily used for digital impressions, their ability to measure tooth colour is increasingly relevant (Mehl et al., 2017; Yoon et al., 2018). However, the terms Accuracy and Precision are often used interchangeably in dentistry, creating confusion. Unlike marginal fit assessments, where Precise and Accurate imply the same outcome, in colour science, these terms have distinct meanings. Accuracy refers to a device's ability to match a reference standard, while precision describes the repeatability of measurements (Berns, 2019).

Traditional colorimetric accuracy is determined through calibration against recognised standards (Clarke, 1972), typically conducted by national standardisation laboratories (Malkin, 1987). Using a single device as a Gold Standard for dental shade measurements is problematic, as different spectrophotometers produce varying results for the same sample (Seghi, 1990; Lehmann et al., 2010). When measuring non-uniform samples like natural teeth, psychophysical experiments, where expert observers visually assess colour differences, offer a more reliable method for evaluating device performance (Halsey, 1954; Kuehni and Marcus, 1979).

The grey scale method (Luo and Rigg, 1986) is widely used in psychophysical studies to compare visual and computed colour differences. The perceived colour difference is denoted as ΔV, while the computed colour difference, ΔE, is calculated using a colour difference formula. The *STRESS* index quantifies the agreement between ΔV and ΔE and is considered the gold standard for evaluating colour difference equations (García et al., 2007; Melgosa et al., 2008).

This study introduces the Visual Instrument Agreement Scale (*VIAS*), a novel method for evaluating visual-instrumental agreement in dental colourimetry. Using in-vivo clinical data from four IOS devices and one spectrophotometer, the study tested the null hypothesis that there would be no significant differences in visual-instrumental agreement among the devices.

2.4.2 Materials and methods

Ethical approval was obtained (EK-Freiburg 21-1169). Sixteen participants under the age of 35 with unrestored teeth were included. The study focused on teeth 21 (left maxillary central incisor), 23 (left maxillary canine), and 26 (first left maxillary molar). Data collection was anonymous, and access was restricted to the project management team.

Five devices were evaluated: four IOS devices (Primescan, Medit i700, CS3700, and Trios 3) and one spectrophotometer (Easyshade V, Vita Zahnfabrik, Germany). IOS devices are gaining interest for tooth colour measurement, while the Easyshade V is widely used as a reference device. Visual shade assessment was performed by an expert observer using a 3D Master shade guide, under controlled lighting conditions with large north-facing windows and colour-corrected ceiling lighting.

Instrumental shade measurements followed a standardised sequence: Easyshade V, Primescan, Medit, Carestream, and Trios. Easyshade V measured three regions (incisal, medial, and cervical), and the average was used for analysis. IOS scans captured the full maxilla, and each device's software suggested the closest shade tab. Patients were given water between measurements to prevent dehydration-induced colour changes.

Spectral data from Easyshade V was processed using ES_Helper software (Vita Zahnfabrik, Germany) to extract reflectance data from 400–700 nm. IOS scans were imported into MeshLab, converted to PNG images, and processed in MATLAB to extract sRGB values, which were converted to CIELAB coordinates using Illuminant D65 and the CIE 1931 standard observer (CIE 2016).

VIAS was computed by comparing ΔV (observer-selected closest shade match) with ΔE (device-recommended closest shade) (**Figure 32**).

The *STRESS* index quantified visual-instrumental agreement, while the *F*-statistic assessed significant differences between devices. *VIAS* was derived as follows:

$$VIAS\ (\%) = 100 - STRESS$$

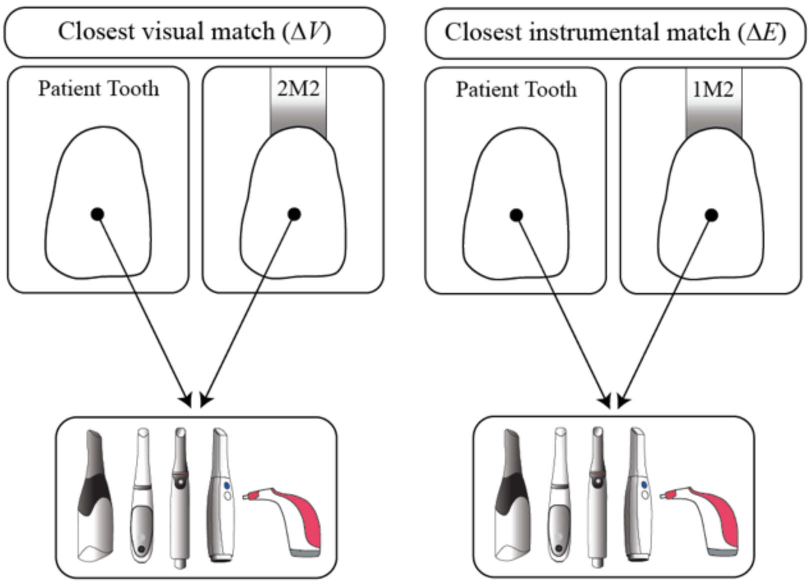

Figure 32. Example of *VIAS* computation. The observer selects '2M2' as the closest match, while the device selects '1M2' based on the smallest computed colour difference. Three CIELAB measurements are used: the target tooth, the observer-selected shade, and the device-

selected shade. The visual colour difference (ΔV) and computed colour difference (ΔE) are inputs for *STRESS* index calculation, forming the basis for *VIAS*.

2.4.3 Results

STRESS values ranged from 18 to 43, corresponding to *VIAS* scores between 57% and 82% (**Table 8**). Carestream CS3700 demonstrated the highest agreement (82%), significantly outperforming other devices. Primescan (76%), Medit i700 (75%), and Trios 3 (72%) exhibited similar performance. Easyshade V had the lowest agreement (57%), significantly worse than all other devices.

Table 8. Results for the *STRESS* index and *VIAS* per device.

Device	*STRESS*	*VIAS* (%)
Carestream	18	82
Trios	24	76
Primescan	25	75
Medit	28	72
Easyshade V	43	57

The *F*-test confirmed that Carestream outperformed all other devices, while no significant differences were found between Primescan, Medit, and Trios. Easyshade V performed significantly worse than all other devices.

2.4.4 Discussion

This study presents *VIAS* as a novel method for assessing visual-instrumental agreement in dental colorimetry. Inspired by psychophysical techniques used in textile colour fastness testing (ISO, 1994), *VIAS* simplifies the assessment by comparing instrumental colour differences with human perception. Unlike traditional accuracy measurements based on reference standards *VIAS* eliminates the assumption that any single device provides “true” colour values.

The results confirm that intraoral scanners generally achieve better visual-instrumental agreement than spectrophotometers, challenging the assumption that spectrophotometers are the gold standard for tooth colour measurement. The findings align with a multi-centre study (Hein et al., 2024) that also employed the *STRESS* index, demonstrating consistency between different psychophysical methodologies.

The lack of clear definitions for accuracy and precision in dental colorimetry has led to widespread misinterpretations. Many studies incorrectly equate inter-device agreement with accuracy or use terms such as Reliability and Reproducibility interchangeably (Tabatabaian et al., 2021; 2022). This confusion has contributed to the persistence of methodologies that do not reflect the perceptual reality of shade matching in clinical practice.

A key limitation of this study is the use of a single expert observer. Ideally, a larger panel of at least 20 observers would provide more robust data (Berns, 2019). However, similar methodologies are commonly used in foundational colour science research. MacAdam's colour discrimination ellipses (MacAdam, 1942), derived from a single observer, remain a cornerstone of just noticeable colour difference studies (Georgoula et al., 2016).

Despite this limitation, the *VIAS* methodology is accessible to researchers and clinicians. A freely available toolbox (www.saschahein.co.uk/downloads) enables easy computation of *VIAS* scores using MATLAB, Python, or Excel. No coding experience is required, as alternative software like Classic Color Meter can also extract CIELAB values from images (Sampaio et al., 2019; Dias et al., 2023).

2.4.5 Conclusion

By shifting the focus from arbitrary accuracy claims to visual perception, *VIAS* offers a more clinically relevant measure of shade-matching performance. The method is easily replicable using the freely available toolbox, making it a valuable tool for researchers and clinicians seeking to improve the reliability of instrumental shade selection in dentistry.

2.5. Percent correct shade identification

2.5.1 Introduction

Accurate shade matching is essential in restorative dentistry, particularly when relying on digital tools such as intraoral scanners (IOS) and spectrophotometers. While these devices have gained popularity for their ease of use and efficiency, their performance in practical clinical applications remains a subject of debate. Many studies have attempted to evaluate the Accuracy of shade measurement devices by comparing their outputs against a reference device, often the Vita Easyshade spectrophotometer. However, this approach confounds accuracy with inter-device agreement, leading to misleading conclusions about device reliability (Tabatabaian et al., 2021; Rashid et al., 2023).

In dental colorimetry, accuracy and precision have distinct definitions. Accuracy refers to the closeness of a measurement to a reference standard, while precision measures the consistency of repeated measurements. Unlike laboratory-grade spectrophotometers, dental shade-matching devices often employ mixed measurement techniques and non-standard illumination geometries, making traditional accuracy assessments challenging (Clarke, 1972).

Rather than evaluating Accuracy in the conventional sense, this study introduces a practical metric: percent correct shade identification. By comparing the device-selected shade to a visual shade assessment performed by an expert observer, the study categorises results into three clinically relevant groups: Exact Match, Acceptable Match (clinically acceptable differences within 2.7 ΔE_{ab}), and Mismatch Type A (moderately unacceptable but still within a reasonable range for clinical use) Paravina et al., 2015).

2.5.2 Materials and Methods

This study received ethical approval (EK-Freiburg 21-1169) and was conducted in accordance with the Declaration of Helsinki. Sixteen participants with natural, unrestored teeth were included. The teeth evaluated were the left maxillary central incisor (tooth 21), left maxillary canine (tooth 23), and first left maxillary molar (tooth 26). Visual shade assessments and instrumental measurements were conducted under controlled lighting conditions to ensure consistency.

Five devices were evaluated: four IOS devices (Primescan, Medit i700, CS3700, Trios 3) and one spectrophotometer (Easyshade V, Vita Zahnfabrik, Germany). Visual shade matching was performed by an expert observer using the Vita 3D Master shade guide, selecting the closest match for each tooth based on three regions: incisal, middle, and cervical.

Instrumental measurements were performed in the same three regions. The Easyshade V spectrophotometer recorded reflectance data from 400–700 nm, processed using ES_Helper software (Vita Zahnfabrik, Germany) to extract CIELAB coordinates. IOS scans were processed in MeshLab and analysed in MATLAB to convert sRGB values into CIELAB coordinates. Each device's closest matching shade selection was recorded.

For each device, the shade selected by the instrument was compared to the expert observer's selection. The results were categorised as:

1. Exact Match: The device-selected shade matched the observer's choice.
2. Acceptable Match: The device-selected shade differed by ≤2.7 ΔE_{ab}
3. Mismatch Type A: The selected shade differed by >2.7 but ≤5.4 ΔE_{ab}

The clinical pass rate was defined as the sum of the three categories, representing the percentage of cases where the device produced a clinically acceptable result. Statistical analysis was performed using chi-square tests with a 95% confidence level ($p = 0.05$).

2.5.3 Results

Averaged results across the three tooth regions (incisal, middle, cervical) showed considerable variability among devices (**Figure 33**). Easyshade V achieved the highest Exact Match rate in the incisal (20.3%) and middle regions (19.4%), while Carestream recorded the highest Acceptable Match rate across all regions. Carestream also had the highest Mismatch Type A rate, indicating that while it selected shades closer to the observer's choice, it sometimes produced moderately unacceptable results.

Averaged across all three regions, Carestream achieved the highest clinical pass rate (78.2%), followed by Easyshade V (63.5%), Primescan (51.2%), Trios (39.5%), and Medit (31.3%). Exact Match rates varied, with Trios achieving the highest (22.1%) and Primescan the lowest (11.3%). The chi-square test confirmed statistically significant differences between devices across all categories ($p < 0.05$) (**Table 9)**.

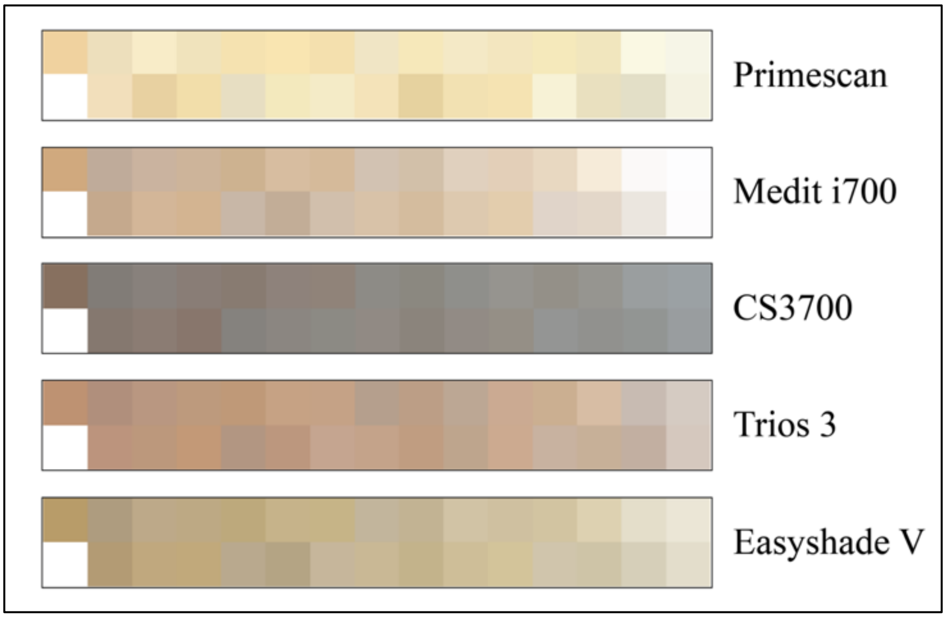

Figure 33. sRGB swatches representing measured tooth colours for each device, averaged across incisal, middle, and cervical regions. The variations in colour appearance demonstrate the differences in colour measurement and processing between devices.

Table 9. Exact, acceptable (>1.2, ≤2.7 ΔE_{ab}), and type A mismatch (<2.7, ≤5.4 ΔE_{ab}) percentages for each device, averaged across cervical, middle, and incisal regions. The clinical pass rate sums these categories, reflecting the likelihood of a clinically acceptable shade selection. Statistical significance was assessed using a chi-square test (p = 0.05, 95% confidence).

Device	Exact match	Acceptable match	Mismatch Type A	Clinical Pass Rate
CS3700	16.6 %	14.0 %	47.7 %	78.2 %
Easyshade V	20.3 %	5.1 %	38.1 %	63.5 %
Primescan	11.3 %	12.3 %	27.6 %	51.2 %
Trios 3	22.1 %	4.3 %	13.2 %	39.5 %
Medit i7000	20.6 %	0 %	10.7 %	31.3 %
χ^2	12.04	58.65	123.66	97.18
$p = 0.05$	$p < 0.0171$	$p < 0.000$	$p < 0.000$	$p < 0.0001$

2.5.4 Discussion

This study assessed the reliability of IOS and spectrophotometers for shade selection in clinical dentistry, focusing on practical usability rather than the conventional but often misleading concept of Accuracy. By categorising results into Exact Match, Acceptable Match, and Mismatch Type A, the study introduced a clinically relevant way of interpreting device performance.

Carestream's high clinical pass rate suggests it is the most reliable device for shade selection. Its ability to frequently produce either an Exact or Acceptable Match makes it a strong candidate for practical clinical use. Easyshade V also performed well, reinforcing its established role as a widely used shade measurement tool.

In contrast, Primescan and Trios exhibited performance close to or below the 50% threshold, raising concerns about their reliability when used without visual confirmation. Medit, with the lowest pass rate (31.3%), showed the least agreement with visual assessments, suggesting that its use should be approached cautiously in shade selection.

The study's results align with psychophysical principles used in visual threshold research, where a 50% cutoff is often applied as a standard for distinguishing reliable from unreliable outcomes (Blackwell, 1953). The findings also highlight the practical limitations of certain IOS devices, demonstrating that while they offer a convenient solution for digital impressions, their colour-matching capabilities vary significantly.

One limitation of the study is the reliance on a single expert observer. Although expert visual assessment is a common standard in dental colour research, a larger observer panel would provide greater statistical robustness. Nevertheless, the methodology ensures consistency in the comparison of instrumental and visual assessments (Berns, 2019).

2.5.5 Conclusion

This study provides a practical evaluation of shade selection reliability among IOS and spectrophotometric devices. By introducing the clinical pass rate as a key metric, it offers a meaningful way to interpret device performance in real-world applications.

Carestream demonstrated the highest reliability for shade selection, followed by Easyshade V. Primescan and Trios performed around or below the 50% threshold, indicating that their use should be carefully considered in cases where precise shade selection is required. Medit exhibited the lowest reliability, suggesting that its shade selection feature may not yet be suitable for standalone use in clinical practice.

These findings emphasise the importance of selecting the appropriate device for shade matching, particularly as intraoral scanners continue to gain popularity in restorative dentistry. Future studies incorporating a larger panel of expert observers may further validate these results and provide deeper insights into the practical application of shade selection technologies.

2.6 Device dependent visual thresholds for the expert observer

2.6.1 Introduction

Accurate shade matching is essential in restorative dentistry, as even minor colour discrepancies can impact clinical outcomes and patient satisfaction (Samorodnitzky-Naveh et al., 2007). While instrumental methods have improved objectivity, visual perception remains the gold standard for evaluating colour differences. Perceptibility and acceptability thresholds (PT and AT) provide a structured approach to assessing colour differences (Paravina et al., 2015), yet they have often been applied across different devices without consideration for measurement variability.

Previous studies have derived PT and AT values using visual assessments of monochromatic ceramic samples, applying ΔE_{ab} and ΔE_{00} colour difference formulas (Paravina et al., 2015). These thresholds have been integrated into industry standards (ISO, 2016), but there is increasing evidence that they may not be universally applicable to all colour measurement devices (Seghi, 1990; Alghazali et al., 2018). Differences in measurement geometry, spectral sensitivity, and calibration protocols introduce significant variability in CIELAB values across different instruments, raising concerns about whether a universal PT and AT can be meaningfully applied.

With the widespread adoption of intraoral scanners and diverse spectrophotometric technologies, it is necessary to reassess whether existing visual thresholds remain applicable across different devices. Additionally, despite the widespread adoption of ΔE_{00}, some tooth colour measurement devices continue to use ΔE_{94}, raising questions about its relevance and performance in visual-instrumental agreement assessments. This study evaluated device-dependent visual thresholds, investigating the variability in PT and AT values across instruments and assessing the suitability of ΔE_{94} for shade-matching applications.

2.6.2 Materials and Methods

Ethical approval (EK-Freiburg 21-1169) was obtained before the study. A total of 154 expert observers, including dental practitioners and laboratory technicians, participated. All observers passed the Ishihara colour vision test to rule out deficiencies. The study was conducted across 16 professional settings, including dental schools, private practices, and commercial laboratories, ensuring diverse environmental conditions and a broad representation of professional expertise.

A magnitude estimation (ME) technique was employed to quantify visual perception of colour differences between maxillary central incisors. Observers were asked to assess colour match quality using a percentage scale (0-100%) and respond to two key questions:

1. "Can you see a colour difference?"
2. "Would you accept this colour difference if this were your patient?"

The aim was to derive device-specific PT and AT values by analysing the proportion of observers who perceived and accepted differences across a range of colour deviations.

Custom-made hyper-realistic phantom models were fabricated to replicate natural tooth morphology, translucency, and surface texture. The samples represented four colour centres within the CIELAB space, with 26 visually scaled sample pairs generated for assessment.

Observations were conducted under standardised lighting conditions using a calibrated viewing cabinet (DLS Color Viewing Light v7, JustNormlicht, Germany) with a D65 illuminant at 1000 lx. Background reflectance was controlled using a Munsell N5 neutral grey backdrop to minimise contextual colour adaptation effects. Colour measurements were performed with seven instruments (Table 10). Each instrument followed a standardised measurement protocol to ensure comparability. Reflectance data were captured at 400 – 700 nm and converted to CIELAB coordinates under the CIE D65 illuminant for the CIE 1931 standard observer. Three colour difference formulas were used for computation, ΔE_{ab}, ΔE_{00} and ΔE_{94}.

Pairwise subtraction of colour differences between devices was performed to evaluate inter-instrument variability. Visual thresholds were computed using the Model-Free Estimation Technique (Zychaluk and Foster, 2009), which applies local linear fitting to estimate PT and AT values without assuming a parametric model.

Statistical analyses were conducted in MATLAB (R2024b) and STATA (v17.0). The *STRESS* index was used to quantify agreement between visual assessments and instrumental measurements, with lower *STRESS* values indicating better correlation. *VIAS* scores were also calculated for each device to evaluate visual-instrumental agreement.

Table 10. Colour measurement devices investigated in this study, including device name, manufacturer, geographical location of manufacturer, and type of device.

Device Name	***Manufacturer***	***Type***
SpectroShade Micro II (SSM II)	Spectroshade USA	Multispectral camera
SpectraScan PR-670 (PR-670)	Photo Research Inc.	Spectroradiometer,
Rayplicker Cobra (RPC)	Borea	Multispectral camera
Optishade (OS)	Smile Line	Imaging colorimeter
eLAB & Nikon D7500 (eLAB)	Emulation	Imaging colorimeter
Vita Easy Shade V (ES-V)	Vita Zahnfabrik	Spectrophotometer
MetaVue (MetaVue)	X-Rite Inc. USA	Imaging spectrophotometer

2.6.3 Results

Significant inter-device variability was observed. Among 21 device pair comparisons, 12 pairs exhibited statistically significant differences ($p < 0.05$) for ΔE_{00} and ΔE_{94}, while six pairs showed differences for ΔE_{ab}. This confirmed that CIELAB values vary across instruments

(Lehmann et al., 2012), necessitating device-specific PT and AT thresholds. PT and AT values varied based on the device and colour difference equation used:

- PT values: ΔE_{00} (0.8), ΔE_{94} (0.9), ΔE_{ab} (1.2)
- AT values: ΔE_{00} (1.8), ΔE_{94} (1.8), ΔE_{ab} (2.8)

Equivalence class partitioning grouped devices with no significant differences in PT and AT values, demonstrating that thresholds cannot be applied uniformly across all instruments (**Figure 34**).

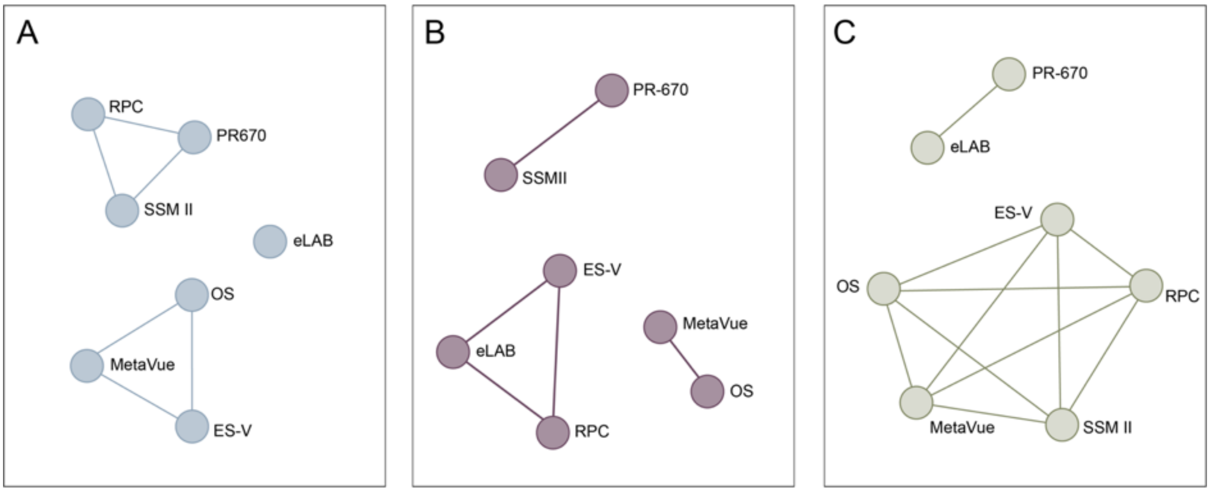

Figure 34. Equivalence class plots for ΔE_{00} (A), ΔE_{94} (B), and ΔE^*_{ab} (C). Each connected component represents devices with no significant differences among them.

STRESS index and *VIAS* scores were calculated for each device. MetaVue and Easyshade V achieved the highest agreement with visual assessments (*VIAS* 77% and 74%, respectively), while SpectroShade Micro II had the lowest agreement (*VIAS* 64%). ΔE_{00} performed best overall, confirming its superiority over ΔE_{94} in evaluating visual-instrumental agreement.

2.6.4 Discussion

The study evaluated the applicability of perceptibility and acceptability thresholds (PT and AT) across different colour measurement devices. While previous research relied on simplified ceramic samples, this study used hyper-realistic phantom models for greater clinical relevance. Expert observers provided assessments, reducing variability linked to mixed observer populations.

The Model-Free Estimation Technique by Zychaluk & Foster produced results consistent with the Takagi-Sugeno-Kang (TSK) Fuzzy Approximation method (Paravina et al., 2015), confirming the reliability of both approaches.

Significant differences in PT and AT values across devices demonstrated the necessity of device-specific thresholds. Equivalence class partitioning showed that a universal threshold is unsuitable without considering measurement design variations.

The study reaffirmed that ΔE_{00} should replace ΔE_{94} in dental applications, as ΔE_{94} did not improve visual-instrumental agreement. However, ΔE_{ab} remained relevant for the restricted gamut of natural tooth colours.

MetaVue showed strong agreement with visual assessments, making it suitable for in-vitro studies but impractical for clinical use. Future research should validate these findings in clinical settings and explore the role of lay observers in visual threshold estimation.

2.6.5 Conclusion

This study confirms that PT and AT values cannot be universally applied across all colour measurement devices. Device-specific visual thresholds are essential for improving shade-matching reliability and ensuring the accuracy of instrumental assessments.

ΔE_{00} consistently outperformed ΔE_{94}, supporting its continued use as the preferred colour difference formula. The findings also reaffirm the validity of ΔE_{ab} within the restricted gamut of natural tooth colours (Hein et al., 2024).

Moreover, the x-rite MetaVue spectrophotometer was found to be well-suited for in-vitro investigations, though its design limitations restrict its applicability in clinical settings. Future studies should validate these results in live clinical settings and investigate the role of non-expert observers in visual threshold determination.

Chapter 3: Discussion

The research presented in this thesis has been primarily concerned with the measurement of tooth colour and its relationship to visual perception. Traditional approaches in dental colorimetry have often focused on instrumental measurements, treating tooth colour as a quantifiable property that can be expressed in mathematical colour spaces such as CIELAB or CAM16-UCS. However, colour perception is a psychophysical phenomenon, influenced by various parametric effects that are challenging to quantify. These include size, shape, surface texture, and translucency, which collectively contribute to the appearance of tooth colour but are not adequately captured by instrumental measurements.

3.1 Key Findings and Contributions

3.1.1. Visual-instrumental agreement in dental colorimetry

A significant part of this research aimed to assess the performance of various colour measurement devices in relation to human visual perception. Traditional research has often assumed that an unambiguous ground truth can be established using spectrophotometers, overlooking the fact that inter-device agreement does not necessarily equate to accuracy. The development of the Visual Instrument Agreement Scale (*VIAS*) introduced a novel approach for evaluating device performance by comparing measured and visually perceived colour differences. This approach moves beyond the ill-conceived notions of 'accuracy and precision' that have previously dominated the field. The results demonstrated that *VIAS* offers a more meaningful method for assessing the reliability of colour measurement devices in clinical practice.

3.1.2. The gamut of natural tooth colours

Another major contribution of this research has been the systematic analysis of the gamut of natural tooth colours. Through large-scale measurements of in vivo data, it was determined that 1,173 unique natural tooth colours exist within the CIELAB colour space. This work also quantified the limitations of current shade guides, which exhibit significant coverage errors. For instance, the Vita Classical shade guide had a coverage error of 4.1 ΔE_{ab}, while the 3D-Master system performed only slightly better at 3.3 ΔE_{ab}. The introduction of 92 Super Shades as an alternative approach demonstrated that a more efficient and perceptually uniform coverage of natural tooth colours could be achieved.

3.1.3. The myth of illuminant metamerism in dentistry

This research also challenged the long-standing belief that illuminant metamerism plays a significant role in dental shade matching. Historically, it has been assumed that tooth colour appearance varies drastically under different lighting conditions, necessitating complex shade selection strategies. However, the findings demonstrated that illuminant metamerism is largely a myth in the context of modern dental materials. The mismatch index (M_{ilm}) between natural teeth and zirconia restorations under ten different illuminants was found to be clinically insignificant, suggesting that concerns regarding shade mismatches under different lighting conditions have been overstated in the literature.

3.1.3 Instrumental shade matching vs. visual perception

A key aspect of this research was the percent correct shade identification of different colour measurement devices. Intraoral scanners, which have traditionally been viewed as inferior to dedicated spectrophotometers, showed unexpectedly high performance in shade matching. For instance, the Carestream CS3700 achieved 82% visual-instrumental agreement, significantly outperforming traditional spectrophotometers, which averaged 57%. This finding underscores the need to reassess the widely held assumption that spectrophotometers represent the 'gold standard' in dental colorimetry.

3.2 Implications for future research and clinical applications

3.2.1. The role of digital technologies in shade matching

The field of dentistry is undergoing a digital transformation, with increasing reliance on CAD/CAM technologies, 3D printing, and digital imaging systems. These advancements present an opportunity to move beyond traditional shade guides, which have remained largely unchanged for decades. This research suggests that custom-shaded dental restorations could become a reality through improved integration between intraoral scanners, digital colour matching, and 3D printing. Future research should focus on developing device colour management systems that enable seamless calibration between intraoral scanners and 3D printers to achieve accurate shade reproduction.

3.2.2 Improving colour difference metrics for dentistry

The findings of this thesis demonstrated that the basic ΔE_{ab} formula performed better than ΔE_{00} and CAM16-UCS in the context of natural tooth colours. This contradicts the widespread assumption that more complex colour difference metrics always provide better visual-instrumental agreement. Future research should explore context-dependent optimisation of colour difference equations tailored to the specific characteristics of natural tooth colour.

3.2.3. The future of shade guides

Given the limitations of existing shade guides, future research should explore alternative approaches for optimising shade tab selection. Computational techniques, such as machine learning and fuzzy clustering algorithms, may offer a viable means of reducing coverage error while maintaining practicality. The super shade concept introduced in this research could be further developed to create a universal shade guide that bridges the gap between instrumental and visual assessments.

3.2.3. Advancing visual scaling techniques in dental colorimetry

Finally, the methodology developed in this research, particularly the use of visual scaling techniques, may serve as a foundation for future psychophysical experiments in dental colorimetry. Instead of relying on outdated notions of instrumental accuracy, future studies could adopt perceptually driven approaches to better understand the relationship between tooth colour and human perception.

3.3 Conclusion

This research has provided critical insights into the limitations of current dental colour measurement methodologies and proposed scientifically robust alternatives for evaluating device performance. The introduction of VIAS, the quantification of the natural tooth colour gamut, and the reassessment of colour difference equations represent significant contributions to the field. As digital technologies continue to reshape dentistry, it is imperative that future research builds upon these findings to develop more accurate, practical, and clinically relevant solutions for shade matching and dental colour management.

Ultimately, the goal should not merely be to refine instrumental measurements but to develop a comprehensive understanding of tooth colour appearance – one that integrates both quantitative and perceptual dimensions of colour science in dental research.

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Appendix: Published Manuscripts

Appendix A1

Hein, S., & Westland, S. (2024). Illuminant metamerism between natural teeth and zirconia restorations evaluated with a chromatic adaptation transform. The Journal of Prosthetic Dentistry. [Online] 132(5), pp.1020–1027. Available from: https://doi.org/10.1016/j.prosdent.2023.07.035

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THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

Illuminant metamerism between natural teeth and zirconia restorations evaluated with a chromatic adaptation transform

Sascha Hein, MDT,[a] and Stephen Westland, PhD[b]

ABSTRACT

Statement of problem. Little is known about the effect of illuminant metamerism between natural teeth and zirconia restorations, despite their increasing clinical popularity.

Purpose. The purpose of this in vitro study was to compare illuminant metamerism between pairs of natural teeth and layered zirconia restorations and pairs of natural teeth and monolithic zirconia restorations under 10 different illuminants and analyze their metameric potential.

Material and methods. Spectral reflectance factors were obtained from 10 pairs of extracted natural teeth and layered zirconia restorations and 28 pairs of extracted natural teeth and monolithic multilayer zirconia restorations. Each pair showed a color match that was within the visual threshold for clinical acceptability (CIEDE2000≤1.8). A special index of metamerism for the change of illuminant (M_{ilm}) was calculated from the CIEDE2000 color difference equation. Descriptive statistics and the one-sample *t* test were used to analyze the results for the M_{ilm} and for both groups of layered and monolithic zirconia restorations (α=.05).

Results. Layered zirconia restorations reached a mean ±standard deviation value for M_{ilm}=0.3 ±0.2 and M_{ilm}=0.5 ±0.4 for monolithic zirconia restorations (P<.01).

Conclusions. The effect of illuminant metamerism between natural teeth and zirconia crowns was weak and generally within the clinical acceptability limit. (J Prosthet Dent 2024;132:1020-1027)

Shade matching in dentistry presents a formidable challenge for the restorative team,[1] and esthetic complications stemming from color mismatches are both common[2] and costly.[3] The challenges are manifold and have been described in the dental literature at great length.[4] Tooth color comprises different factors, including the influence of the light source, the reflectance and transmittance of the tooth, and the human visual system.[5] The human eye responds to a given stimulus not exactly based on wavelength integration across the visible spectrum but on the integrated stimulation of 3 types of receptors referred to as the L, M, and S cones.[6] If 2 separate stimuli cause the same L, M, and S cone responses, then, when viewed under the same illuminant, they will look the same, regardless of their spectral composition. To form a pair with a visually appreciable degree of metamerism, when the illuminant is changed, the spectral composition of the 2 stimuli must intersect at 3 or more wavelengths located within the L, M, and S cone sensitivity spectrum and with reasonable convergence among them.[7] Illuminant metamerism thus refers to the phenomenon in which 2 objects with different spectral reflectance properties can appear to have the same color under one illumination but not under another.[8]

The field of dentistry has generally accepted the view that illuminant metamerism can contribute negatively to the quality of a perceived color match when viewed by the patient under changing light conditions.[9–14] The effect of illuminant metamerism has also been taught in predoctoral and graduate programs.[15]

The complexity of color appearance under different lighting conditions is demonstrated in Figure 1. The intraoral situation depicted on the left shows the visual appearance under a light source representing average daylight with a correlated color temperature (CCT) of approximately 6500 K. Shown in the middle is a simulation of the corresponding color under a fluorescent type of illumination with

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Clinical Implications

Illuminant metamerism between natural teeth and closely matching zirconia restorations should not be a major concern for esthetically challenging restorations.

a CCT of approximately 4200 K. Despite the strong color cast, a reasonable representation of a normal tooth color is still preserved because of the visual mechanisms of simultaneous color contrast and chromatic adaptation. Finally, the image on the right reveals the effect of color inconstancy, which is simply the difference in visual appearance between the conditions in the top and middle rows.

The Commission Internationale de L'Eclairage (CIE) recommends a chromatic adaptation transform (CAT) to predict the corresponding colors, for instance, of teeth under an illuminant that is different from the reference illuminant (D65). A comprehensive description of this type of advanced colorimetry and its potential applications in dentistry was provided by Fairchild.[16] The current CIE recommendation for this operation is CIECAM02, but a more recent version known as CAT16 is set to replace it because of its better performance as demonstrated in psychophysical experiments.[17,18] Typical test illuminants currently recommended by the CIE are standard illuminant A and 1 of the FL-type illuminants representing fluorescent lamps, usually FL2, FL7, or FL11.[19] By convention, these are simply referred to as F2, F7, and F11 in the scientific literature and are hereafter referred to accordingly.

The European Union Commission has recently published a new Restriction of Hazardous Substances Directive, which effectively bans the sale of any light sources containing mercury by August 2023.[20] The recent Tracking Report on Lighting published by the International Energy Agency indicates that these sources are set to be superseded by more modern light-emitting diode (LED) lamps. It estimates that currently more than half of the world's lighting markets already use LED technology, with increasing adoption.[21] To account for this shifting trend, the CIE has recently introduced a range of LED illuminants. These include LED-B1 to LED-B5 to represent the phosphor-converted blue LEDs which are currently predominantly used, and LED-BH1 to represent blue hybrid LEDs.[19]

A special index of metamerism (M_{ilm}) has been recommended by the CIE to provide an appropriate metric for the evaluation of metamerism, which is simply the color difference between the measured CIELab values of 2 objects under the reference and test illuminant evaluated with a suitable color difference equation such as CIEDE2000 (ΔE_{00}).[19] In the case of Figure 1, this would be the color difference between both maxillary central incisors shown on the left and in the middel. The image on the right depicts the effect of color inconstancy, and 2 teeth are said to be metameric if they possess different color inconstancies.[8] A ranking scale for visual thresholds in clinical dentistry was provided by Paravina et al,[22] suggesting that a color difference of less than 1.8 ΔE_{00} units is clinically acceptable.

Because of its clinical and laboratory advantages, the use of zirconia restorations has experienced impressive growth over the last 10 years. A recent report estimates that the market for zirconia restorations is set to grow from $292.7 million in 2023 to $510 million by 2030.[23] From a laboratory perspective, such restorations are seen as more cost effective to produce than glass-ceramic restorations, and clinicians appreciate the better mechanical strength of zirconia. A recent survey conducted by the American Dental Association showed that 45% of participants used monolithic zirconia restorations and that, in the anterior region, layered zirconia was used in 42% of all crowns. Interestingly, the same survey also listed shade matching among the top 2 cited disadvantages of zirconia restorations.[24]

Previous work has investigated similar aspects in relation to other materials that are commonly used in restorative dentistry, but with more basic colorimetric methods. One early study[25] investigated the effects of metamerism on pairs of dental materials and bovine teeth with a similar color under 2 illuminants. The spectral reflectance factors obtained were simply converted to CIELab values for the

Figure 1. Sequence of intraoral images to demonstrate chromatic adaptation. A, Appearance of natural smile under light source representing average daylight with CCT of approximately 6500 K. B, Same situation with corresponding color simulated under fluorescent type of illumination with CCT of about 4200 K. Appearance of normal tooth color preserved despite strong color cast. C, Noticeable difference between both conditions known as color inconstancy (illustration adapted from Fairchild[16]). CCT, correlated color temperature; K, Kelvin.

reference and test illuminants, and the color differences were then evaluated using the shortest Euclidian distance (ΔE^*_{ab}). This approach subsequently became the standard in dental research. The results showed an average color difference of 1 ΔE^*_{ab} from the change of illuminant, which is barely visible. Others[26] have proposed a modified metamerism index by calculating the ratio of color differences between parameric pairs of specimens measured under the reference and test conditions. When they compared 10 human dentin specimens with dental materials, they concluded that no evidence of a metameric effect could be found. The modified metamerism index was applied in several studies thereafter,[27–29] including a study[30] that investigated the metameric effect between natural teeth measured in vivo and 2 shade guide brands. Much like in previous studies, only a very moderate metameric effect, which was well below the threshold for clinical acceptability, could be found.

The aim of this study was to quantify illuminant metamerism between pairs of natural teeth and closely matching zirconia restorations milled from multilayer monolithic zirconia materials and manually veneered zirconia restorations using the CAT16 chromatic adaptation transform. The null hypothesis was that a change in illuminant would not result in color changes exceeding the threshold for clinical acceptability of $\Delta E_{00} \leq 1.8$.

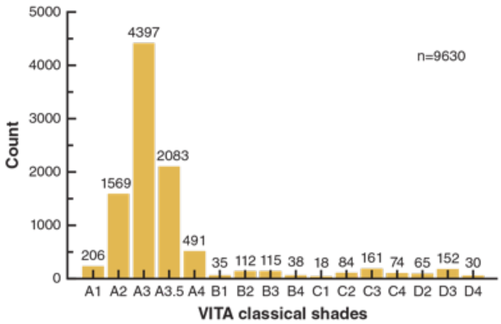

Figure 2. Statistical evaluation showing shade preference of 230 dental practitioners (courtesy of biodentis GmbH).

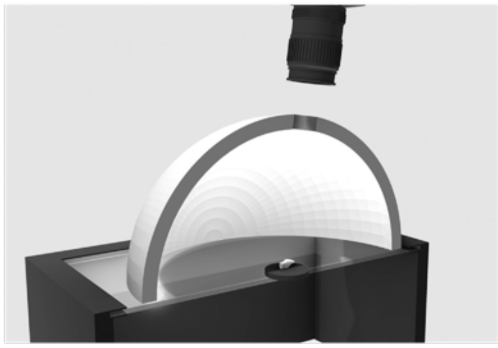

Figure 3. Schematic illustration showing cross-section of illumination geometry used for study.

MATERIAL AND METHODS

The specimens in this study were divided into 3 initial groups. The first consisted of 114 human maxillary central teeth (ethical committee approval number: LTDESN-164), which were extracted for periodontal reasons and contained no fillings or caries and showed no signs of damage. The teeth were cleaned, polished with pumice, and stored in a 1% thymol solution to prevent dehydration and preserve their color. The second group consisted of 31 hand-layered zirconia restorations of various, unspecified custom shades. The third group consisted of 75 monolithic zirconia restorations, which were milled from multilayered blanks (Table 1). The shade selection for the monolithic zirconia restorations was based on a statistical evaluation of the shade preferences of 230 dental practitioners for a total of 9630 patients. These data were provided by a digital dental laboratory (biodentis GmbH) and showed that the A-shades from the Vita Classical shade guide were the most popular choices (Fig. 2). Shades from A1 to A3.5, and 1 bleach shade were included to take account of the increased preference for brighter tooth shades by the public, a trend that may not be fully represented in previous data.[31] Both groups of zirconia restorations had a labial thickness of between 1.2 and 1.7 mm and were seated over shade ND4 tooth-colored dies (Natural Die Material; Ivoclar AG).

A calibrated telespectroradiometer (SperctraScan PR-670; Photo Research Inc) was used. The advantages of a telespectroradiometer when measuring natural teeth have included the prevention of edge loss[32] and having a visual geometry that correlates well with human

Table 1. List of multilayer zirconia blanks and shades included in study

Manufacturer	Source	Shades
IPS e.max ZirCAD prime	Ivoclar AG	BL-4, A1 to A3.5
Cercon xt ML	Dentsply Sirona Deutschland GmbH	BL, A1 to A3.5
Amann Girrbach Zolid FX	Amann Girrbach AG	A0, A1 to A3.5
Katana STML	Kuraray Europe GmbH	NW, A1 to A3.5
ZirkonZahn Pretau 2 Dispersive	Zirkonzahn GmbH	Bleach 1, A1 to A3.5

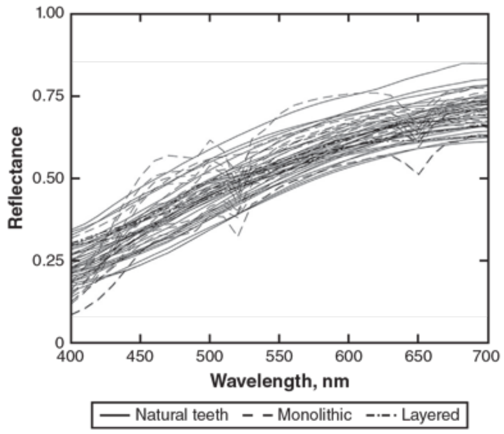

Figure 4. Spectral reflectance factors of parameric pairs consisting of natural teeth and layered zirconia restorations and natural teeth and monolithic zirconia restorations included in study. Each pair showed color difference within threshold for clinical acceptability. Layered, layered zirconia restorations; Monolithic, monolithic zirconia restorations.

perception (Fig. 3).[33] The telespectroradiometer was used together with an integrating hemisphere to provide 8-degree diffuse reflectance, as described by Molenaar et al.[34] The distance between the target tooth and the telespectroradiometer was approximately 40 cm, and the measurement aperture was set to 1 degree, which represented a measurement spot of approximately 20 mm^2. This arrangement was chosen because it provided illumination from all spatial directions and hence ideal conditions for the collection of spectral reflectance factors from diffusely scattering media like human teeth or dental materials, which do not have a flat surface. The original design was adapted by replacing the halogen rods with a xenon light source (XBO 75W/2; Zeiss).

When 2 objects present with a close visual match under 1 set of viewing conditions but without sharing actual colorimetric equality ($\Delta E_{00}\neq 0$), they are referred to as a parameric pair.[8] For the final test groups to be evaluated, a computer routine (MATLAB R2022a; MathWorks) identified parameric pairs consisting of either a natural tooth and a monolithic zirconia crown (28 pairs) or of a natural tooth and a layered zirconia crown (10 pairs) with a color difference that was coincidentally within the visual threshold for clinical acceptability of $\Delta E_{00}\leq 1.8$ when calculated under CIE standard illuminant D65 for the CIE 1931 standard colorimetric observer (Fig. 4).

The M_{ilm} recommended by the CIE requires that 2 samples differ spectrally but possess colorimetric equality ($\Delta E_{00}=0$) under a reference illuminant, usually CIE standard illuminant D65 for the CIE 1931 standard colorimetric observer, to form a metameric pair. However, 1 study analyzed the frequency of metamerism in natural scenes and concluded that the probability of finding such a metameric pair was "vanishingly small."[35] It is much more common for 2 samples to appear to be a metameric match without possessing actual colorimetric equality under the reference illuminant, in which case they form a parameric pair.[36] To abolish the residual color difference, the CIE recommends a multiplicative correction for the calculation of a M_{ilm} for parameric pairs,[19] and this was followed accordingly.

Despite the new legislation that will lead to the eventual discontinuation of all FL-illuminants, it was decided to follow the CIE guidelines and include illuminants F2, F7, and F11, as well as CIE standard illuminant A, in the investigation since these are still widely used around the world. To focus on the more modern LED illuminants that are set to replace them, CIE illuminants LED B1 to B5 and LED BH1 were also included (Table 2). Older types such as LED-V1, V2, and LED-RGB which mix red, green, and blue to create white light, have already been superseded and were therefore not included in this study.[37]

The spectral reflectance factors of all specimens were first transformed to trichromatic XYZ values for each of the 10 test illuminants and for the CIE 1931 standard colorimetric observer to serve as the test condition. To predict the corresponding colors under the reference illuminant D65 for the same observer condition, CAT16 was used with an adaptation luminance LA=64 cd/m^2, which equals a photopic illuminance of 1000 lx, a degree of adaptation D=1, and an average surround F=1.[38] The resulting trichromatic XYZ values were then converted to the CIELab color space under the same reference condition. The M_{ilm} was then calculated using the ΔE_{00} color difference equation with weighting functions S_L, S_C, and S_H set to 2:1:1 in accordance with Pecheo et al,[39] who showed that these parameters provided a good representation of the visual perception when the Vita classical shades were used. A schematic flow chart of the computation is shown in Figure 5.

Descriptive statistics and the 1-sample t test were used to analyze the results for the M_{ilm} and for both groups of layered and monolithic zirconia restorations, with a test value of 1.8 representing the threshold for clinical acceptability. A statistical software program (IBM SPSS

Table 2. List of all included test illuminants with corresponding correlated color temperatures (CCT)

Test Illuminant	A	LED-B1	LED-B2	LED-B3	LED-B4	LED-B5	LED-BH1	F2	F7	F11
CCT	2856 K	2733 K	2998 K	4103 K	5109 K	6598 K	2851 K	4230 K	6500 K	4000 K

K, Kelvin.

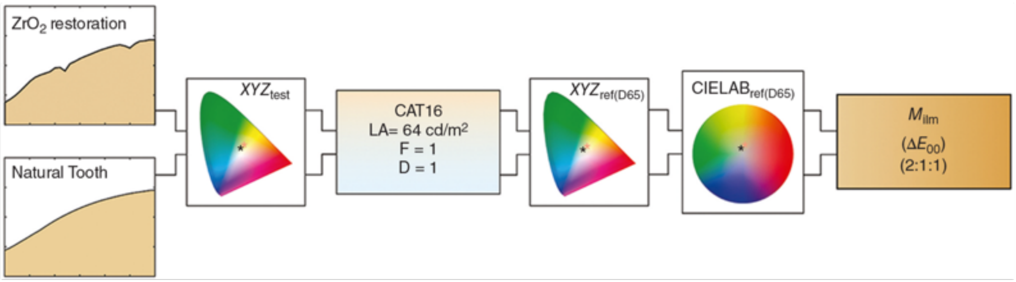

Figure 5. Flow chart showing computation of M_{ilm} using CIE 1931 standard colorimetric observer. CAT16, chromatic adaptation transform; D, degree of adaptation; ΔE_{00}, CIEDE2000 color difference equation; F, average surround; LA, luminance adaptation; M_{ilm}, special index of metamerism; *XYZ*, CIE trichromatic color space.

Statistics, v26.0; IBM Corp) was used for the analysis (α=.05).

RESULTS

The mean ±standard deviation color differences for the layered and monolithic groups were 0.3 ±0.2 ΔE_{00} units (min=0.1, max=1.1) and 0.5 ±0.4 ΔE_{00} units (min=0.3, max=1.9), respectively. The 1-sample *t* test revealed that the mean of the measured values for the M_{ilm} was significantly (P<.01) below the test value of 1.8 shown in Table 3. The M_{ilm} by the type of CIE illuminant for the group of layered and monolithic zirconia restorations is shown in Figure 6, and the 3 components of their average color differences are shown in Figure 7. Figure 8 shows the frequency of M_{ilm} by the type of zirconia restoration.

DISCUSSION

The null hypothesis was accepted for both groups (layered and monolithic zirconia restorations), since

Table 3. One Sample *t* test for M_{ilm} between both groups and natural teeth (test value=1.8, α=.05)

M_{ilm}	*t*	df	*P*	Mean Difference
Layered zirconia restorations	64.5	99	<.001	-1.50
Natural teeth	80			
Monolithic zirconia restorations	58.4	279	<.001	-1.27
Natural teeth	77			

df, degrees of freedom; M_{ilm}, special index of metamerism.

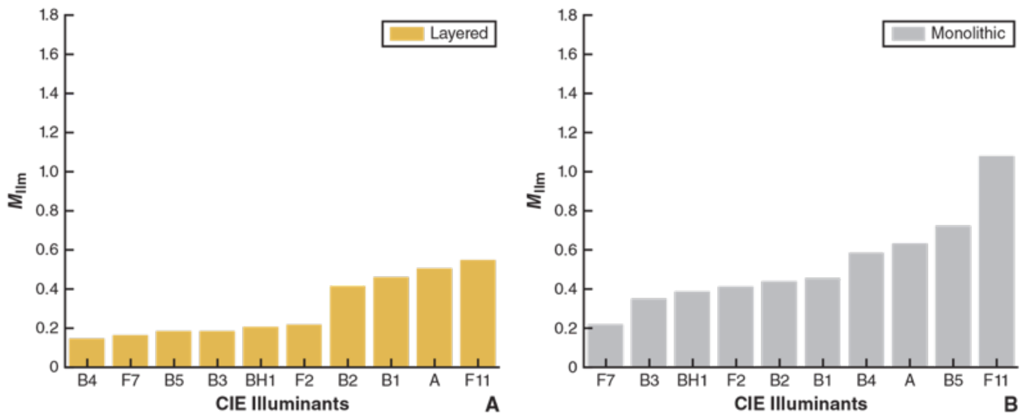

Figure 6. Mean results of M_{ilm} ranked by type of CIE illuminant and for groups of (A) layered zirconia restorations and (B) monolithic zirconia restorations. Layered, layered zirconia restorations; M_{ilm}, special index of metamerism; Monolithic, monolithic zirconia restorations.

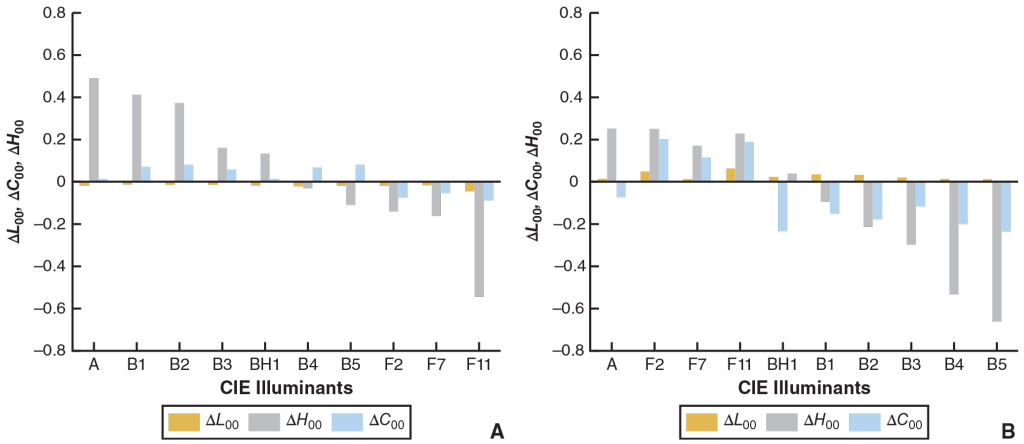

Figure 7. Three components of average color differences for groups of (A) layered zirconia restorations and (B) monolithic zirconia restorations by CIE test illuminants. ΔC_{00} chroma difference; ΔH_{00}, hue difference; ΔL_{00}, lightness difference.

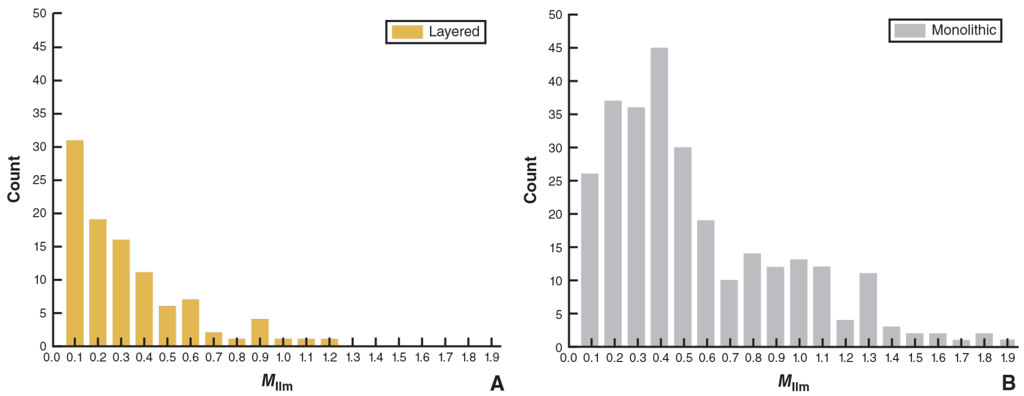

Figure 8. Frequency of M_{ilm} by groups of (A) layered crowns and (B) monolithic crowns. On average, layered crowns reached smaller values than monolithic crowns under all test illuminants. Layered, layered zirconia restorations; M_{ilm}, special index of metamerism; Monolithic, monolithic zirconia restorations.

M_{ilm} was significantly lower than the test value for the visual threshold of clinical acceptability. This suggests that illuminant metamerism between natural teeth and closely matching zirconia restorations should not be a major concern for the clinician when considering such restorations. Although the overall metameric effect was generally very small, it was slightly smaller for layered zirconia restorations than for monolithic restorations. The result of the present study challenges the currently established paradigm regarding the role of illuminant metamerism in dentistry.[10,11,40] The results can be explained by the fact that the zirconia restorations generally exhibited smooth spectral reflectance curves that matched those of their natural tooth partners reasonably well (Fig. 4). Natural teeth, layered zirconia restorations, and Katana STML all exhibited smooth reflectances, whereas all other monolithic groups showed distinct dips at 520 nm and 650 nm (Fig. 4). These dips are indicative of the presence of erbium ions (Er^{3+}), which are often used as a red or pink coloring component and exhibit narrow absorption bands at these specific wavelengths in the visible spectrum.[41] Katana STML, however, does not incorporate Er^{3+} as a color component.[42] When present, these dips caused multiple crossover points with the spectra of their parameric partner, but in most cases, they were too small to cause any significant color differences. This finding suggests that when a natural tooth and a zirconia restoration match to a clinically acceptable degree, they do so precisely because of their spectral similarities. Therefore, the assumption that the difference in chemical composition between dental materials and natural teeth must lead to inherently different spectral characteristics[13] may be incorrect.

The color difference of 1 monolithic crown (Amann Girrbach Zolid A3) exceeded the value for clinical acceptability by 0.08 ΔE_{00} units under illuminant F11. However, the current range of fluorescent types of lamps, including F11, is set to be discontinued and replaced by LED lamps toward the end of 2023.[20] The LED illuminants tested in this study were unproblematic, suggesting their introduction might reduce any metamerism between natural teeth and closely matching zirconia restorations in general.

Limitations of the present study included the fact that only A-shades were tested since research funding did not permit testing the complete range of multilayer zirconia blanks from all manufacturers to cover the entire range of the Vita Classical shades.

Future research might evaluate tooth color by replacing the CIELab system with a more modern color appearance model such as CIECAM16 in combination with a color difference equation such as CAT16-UCS.[18] This approach would require new thresholds for clinical acceptability since the current ones are based on the use of the ΔE^*_{ab} and ΔE_{00} color difference equations. The ΔE_{00} color difference is still recommended by the CIE for small color differences ($\Delta E^*_{ab}<5$), although there is abundant evidence to challenge this recommendation.[18] Therefore, the application of CAT16-UCS in dental-related color research may provide a new avenue for scientific inquiry.

CONCLUSIONS

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

1. Illuminant metamerism between natural teeth and both layered and monolithic zirconia restorations was small and well within the limits of clinical acceptability, except for 1 case where this threshold was exceeded by 0.08 CIE units (and which was not statistically significant).
2. Although the metameric effects were small overall, layered zirconia restorations were, on average, slightly less metameric than their monolithic counterparts.

APPENDIX A. SUPPLEMENTAL MATERIAL

Supplemental data associated with this article can be found in the online version at doi:10.1016/j.prosdent.2023.07.035.

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Appendix A2

Hein, S., Saleh, O., Li, C., Nold, J., and Westland, S. (2024). Bridging instrumental and visual perception with improved color difference equations: A multi-center study. Dental Materials.[Online]. 40(10), pp.1497–1506. Available from: https://doi.org/10.1016/j.dental.2024.07.003

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Bridging instrumental and visual perception with improved color difference equations: A multi-center study

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ABSTRACT

Objectives: This multicenter study aimed to evaluate visual-instrumental agreement of six color measurement devices and optimize three color difference equations using a dataset of visual color differences (ΔV) from expert observers.

Methods: A total of 154 expert observers from 16 sites across 5 countries participated, providing visual scaling on 26 sample pairs of artificial teeth using magnitude estimation. Three color difference equations (ΔE^*_{ab}, ΔE_{00}, and CAM16-UCS) were tested. Optimization of all three equations was performed using device-specific weights, and the standardized residual sum of squares (*STRESS*) index was used to evaluate visual-instrumental agreement.

Results: The ΔE^*_{ab} formula exhibited *STRESS* values from 18 to 40, with visual-instrumental agreement between 60 % and 82 %. The ΔE_{00} formula showed *STRESS* values from 26 to 32, representing visual-instrumental agreement of 68 % to 74 %. CAM16-UCS demonstrated *STRESS* values from 32 – 39, with visual-instrumental agreement between 61–68 %. Following optimization, *STRESS* values decreased for all three formulas, with $\Delta E^{'}$ demonstrating average visual-instrumental agreement of 79 % and ΔE_{00} of 78 %. CAM16-UCS showed average visual-instrumental agreement of 76 % post optimization.

Significance: Optimization of color difference equations notably improved visual-instrumental agreement, overshadowing device performance. The optimzed $\Delta E^{'}$ formula demonstrated the best overall performance combining computational simplicty with outstanding visual-instrumental agreement.

1. Introduction

Over recent decades, instrumental color measurement in dentistry has gained prominence for its objectivity and precision in assessing tooth color [1,2]. However, the exclusive focus on instrumental measurements often neglects the critical role of visual color perception. A notable challenge arises when there is a discrepancy between instrumental measurements and visual perception, leading to situations where a restoration appears visually dissimilar despite a small, measured color difference. Typically, the accuracy of tooth color measurements is not only dependent on the device's performance but also significantly influenced by the color difference equations used. This raises critical questions: are discrepancies between visual and instrumental evaluations the result of the device's capabilities, or the equations applied? And how do we disentangle these two things?

The widespread use of CIELAB color space in dentistry [3–5] has spurred extensive research comparing color measurement instruments to establish their relative accuracy [6,7]. Yet, within dental colorimetry research, confusion persists between the concepts of accuracy and precision, sparking debates over the most reliable instruments [8–11]. Lack of precision, stemming from random noise, differs from lack of accuracy, which results from systematic bias [12]. True accuracy in color measurement requires calibration against recognized standards. These standards are usually measured by a national standardizing laboratory equipped with the finest instrumentation and procedures. Each standard comes with a certificate detailing an estimate of the associated measurement uncertainty, providing a definitive benchmark for evaluating the accuracy of color measurements [13,14]. In tooth color measurement, accuracy is usually defined as the system's ability to record the 'true' CIELAB values, yet determining these values poses challenges [5].

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The perennial quest to describe visual color differences with a single distance metric began with the conception of CIELAB in 1976 as an approximately uniform color space, within which equal visual color differences are represented by equal Euclidean distances (ΔE^*_{ab}) [15]. However, it soon became evident that ΔE^*_{ab} fell short of expectations [16], catalyzing the development of more advanced color difference equations such as the CIEDE2000 (ΔE_{00}) [17] which is currently the CIE recommendation for small color differences [18]. However, such efforts have largely focused on color match specifications rather than perceptual color appearance properties [19]. This has led to the development of more advanced colorimetry such as CAM16-UCS [20] which has been the subject of recent investigations in dental research [21,22].

Given the evolution of color difference equations, several methods are now available for instrumental color difference evaluation. These range from straightforward computations to those considered state-of-the-art technological advancements, featuring considerable complexity. However, it remains unclear which of these methods offer the best visual-instrumental agreement, posing an important question for dental practitioners seeking reliable color measurement solutions for clinical applications.

Therefore, the aim of this study is to investigate visual-instrumental agreement of six devices and to optimize three color difference equations, using a large visual dataset from expert observers collected as a multi-center study. The study explores two distinct null hypotheses to thoroughly assess the performance and optimization of color difference equations in capturing perceived color differences through instrumental evaluation:

1. There is no significant difference in visual-instrumental agreement among the tested devices in reflecting perceived color differences.
2. Optimized color difference equations offer no significant improvement in performance over their generic counterparts.

By clarifying which devices and equations may offer improved visual-instrumental agreement, this study aims to support dental professionals in making informed decisions regarding color measurement in clinical practice, ultimately contributing to enhanced patient care and treatment outcomes.

2. Material and methods

2.1. Visual scaling technique

To examine visual color differences (ΔV), a suitable scaling technique needs to be applied to quantify visual differences between pairs of teeth. The gathered ΔV data plays a key role in assessing the performance of color measurement devices by examining the correlation between instrumental color difference (ΔE) and ΔV [23]. A technique commonly referred to as magnitude estimation (ME) was selected as the visual scaling technique for this study due to its successful application in color-difference research [24]. This technique involves expert observers assigning numerical values to perceived color differences, thus enabling a consistent and quantifiable assessment of ΔV [25]. The robustness and reliability of ME in quantifying subtle color differences are particularly relevant in dentistry. This is because the color differences typically encountered in this field are relatively small [26], in contrast to the larger color differences often found in visual datasets from other industries [27].

2.2. Selection of expert observers

In preparation for this study, an application for proportional ethical review was submitted and subsequently granted (Ethical approval number LTDESN-196). To fulfill the specialized needs for ME, 154 expert observers were recruited who passed the Ishihara test for color deficiency. They consisted of dental practitioners and dental technicians with relevant experience in the field of restorative dentistry. The demographic overview (Table 1) presents data on 105 dental practitioners and 49 dental technicians.

2.3. Selection of multi-center sites

Sites were strategically chosen to be reflective of a broad spectrum of professional settings. The 16 centers participating in this investigation include renowned universities with dedicated dental schools, specialized private dental laboratories, and dental practices known for their excellence in dental care and research. Table 2 provides an overview of the locations and types of centers that contributed to this study.

2.4. Visually scaled samples

Four hyper-realistic phantom models were custom fabricated by an experienced master dental technician. These models were made of micro filler reinforced composite denture teeth (Physiodens, Vita Zahnfarbrik, Germany) as depicted in Fig. 1. To analyze the correlation between visually perceived color differences and those calculated from each device, colorimetric data from appropriate sample pairs was necessary. Four color centers within CIELAB color space were identified for this study, as shown in Fig. 2. Each phantom model, representing one base shade (1M2, 2M2, 3M2, and 4M2), was combined with 5 to 7 exchangeable teeth per model, to create 26 visually scaled sample pairs. This regime led to the creation of four color-centers of different lightness, where sample pairs primarily differed in hue and chroma, accommodating findings that simultaneous assessment of lightness and chromaticness can increase observational uncertainty [28]. The color difference between each of the 26 sample pairs was less than 5 ΔE^*_{ab} units [18].

2.5. Psychophysical experiment

To determine visual-instrumental agreement, a psychophysical experiment was carried out under controlled conditions. Observers viewed sample pairs at a distance of approximately 35–50 cm against a 45° angled surface painted in Munsell N5 neutral grey (GTI Gmbh, Harrislee, Germany). Simulated daylight of 6500 K was provided by a viewing cabinet (DLS Color Viewing Light v7, JustNormlicht, Germany) with an illuminance of approximately 1000 lx [29]. The setup allowed observations while standing in a darkened room. In accordance with the ME technique, each participant was then asked to rate the sample match for each pair from 0 % (worst match) to 100 % (perfect match). Phantom models were used in random order, with each maxillary central tooth drawn from a bag without replacement. Responses were recorded in an Excel sheet (Microsoft Corp., Redmond, WA, USA) using custom drop-down menus for consistency in data collection. Each participant's session lasted approximately 20–30 min.

2.6. Instrumental measurement of sample pairs

In this study, a range of color measurement devices frequently cited in dental literature for tooth color assessment were evaluated and they are listed in Table 3. The selection included both established systems and newer technologies for which there is currently limited data available. Sample pairs were mostly measured with devices specifically designed for dentistry, each with its own illumination geometry and straightforward measurement regime.

Exceptions to this standard procedure involved two systems:

1. **Tele-radiospectrometer (PR-670):** Measurements were taken using a calibrated tele spectroradiometer (SpectraScan PR-670, Photo Research Inc., Syracuse, NY, USA) with a 1° aperture and a 45°:0° illumination geometry provided by the same viewing cabinet that was used for the visual experiment.

Table 1
Gender and age (yrs) distribution of expert observers participating in this study.

Profession	n	Male	Female	18-24 yrs	25-34 yrs	35-44 yrs	45-54 yrs	55-64 yrs	≥ 65 yrs
Dental practitioners	105	56	49	6	64	12	11	8	0
Dental technicians	49	29	20	2	12	22	11	5	1

Table 2
Participating centers in the multi-center study, including location and type of institution.

Country	City/ Region	Center Name	Type
Austria	Oetztal	Die Zahnmanufaktur	Private Dental Laboratory
France	Strasbourg	University of Strasbourg	Faculty of Dental Medicine
Germany	Cham	Cham Zahntechnik	Private Dental Laboratory
Germany	Munich	Ludwig-Maximilians-University Munich	School of Dental Medicine
Germany	Landshut	Hofmann Dentaltechnik GmbH	Private Dental Laboratory
Germany	Erlstaett	Oral Design Chiemsee GmbH	Private Dental Laboratory
Germany	Freiburg	Albert-Ludwigs-University Freiburg	School of Dental Medicine
Germany	Frankfurt	Goethe University	School of Dental Medicine
Germany	Bonn	University of Bonn	School of Dental Medicine
Germany	Duesseldorf	Heinrich Heine University	School of Dental Medicine
Switzerland	Bern	Zahnmanufaktur Zimmermann & Maeder AG	Private Dental Laboratory
Switzerland	Bern	Praxis Mathey	Private Dental Practice
Switzerland	Bern	University of Bern	School of Dental Medicine
Switzerland	Zurich	University of Zurich	School of Dental Medicine
United Kingdom	London	University College London	Eastman Dental Institute
United Kingdom	Leeds	University of Leeds	NHS Teaching Hospital

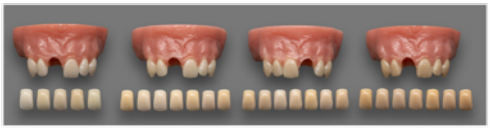

Fig. 1. Hyper-realistic phantom models were fabricated each in one base shade (from left to right: 1M2, 2M2, 3M2, and 4M2) to closely mimic natural teeth and for facilitating a more realistic assessment of color differences in a clinical setting.

2. **eLAB System (eLAB):** Not a device but a system for calibrating digital RAW images. Samples were photographed using a Nikon D7500 digital camera equipped with a 105 mm macro lens (Nikon Corp., Germany) and a ring flash (MK-14EXT, Meike, Germany) alongside a cross-polarization filter (polar_eyes, Emulation, Germany). The samples were positioned within the viewing cabinet, with a grey card (white_balance, Emulation, Germany) placed beneath the incisal edges to ensure consistent exposure settings. The eLAB protocol was stringently followed, setting the aperture at f22, exposure time at 1/125 s, ISO at 100, and using the RAW image format [30]. Subsequent processing and calibration in the eLAB software allowed for CIELAB value measurements.

To account for variability across the tooth surface, each sample was measured three times in each of three distinct regions and averaged: cervical, middle, and incisal areas of the labial tooth surface.

2.7. Computation of color differences between sample pairs

In the scope of this research, distinguishing between the performance of color measurement devices and the efficacy of color difference equations poses a significant challenge. To ensure consistency across all assessments, all color differences were computed under Illuminant D65 and for the CIE 1931 standard colorimetric observer [31]. Three color difference metrics were then employed as baseline assessments:

1. **ΔE^*_{ab}:** Utilizes the Euclidean distance for color difference calculation, providing a straightforward approach to quantifying color variations.
2. **ΔE_{00}:** Incorporates weighting functions S_L, S_C, S_H, each set to 1, enhancing the model's sensitivity to hue, chroma, and lightness differences.
3. **CAM16-UCS:** A uniform color space that designates J for lightness and a and b for chromaticity coordinates, indicating redness-greenness and yellowness-blueness, respectively. Since visual observations were carried out in a viewing cabinet, luminance levels for each instrument were considered to be the same, defining the surround parameters as 'average' with $F = 1.0$, $c = 0.69$ and $N_c = 1$. The background parameter was set to $Y_B = 20$ due to the neutral grey paint against which the samples were viewed ($L^* = 50$). The luminance level provided by the viewing cabinet was approximately 1000 lx, therefore the reference white in the reference illuminant was set to $Y_W = 100$ with an adaptation luminance of $L_A = 64$ cd/m^2 [20].

2.8. Statistical analysis

Data evaluation was performed using a specialized color toolbox in MATLAB (R2023b; MathWorks, Natick, MA, USA), which provides various functions for computational color science [32]. A MATLAB routine was also used to access the Excel sheet containing anonymized participant data, enabling efficient extraction of relevant information. The visually scaled color differences were determined by calculating geometric and arithmetic means, as well as the median for each observer response. The performance of each color measurement device was assessed by computing color differences for each sample pair. The standardized residual sum of squares (*STRESS*) index was used for performance evaluation where values ranging from 0 to 100 are indicative of device performance, with lower values signaling better visual-instrumental agreement [33]. Conversely, 100 - *STRESS* provides a direct measure of visual-instrumental agreement [34]:

$$STRESS = 100\left(\frac{\sum_i(\Delta E_i - F_1\Delta V_i)^2}{\sum_i F_i^2 \Delta V_i^2}\right)^{1/2} \text{ and } F = \frac{\sum_i \Delta E_i^2}{\sum_i \Delta E_i \Delta V_i}$$

STRESS can also be used to express observer variability or the difference in performance between two devices since the square of the ratio of *STRESS* values from two visual data sets follows a two-tailed *F*-distribution, as it is equivalent to the ratio of two chi-squared variables [35]. In simpler terms, when comparing the performance of two devices, the *STRESS* value is analyzed, which follows a specific statistical distribution.

In statistical terms, this distribution adheres to an *F*-variable, where a

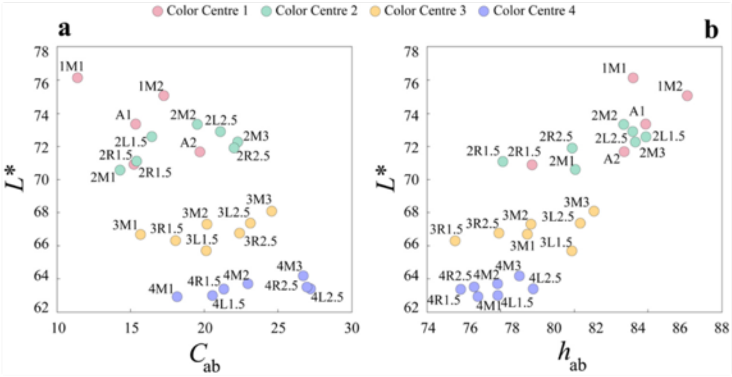

Fig. 2. Color coordinates for 26 visually scaled samples plotted by their lightness (L^*) and chroma (C^*_{ab}) distribution (A) and by their lightness (L^*) and hue angle (h_{ab}) distribution (B). Four color centers were identified, corresponding to the shades 1M2 (Color Center 1), 2M2 (Color Center 2), 3M2 (Color Center 3), and 4M2 (Color Center 4).

Table 3
Color measurement devices investigated in this study, including device name, manufacturer, geographical location of manufacturer, and type of device.

Device Name	Manufacturer	Location	Type
SpectroShade Micro II (SSM II)	Spectroshade USA	Oxnard, CA, USA	Multispectral camera
SpectraScan PR−670 (PR−670)	Photo Research Inc.	Syracuse, NY, USA	Tele radiospectrometer
Rayplicker Cobra (RPC)	Borea	France	Multispectral camera
Optishade (OS)	Smile Line	Switzerland	Calibrated camera
eLAB & Nikon D7500 (eLAB)	Emulation	Germany	Calibrated camera
Vita Easy Shade V (ES-V)	Vita Zahnfabrik	Germany	Photo spectrometer

critical value (F_C) denotes the threshold for rejecting the null hypothesis. The null hypothesis, in this context, suggests that two devices (A and B) exhibit no significant differences. To evaluate this hypothesis, the *F*-value is derived from the *STRESS* index:

$$F = \frac{STRESS_A^2}{STRESS_B^2}$$

If the *F*-value falls below a certain critical threshold ($F<F_C$) or exceeds the inverse of that threshold ($F>1/F_C$), the null hypothesis must be rejected. This critical threshold for F_C is determined by the two-tailed *F*-distribution with a 95 % confidence level and degrees of freedom (N − 1, N − 1), where N represents the sample size. In the present case this results in:

$$F_C = 1.955$$

$$\frac{1}{F_C} = 0.512$$

In addition to *STRESS*, the correlation between computed and visually scaled color differences was assessed using the R-squared method to further elucidate the relationship between instrumental measurements and visual assessments.

2.9. Optimization of color difference equations

It has been suggested that a correction of color difference equations can be used to improve their performance, in particular for very small color differences [34]. For this purpose, initial metrics, ΔE^*_{ab}, ΔE_{00} and CAM16-UCS, underwent optimization to enhance their alignment with perceptual color differences. First, the conventional ΔE^*_{ab} formula was subjected to a targeted optimization process:

$$\Delta E' = \sqrt{S_L(L_1 - L_2)^2 + S_C(a_1 - a_2)^2 + S_H(b_1 - b_2)^2}$$

where $\Delta E'$ is the improved color distance equation to achieve better congruency between computed and visually perceived color difference by optimizing parameters S_L, S_C, S_H.

For ΔE_{00}, optimization was pursued through the tailored adjustment of its weighting functions: S_L, S_C, and S_H:

$$\Delta E_{00} = \left[\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)\right]^{1/2}$$

Similarly, CAM16-UCS underwent optimization, also with tailored parameters S_L, S_C, S_H:

$$\Delta \overline{E} = \sqrt{S_L(J_1 - J_2)^2 + S_C(a_1 - a_2)^2 + S_H(b_1 - b_2)^2}$$

These adjustments are device-specific, acknowledging the unique color measurement capabilities and limitations inherent to each device. In all three cases the *fminsearch* function from the MATLAB optimization toolbox was used to find the optimal parameters as evaluated by the *STRESS* index.

3. Results

3.1. Visual-instrumental agreement

Visually scaled color differences from 154 observers for 26 sample pairs were averaged using the arithmetic mean, as it yielded the best

Table 4
Average results for all color measurement devices using ΔE^*_{ab} color difference equations showing mean and standard deviation (SD) for the *STRESS* index, visual-instrumental agreement, and R-squared values.

Device	STRESS	Visual-instrumental agreement (%)	R^2
eLAB	18	82	0.8
RPC	24	76	0.7
OS	24	76	0.7
PR−670	25	75	0.7
ES-V	25	75	0.7
SSM II	40	60	0.4
Mean	**26**	**74**	**0.7**
sd	7.4	7.4	0.2

Table 5
Results for *F*-test between different devices using ΔE^*_{ab} color difference equation. Yellow cells in column indicate that a given device performs significantly better than another device in corresponding row. Grey cells indicate significantly worse performance and blue cells indicate no significant difference.

Device	eLAB	RPC	OS	PR-670	ES-V	SSM II
eLAB	1.0	0.563	0.563	0.518	1.000	0.203
RPC	1.778	1.0	1.000	0.922	0.922	0.360
OS	1.778	1.000	1.0	0.922	0.922	0.360
PR-670	1.929	1.085	1.085	1.0	1.000	0.391
ES-V	1.929	1.085	1.000	1.000	1.0	0.391
SSM II	4.938	2.778	2.560	2.560	2.560	1.000

Table 6
Average results for all color measurement devices using the ΔE_{00} difference equation showing standard deviation (SD) for the *STRESS* index, visual-instrumental agreement, and R-squared values.

Device	STRESS	Visual-instrumental agreement (%)	R^2
ES-V	26	74	0.7
PR−670	30	70	0.5
RPC	30	70	0.6
OS	30	70	0.6
eLAB	30	70	0.6
SSM II	32	68	0.5
Mean	**30**	**70**	**0.5**
sd	1.8	1.8	0.05

Table 8
Average results for all color measurement devices using CAM16-UCS, showing standard deviation (SD) for the *STRESS* index, visual-instrumental agreement, and R-squared values.

Device	STRESS	Visual-instrumental agreement (%)	R^2
ES-V	32	68	0.5
SSM II	34	66	0.5
PR−670	36	64	0.4
RPC	39	61	0.4
OS	39	61	0.4
eLAB	39	61	0.4
Mean	**36**	**64**	**0.4**
sd	3.0	3.0	0.1

alignment with the overall measured color differences. From these calculated means, the *STRESS* index for each color difference equation was determined, alongside the evaluation of inter-observer variability [36] which was 45 *STRESS* units on average.

Table 4 illustrates visual-instrumental agreement results for the ΔE^*_{ab} equation, while Table 5 presents *F*-test outcomes for each device under the ΔE^*_{ab} computation. Visual-instrumental agreement results for the ΔE_{00} equation are displayed in Table 6, with Table 7 showing the corresponding *F*-test results. Table 8 lists visual-instrumental agreement for CAM16-UCS, and Table 9 presents *F*-test results for each device under CAM16-UCS computation.

3.2. Visual-instrumental agreement after optimization of color difference equations

Device specific parameters, as optimized by the *fminsearch* function in MATLAB are listed in Table 10 collectively for $\Delta E'$, ΔE_{00} and $\Delta \bar{E}$ color difference equations. Table 11 shows the average results (*STRESS* index, visual-instrumental agreement, and R-squared values) for the $\Delta E'$ equation while Table 12 further compares the subsequent performance of all devices. In the case of the ΔE_{00} color difference equation, Table 13 and Table 14 present the equivalent improvements and device performance comparison, after the optimization of individual weights (S_L, S_C, S_H). Lastly, Table 15 shows the results for the optimized $\Delta \bar{E}$ color difference formula and Table 16 compares the improved performance among all devices.

3.3. Performance of color difference equations

Further analysis of the performance of the generic and optimized color difference equations for each device using the *F*-statistic is available in the appendix. The results varied depending on the device, and a comprehensive summary of the performance of each color difference equation across all devices is presented in Fig. 3. The $\Delta E'$ equation produced significantly better results more often than other equations under a 95 % significance level.

4. Discussion

While an extensive body of research compares various instruments used to measure tooth color, aiming to establish their relative accuracy [6,7], confusion persists between inter-device agreement and the true definition of colorimetric accuracy [7–10]. Few attempts were made to adequately address the question of accuracy in dental colorimetry by employing a set of calibration standards [37,38]. However, these efforts rely purely on instrumental metrics, overlooking the critical aspect of the congruency between instrumental measurements and visual perception.

The purpose of this study was to investigate the visual-instrumental agreement of six color measurement devices and to optimize three color difference equations based on a visual dataset of color differences obtained from expert observers. The findings shed light on the under-studied interplay between device performance and the choice of color difference equations. Statistical analysis, based on the *STRESS* index and associated *F*-parameter, showed no statistically significant differences in

Table 7
Results for *F*-test between different devices using ΔE_{00} color difference equation using standard weights (1:1:1) for S_L, S_C, S_H.

Device	ES-V	eLAB	PR-670	RPC	OS	SSM II
ES-V	1.0	0.751	0.751	0.751	0.751	0.522
eLAB	1.331	1.0	1.0	1.0	1.0	0.694
PR-670	1.331	1.0	1.0	1.0	1.0	0.694
RPC	1.331	1.0	1.0	1.0	1.0	0.694
OS	1.331	1.0	1.0	1.0	1.0	0.694
SSM II	1.515	1.138	1.138	1.138	1.138	0.790

Table 9
Results for *F*-test between different devices using CAM16-UCS color difference equation.

Device	ES-V	SSM II	PR-670	RPC	OS	eLAB
ES-V	1.0	0.886	0.790	0.673	0.673	0.673
SSM II	1.129	1.0	0.892	0.760	0.760	0.760
PR-670	1.266	1.121	1.00	0.852	0.852	0.852
RPC	1.485	1.316	1.174	1.0	1.0	1.0
OS	1.485	1.316	1.174	1.0	1.0	1.0
eLAB	1.485	1.316	1.174	1.0	1.0	1.0

Table 10
Device specific parameters and weights for optimizing color difference equations: S_L, S_C, S_H for the ΔE^*, ΔE_{00} and $\Delta\bar{E}$ equations for each of the six devices. Note that the S_L, S_C, S_H parameters are distinct between the different equations.

	ΔE^*			ΔE_{00}			$\Delta\bar{E}$		
Weights	S_L	S_C	S_H	S_L	S_C	S_H	S_L	S_C	S_H
SSM II	0.0	2.6	0.6	3	1	1	1.3	1.0	3.0
PR−670	0.2	2.4	1.0	1.8	0.6	0.9	1.0	1.0	3.0
RPC	0.2	2.4	0.8	2.7	0.8	1.0	1.0	3.0	3.0
OS	0.4	2.1	1.0	2.4	0.8	1.1	1.0	1.8	3.0
eLAB	0.5	1.5	1.1	2.0	0.7	1.1	1.0	1.0	3.0
ES-V	0.5	2.1	0.7	1.6	0.9	1.1	1.0	3.0	3.0

Table 11
Average results for color measurement devices using ΔE^* equation including *STRESS* index, visual-instrumental agreement, and R-squared values.

Device	STRESS	Visual-instrumental agreement (%)	R^2
eLAB	17	83	0.9
RPC	19	81	0.8
OS	20	80	0.8
PR−670	21	79	0.8
ES-V	23	77	0.7
SSM II	24	76	0.7
Mean	**21**	**79**	**0.8**
sd	2.7	2.7	0.1

performance among investigated devices, except for SSM II. Nonetheless, this led to the rejection of the first null hypothesis.

Further analysis yielded unexpected findings regarding the performance of color difference equations. The basic ΔE^*_{ab} formula achieved on average greater agreement with the visual data than the ΔE_{00} equation or CAM16-UCS. One explanation for this might be that this research is restricted to a relatively small gamut (that of tooth color) in color space. However, it is important to acknowledge that, while ΔE^*_{ab} performed well within this limited color gamut, there is ample evidence suggesting that, across a broader spectrum, it may not perform as effectively as the other two metrics. This suggests that the suitability of ΔE^*_{ab} is context-dependent, excelling in specific applications like dental colorimetry but potentially falling short in more expansive color spaces [39].

Many factors may influence color discrimination besides the similarity or dissimilarity of color. The visual task to decide which device and distance measurement correlates best with visually perceived color differences is considerably affected by parametric effects, some of which may be of relevance to clinical dentistry, such as sample edge separation, surface texture, translucency or sample shape and size [40–42]. Failure to account for these may be one reason for low correlation between visual and instrumental color differences [43]. To control for such parametric effects, four hyper realistic phantom models were chosen to resemble the appearance of natural teeth. Considering the large inter-observer variation of 45 *STRESS* units, the observed baseline *STRESS* values for ΔE^*_{ab}, ΔE_{00}, and CAM16-UCS were relatively low, consistent with those reported in other, rigorously controlled visual studies [39,44]. Despite these results, it became evident that further optimization resulted in significantly better visual-instrumental agreement compared to when the generic color difference equations were used (Fig. 3). This led to the rejection of the second null hypothesis.

Johnston [5] described accuracy as an instrument's ability to yield color measurements that align with a reference instrument. However, the criteria for choosing this reference instrument were not specified. More recently [37] this role was assigned to a tele-radiospectrometer of the same type among the investigated devices in the present research. This decision was based on measurements of 240 reference standards provided by a GretagMacbeth DC color checker, yet no direct measure of accuracy, such as the color difference between the reference values and those obtained by the tele-radiospectrometer, was reported. Evaluating inter-device agreement, the performance of Vita Easy Shade and SpectroShade MHT against the nominated gold standard (PR-670) suggested that SpectroShade MHT exhibited the closest congruency with the latter, recommending its use when the gold standard instrument is not

Table 13
Average results for color measurement devices using ΔE_{00} equation, including *STRESS* index, visual-instrumental agreement, and R-squared values.

Device	STRESS	Visual-instrumental agreement (%)	R^2
eLAB	18	82	0.8
PR−670	21	79	0.8
RPC	21	79	0.8
OS	22	78	0.8
ES-V	24	76	0.7
SSM II	27	73	0.6
Mean	**22**	**78**	**0.8**
sd	3.0	3.0	0.1

Table 12
Results for *F*-test between different devices using optimized ΔE^* equation using custom weights (S_L, S_C, S_H).

Device	eLAB	RPC	OS	PR-670	ES-V	SSM II
eLAB	1.0	0.801	0.903	0.655	0.546	0.502
RPC	1.249	1.0	0.903	0.819	0.682	0.627
OS	1.384	1.108	1.0	0.907	0.756	0.694
PR-670	1.526	1.222	1.103	1.0	0.834	0.766
ES-V	1.830	1.465	1.323	1.200	1.0	0.918
SSM II	1.993	1.596	1.440	1.306	1.089	1.0

Table 14
Results for *F*-test between different devices using ΔE_{00} equation using custom weights S_L, S_C, S_H.

Device	eLAB	PR-670	RPC	OS	ES-V	SSM II
eLAB	1.0	0.735	0.735	0.669	0.563	0.444
PR-670	1.361	1.0	1.000	0.911	0.766	0.605
RPC	1.361	1.000	1.0	0.911	0.766	0.605
OS	1.494	1.098	1.098	1.0	0.840	0.664
ES-V	0.735	1.306	1.306	1.190	1.0	0.790
SSM II	2.250	1.653	1.653	1.506	1.266	1.0

Table 15
Average results for color measurement devices using $\Delta\bar{E}$ equation, including *STRESS* index, visual-instrumental agreement, and R-squared values.

Device	STRESS	Visual-instrumental agreement (%)	R^2
eLAB	19	81	0.8
OS	23	77	0.7
ES-V	24	76	0.7
PR–670	25	75	0.7
RPC	26	74	0.7
SSM II	29	71	0.7
Mean	**24**	**76**	**0.7**
sd	3.3	3.3	0.1

available. In contrast, the present study reveals that the selected color difference equation overshadows variations in device performance. This discrepancy can be attributed to the disparity in methodologies employed, specifically, one based solely on instrumental assessment versus the evaluation of visual-instrumental agreement through the *STRESS*-index, currently regarded as the gold standard in color research [33, 36, 39, 44].

One limitation of this study is the restricted number of sample pairs that were visually scaled, primarily due to the limited availability of distinct color centers of denture teeth in the 3D Master system. Although the 3D Master system offers the broadest range of available shade tabs, which follow a systematic order, its coverage error relative to the gamut of natural tooth color is well documented [45]. Psychometric studies typically fall into one of two categories: either utilizing few expert observers with hundreds of sample pairs to visually scale or employing many observers with few sample pairs [46]. In this study, we opted for the latter, prioritizing hyper-realistic sample pairs resembling the appearance of natural teeth to consider the influence of parametric effects more realistically, even if it meant accepting a smaller population of visually scaled samples. Furthermore, utilizing 26 sample pairs allowed for shorter session durations, preventing eye fatigue or loss of interest. Despite these limitations, the methodology outlined in this study - employing a visual scaling technique for judging the difference between two samples - may offer a pathway for future dental color research by dental researchers, diverging from the conventional approach of measuring identical samples with different devices and comparing multivariate coordinates separately.

Table 16
Results for *F*-test between different devices using $\Delta\bar{E}$ equation using custom weights (S_L, S_C, S_H).

Device	eLAB	OS	ES-V	PR-670	RPC	SSM II
eLAB	1.0	0.682	0.627	0.578	0.534	0.429
OS	1.465	1.0	0.918	0.846	0.783	0.629
ES-V	1.596	1.089	1.0	0.922	0.852	0.685
PR-670	1.731	1.181	1.085	1.0	0.925	0.743
RPC	1.873	1.278	1.174	1.082	1.0	0.804
SSM II	2.330	1.590	1.460	1.346	1.244	1.0

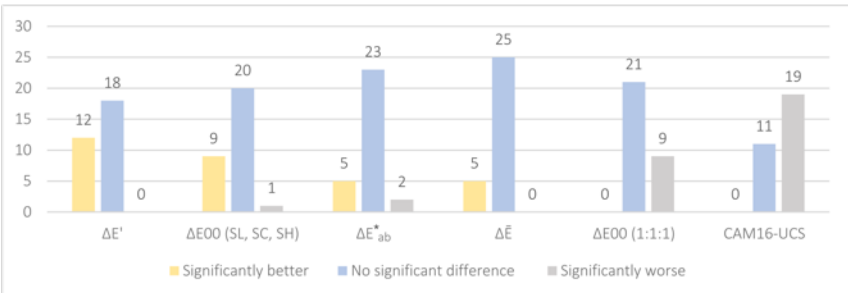

Fig. 3. Average results of performance of color difference equations for each device, counting occurrences where a given equation performed significantly better, worse, or showed no significant difference compared to any other equation, under a 95 % significance level.

5. Conclusion

The findings of our study highlight that discrepancies between visual and instrumental evaluations are primarily influenced by the choice of color difference equation rather than device performance. This suggests that practitioners can significantly enhance color difference prediction by selecting the equation tailored to the specific device in use. Notably, the consistent superiority of the optimized ΔE^*_{ab} equation ($\Delta E'$) across all tested devices underscores its potential for clinical dentistry, providing dental practitioners with a straightforward strategy to improve visual-instrumental agreement in tooth color measurements. This study serves as a foundation for further exploration and refinement of color measurement methodologies, offering valuable insights for both research and practical applications in color science and dentistry.

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Appendix

This appendix offers a comprehensive analysis of the performance of six color difference equations applied to each of the six color measurement devices tested included in this research. Each table corresponds to a specific device and lists the *F*-statistic for evaluating the performance of the six color difference equations. These equations include three generic equations and their three optimized versions, adjusted with device specific parameters S_L, S_C, and S_H.

The *F*-test, conducted to compare the performance among the different equations, is based on a 95 % significance level, with $F_C = 1.955$ and $1/F_C = 0.512$. Yellow cells highlight instances where an equation performs significantly better than another, blue cells denote no significant performance difference, and grey cells signal a significantly poorer performance than the corresponding equation in row.

Table A.1
Performance of color difference equations for eLAB.

Formula	$\Delta E'$	ΔE_{ab}	$\Delta \hat{E}$	ΔE_{00} (S_L, S_C, S_H)	ΔE_{00} (1:1:1)	CAM16-UCS
$\Delta E'$	1.0	0.892	0.801	0.502	0.321	0.190
ΔE_{ab}	1.121	1.0	0.898	0.563	0.360	0.213
$\Delta \hat{E}$	1.249	1.114	1.0	0.627	0.401	0.237
ΔE_{00} (S_L, S_C, S_H)	1.993	1.778	1.596	1.0	0.640	0.379
ΔE_{00} (1:1:1)	3.114	2.778	2.493	1.563	1.0	0.592
CAM16-UCS	5.263	4.694	4.213	2.641	1.690	1.0

Table A.2
Performance of color difference equations for RPC.

Formula	$\Delta E'$	ΔE_{00} (S_L, S_C, S_H)	ΔE_{ab}	$\Delta \hat{E}$	ΔE_{00} (1:1:1)	CAM16-UCS
$\Delta E'$	1.0	0.903	0.627	0.534	0.401	0.237
ΔE_{00} (S_L, S_C, S_H)	1.108	1.0	0.694	0.592	0.444	0.263
ΔE_{ab}	1.596	1.440	1.0	0.852	0.640	0.379
$\Delta \hat{E}$	1.873	1.690	1.174	1.0	0.751	0.444
ΔE_{00} (1:1:1)	2.493	2.250	1.563	1.331	1.0	0.592
CAM16-UCS	4.213	3.803	2.641	2.250	1.690	1.0

Table A.3
Performance of color difference equations for SSM II.

Formula	$\Delta E'$	ΔE_{00} (S_L, S_C, S_H)	$\Delta \hat{E}$	ΔE_{00} (1:1:1)	CAM16-UCS	ΔE_{ab}
$\Delta E'$	1.0	0.790	0.685	0.563	0.498	0.360
ΔE_{00} (S_L, S_C, S_H)	1.266	1.0	0.867	0.712	0.631	0.456
$\Delta \hat{E}$	1.460	1.154	1.0	0.821	0.728	0.526
ΔE_{00} (1:1:1)	1.778	1.405	1.218	1.0	0.886	0.640
CAM16-UCS	2.007	1.586	1.375	1.129	1.0	0.723
ΔE_{ab}	2.778	2.195	1.902	1.563	1.384	1.0

Table A.4
Performance of color difference equations for PR-670.

Formula	$\Delta E'$	ΔE_{00} (S_L, S_C, S_H)	ΔE_{ab}	$\Delta\hat{E}$	ΔE_{00} (1:1:1)	CAM16-UCS
$\Delta E'$	1.0	1.0	0.706	0.706	0.490	0.340
ΔE_{00} (S_L, S_C, S_H)	1.0	1.0	0.706	0.706	0.490	0.340
ΔE_{ab}	1.417	1.417	1.0	1.0	0.694	0.482
$\Delta\hat{E}$	1.417	1.417	1.0	1.0	0.694	0.482
ΔE_{00} (1:1:1)	2.041	2.041	1.440	1.440	1.0	0.694
CAM16-UCS	2.939	2.939	2.074	2.074	1.440	1.0

Table A.5
Performance of color difference equations for OS.

Formula	$\Delta E'$	ΔE_{00} (S_L, S_C, S_H)	$\Delta\hat{E}$	ΔE_{ab}	ΔE_{00} (1:1:1)	CAM16-UCS
$\Delta E'$	1.0	1.0	0.756	0.694	0.444	0.263
ΔE_{00} (S_L, S_C, S_H)	1.0	1.0	0.756	0.694	0.444	0.263
$\Delta\hat{E}$	1.323	1.323	1.0	0.918	0.588	0.348
ΔE_{ab}	1.440	1.440	1.089	1.0	0.640	0.379
ΔE_{00} (1:1:1)	2.250	2.250	1.701	1.563	1.0	0.592
CAM16-UCS	3.803	3.803	2.875	2.641	1.690	1.0

Table A.6
Performance of color difference equations for ES-V.

Formula	$\Delta E'$	ΔE_{00} (S_L, S_C, S_H)	$\Delta\hat{E}$	ΔE_{ab}	ΔE_{00} (1:1:1)	CAM16-UCS
$\Delta E'$	1.0	1.0	0.918	0.846	0.783	0.517
ΔE_{00} (S_L, S_C, S_H)	1.0	1.0	0.918	0.846	0.783	0.517
$\Delta\hat{E}$	1.089	1.089	1.0	0.922	0.852	0.563
ΔE_{ab}	1.181	1.181	1.085	1.0	0.925	0.610
ΔE_{00} (1:1:1)	1.278	1.278	1.174	1.082	1.0	0.660
CAM16-UCS	1.936	1.936	1.778	1.638	1.515	1.0

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Appendix A3

Hein, S., Morovič, J., Morovič, P., Saleh, O., Lüchtenborg, J., and Westland, S. (2025). How many tooth colors are there?. Dental Materials. [Online] 41(1), pp.51–57. Available from: https://doi.org/10.1016/j.dental.2024.10.016

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How many tooth colors are there?

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ABSTRACT

Objectives: This study aimed to estimate the number of distinct tooth colors using a large dataset of in-vivo CIELAB measurements. It further assessed the coverage error (CE) and coverage error percentage (CEP) of commonly used shade guides and determined the number of shades needed for an ideal guide, using the Euclidean distance (ΔEab) and thresholds for clinical perceptibility (PT) and acceptability (AT) as evaluation criteria.
Methods: A total of 8153 untreated maxillary and mandibular anterior teeth were measured in vivo using calibrated dental photography. Cardinality was applied to determine the number of unique natural tooth colors. The CE and CEP were calculated for the Vita Classical and Vita 3D-Master shade guides, while the cardinality method was also used to estimate the number of shades required to adequately cover the estimated gamut of natural tooth colors.
Results: The cardinality analysis revealed 1173 unique natural tooth colors. The CE for the Vita Classical shade guide was 4.1 ΔEab, with a CEP of 75 % beyond AT, while the 3D-Master shade guide had a CE of 3.3 ΔEab and a CEP of 70 % beyond AT. Based on cardinality computation, 92 discrete shades are required to adequately cover the estimated gamut of natural tooth colors with a CE of 1.2 ΔEab and CEP of 0.3 % beyond AT.
Conclusions: Cardinality computations estimated 1173 unique tooth colors while 92 discrete shades are estimated for full coverage. Such a number is impractical for physical shade guides, but new digital tools and 3D printing may offer future solutions. Both, the Vita Classical and 3D-Master shade guides do not fully represent the range of natural tooth colors.
Clinical significance: This study highlights the limitations of existing shade guides and underscores the potential for new developments.

1. Introduction

Accurate shade matching, particularly for challenging single anterior restorations, remains a critical task in restorative dentistry. Clinicians frequently report complications with shade matching [1–3], which often leads to patient dissatisfaction [4] and a significant re-make rate [5]. Studies which have compared the benefits of instrumental shade measurement with visual shade selection [6–8] commonly agree that the latter is more subjective and less reliable [9,10], yet it remains the most common approach to shade matching in dentistry [11]. Vita Classical and Vita 3D-Master are the two most popular shade guides for visual shade selection [12].

Despite their widespread use, the coverage error (CE) or its percentage (CEP) associated with these shade guides (i.e., the average distance between a natural tooth color and the closest shade tab [13]) often exceeds the threshold for clinical acceptability [13–22]. Studies have analyzed sample populations ranging from 60 [18] to 2067 [19] human teeth with reported CEs between 2.5 [22] and 8.4 [20] ΔE_{ab} units. This significant error has led to the development of hypothetical shade guides designed either to reduce the CE with the same number of shade tabs [16] or to maintain the same error with fewer tabs [14,23], thereby simplifying the shade matching process. However, none of these

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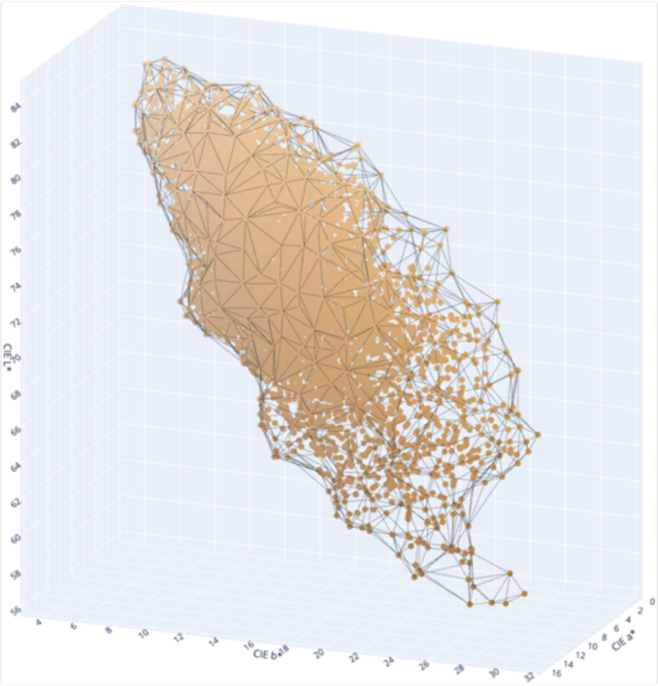

Fig. 1. Alpha hull representation of volume enclosing 8153 natural tooth colors measured in vivo in CIELAB color space ($\alpha = 2\ \Delta E_{ab}$).

suggested improvements have found their way into new shade guides to enhance clinical practice. Determining the optimal number of samples for an ideal shade guide requires consideration of several factors, including the chosen visual acceptance threshold and the gamut of natural tooth colors, which remains elusive.

Cardinality is a mathematical concept that counts the number of distinct elements in a set [24]. Understanding the cardinality of natural tooth colors—how many unique, visually distinguishable tooth colors exist—based on measured CIELAB data from a representatively large population allows for the estimation of the number of shades needed for an ideal shade guide, improving representation and shade matching accuracy in dentistry.

The eLAB system is a color measurement tool that utilizes calibrated RAW images captured with a DSLR or mirrorless camera equipped with a macro lens and a ring or lateral flash [25]. Cross-polarization is used to eliminate specular reflections from the tooth surface [26] to allow for unobstructed color measurement [27–29] regardless of ambient light conditions [30]. For consistent tooth color representation across different digital cameras, a gray reference card is used, equipped with a color checker consisting of 22 patches [31] which serve for computing a transformation matrix that relates their sRGB values to known CIELAB values. This matrix is then applied to the entire image, converting sRGB to CIELAB and subsequently back to sRGB for accurate color rendering based on the reference CIELAB data [32]. This process ensures standardization across images from different cameras, allowing for direct comparison of tooth colors [33]. The eLAB system has been used to detect tooth color changes comparable to spectrophotometric analysis [34] and to monitor changes in white spot lesions (WSLs) as a function of treatment [35]. It has been used to analyze the shade variance of identically labeled direct composite materials from different manufacturers [36] and to assess the efficiency of at-home bleaching protocols [37]. A recent multicenter study demonstrated that the eLAB system achieved visual-instrumental agreement with no significant difference in performance compared to other commonly mentioned color measurement devices including spectrophotometer, multispectral cameras and tele-spectroradiometers [38].

The aims of this study were to first estimate the number of distinct tooth colors using a large dataset of in-vivo CIELAB measurements obtained from the eLAB system, then to identify a set of hypothetical 'super shades' to best cover the gamut of natural tooth colors, and finally to assess the CE, CEP, and the frequency of individual shades for both, the most common shade guides and the identified super shades.

2. Material and methods

2.1. Study design

This study was conducted following the approval of the research ethics committee, granted under reference number 1366. All procedures adhered to ethical guidelines and received necessary consent from participants, in compliance with the EU's General Data Protection Regulation (GDPR).

2.2. Data collection

Over 29 months, a total of 121,198 RAW images were collected from users of the eLAB_prime shade matching software (Emulation, Freiburg, Germany) across 98 countries worldwide. A multi-step AI-based approach was utilized to vet the data pool. A convolutional neural network was used to assess and filter images based on quality metrics

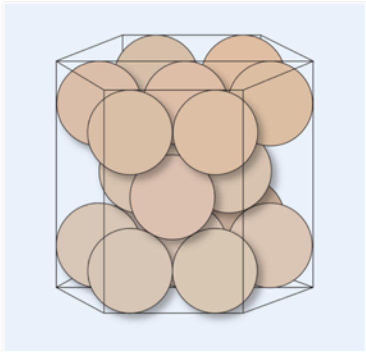

Fig. 2. Example of hexagonal close-packed sphere model of visually distinguishable tooth colors used in this study. The diameter of each sphere corresponds to the clinical threshold chosen.

[39,40], such as correct exposure, presence of a grey reference card. For duplicate detection, feature extraction followed by clustering and perceptual hashing was used [41,42]. Object detection and semantic segmentation models [43] identified and excluded images with artificial restorations. The resulting pool of images was further examined visually by five experienced master dental technicians using the eLAB_prime software (Emulation, Freiburg, Germany). This resulted in a total of 2038 RAW images to be included for the CIELAB tooth color measurement of 8153 untreated maxillary and mandibular anterior incisors.

Color measurements were taken across the incisal and medio-cervical regions of the labial surface, providing a broad representation of the tooth's color. The final color was calculated as the average of these CIELAB values, consistent with methodologies used in other studies [37,44–46].

For each Vita Classical (VC) and 3D Master (3D) shade tab, their colorimetric data were obtained using the eLAB system, following the same method used for the natural tooth color population. The reference numbers for the shade guides were +J017B0271 for VC and +J017B36002 for 3D.

2.3. Computation of cardinalities

The required condition to answer the question of how many tooth colors exist is that each color is unique, with no other color matching it. In a finite, countable set of numbers—such as tooth colors, which occupy only a small region of the CIELAB color space—cardinality simply refers to the number of unique elements in that set. Therefore, working with a restricted set of elements makes this task manageable, unlike trying to determine how many colors there are in total, from a set of infinite or practically infinite elements [47,48].

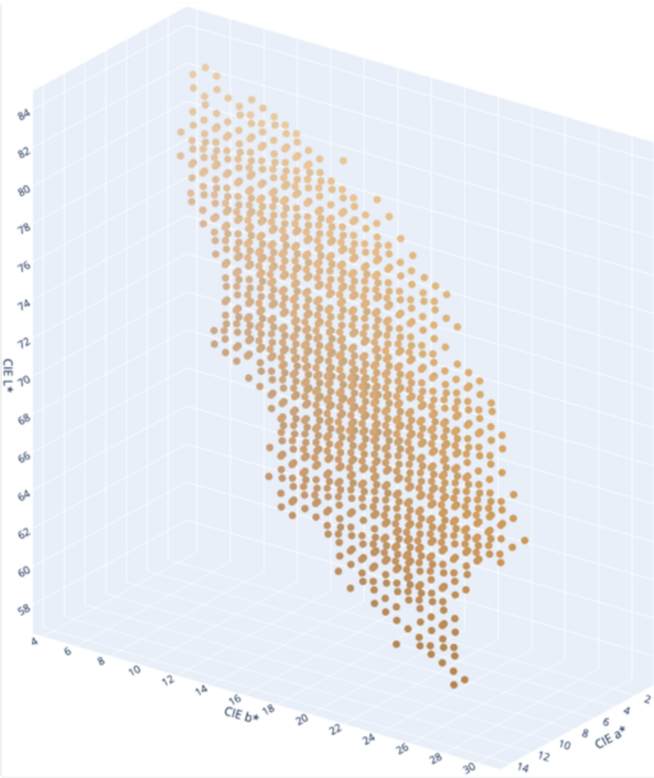

Fig. 3. Depiction of cardinalities revealing 1173 unique natural tooth colors.

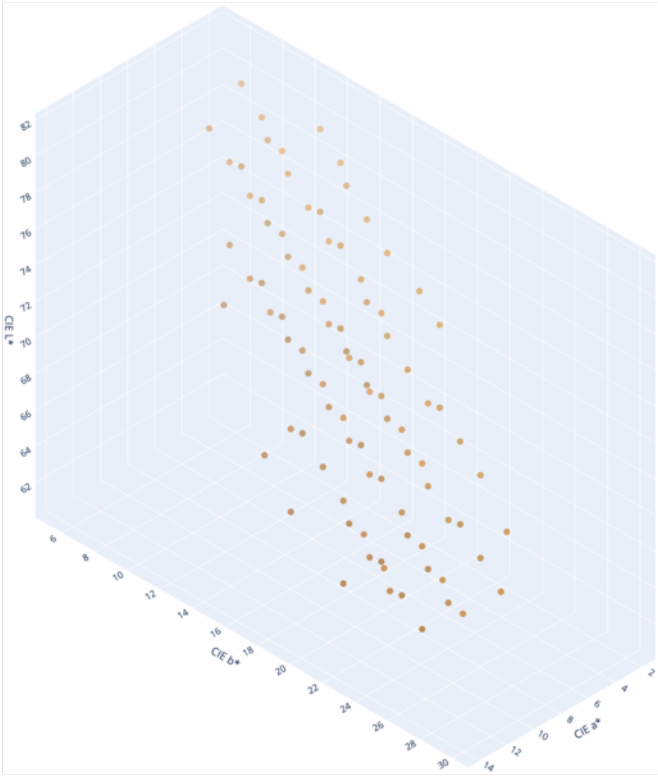

Fig. 4. Representation of 92 super shades, indicating minimum number of shade tabs required for an ideal shade guide.

First, an appropriate color difference metric needed to be nominated. In this case the CIE 1976 ΔE_{ab} formula was chosen because a recent multicenter study [38] demonstrated that the eLAB system achieved an outstanding 82 % visual-instrumental agreement using ΔE_{ab}, outperforming much more complex color difference equations such as CIEDE2000 and CAM16-UCS.

Next, a volume space containing 8153 natural tooth coordinates S in CIELAB color space was used for the efficient construction of a convex hull called an α-shape which presents the hull containing all points of S such that no more than three hull vertices are contained in a sphere of radius α [49]. In this context, α is a sufficiently small, positive real number chosen to construct a boundary of the natural tooth color gamut such that its value represents a desired level of tolerance to concavity. In the present case a value of $\alpha = 2$ ΔE_{ab} units was chosen for the construction of the convex hull since it provided a good balance between the density of S and the low thresholds used for perceptibility and acceptability in dentistry [50] (Fig. 1). Then, a custom Python routine (Python Software Foundation, Wilmington, DE, USA) was employed to quantify the cardinality of the most densely packed set of unique colors in the α-shape of natural tooth shades, ensuring that the difference between any two points is greater than or equal to the threshold for clinical perceptibility, set at 1.2 ΔE_{ab} units [50]. This was achieved with a hexagonal closed sphere-packing model [51], where each tooth color was represented by a sphere with its center at that color and with a diameter matching the corresponding ΔE_{ab} threshold value of 1.2 ΔE_{ab}. The number of non-overlapping spheres within the dataset indicated the cardinality, providing a measure of distinct tooth colors (Fig. 2).

2.4. *Identifying super shades*

To identify a set of 'super shades,' representing hypothetical tooth colors that best cover the range of natural tooth colors, the cardinality calculation was repeated. The goal of an ideal shade guide is to provide adequate coverage of the natural tooth color gamut within the clinically acceptable range, while remaining as practical as possible. Therefore, the same convex hull and sphere packing model was employed, but with the sphere diameter was set to 2.7 ΔE_{ab} units corresponding to the threshold for clinical acceptability [50].

2.5. *Computation of coverage error and coverage error percentage*

To compute the CE and the CEP for the VC and 3D shade guides, the color differences between each of the 8153 sample tooth colors and each reference shade tab from both shade guides were calculated under Illuminant D65 and for the CIE 1931 standard colorimetric observer [52] using the ΔE_{ab} color difference equation in MATLAB (MathWorks, Natick, MA, USA). For each natural tooth color, the reference shade tab with the minimum color difference was identified, and the frequency of each reference shade tab being the closest match was recorded. The CE was determined by averaging the minimum ΔE_{ab} values across all sample tooth colors using this formula:

Table 1
CE and CEP along with standard deviations (SD) for the Vita Classical (VC) and for the 3D-Master (3D) shade guides respectively.

Shade Guide	CE (ΔE_{ab}) (SD)	CEP ≤PT (SD)	CEP >PT, ≤ AT (SD)	CEP >AT (SD)
VC	4.1 (1.8)	1.1 % (0.2)	24.3 % (0.4)	74.6 % (1.6)
3D	3.3 (1.4)	3.0 % (0.2)	27.8 % (0.7)	70.3 % (1.2)
Super Shades	1.2 (0.4)	33.8 % (0.2)	65.9 % (0.3)	0.3 % (1.5)

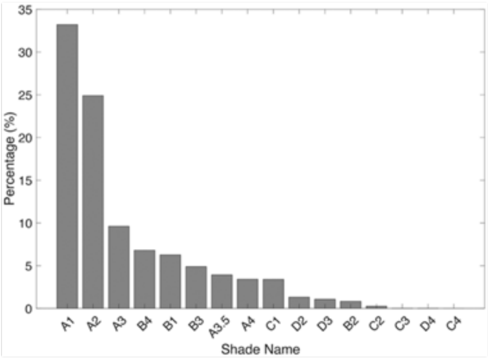

Fig. 5. Percentages of shade frequency for Vita Classical shades.

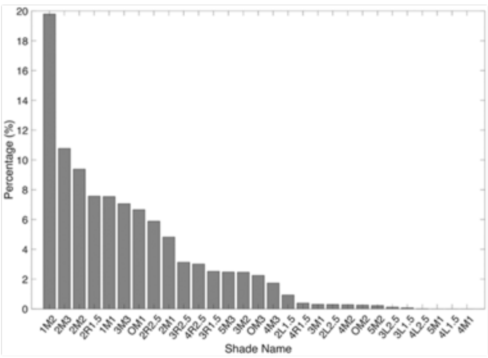

Fig. 6. Percentages of shade frequency for Vita 3D-Master shades.

$$CE = \frac{\sum_{i=1}^{n} \min(\Delta E_i)}{n}$$

To express the CEP, the proportion of occurrences for each shade tab was calculated and normalized by the total number of sample tooth colors using this formula:

$$CEP_j = \left(\frac{occurences_j}{n}\right) \times 100$$

The resulting percentages were then sorted from high to low, to facilitate a comparative analysis. Accordingly, the same computations were carried out to evaluate the effectiveness of super shades.

3. Results

3.1. Cardinalities and super shades

Based on the threshold for clinical perceptibility (ΔE_{ab} 1.2), the computation of cardinalities revealed 1173 unique natural tooth colors (Fig. 3) and 92 super shades when the thresholds for clinical acceptability (ΔE_{ab} 2.7) was used, representing the minimum number of shade tabs that an ideal shade guide would need (Fig. 4).

3.2. Coverage error of shade guides and super shades

Table 1 lists the CE and CEP results for VC, 3D shade guides and the super shades, along with their standard deviations. Fig. 5 shows the percentages for the most common shades of the VC shade guide while Fig. 6 displays the corresponding values for the 3D shade guide and Fig. 7 for the super shades.

4. Discussion

This study aimed to estimate the number of distinct tooth colors based on 8153 in-vivo CIELAB measurements and to determine the CE and CEP of the most common shade guides alongside a set of hypothetical 'super shades'.

Previous studies have reported similar CEs for the VC and 3D shade guides, averaging 4.4 ΔE_{ab} and 4.2 ΔE_{ab}, respectively [13–22,53–57]. Our findings align with these reports, confirming that while widely used, current shade guides are limited in covering the full range of natural tooth colors. Using cardinality computation, this study estimated that a set of 92 super shades could potentially cover the gamut of natural tooth colors with a CEP of only 0.3 % outside the threshold for clinical acceptabitly.

The reported frequencies of individual shades with the lowest CEP also vary considerably. The findings of this study are generally in agreement with those of Ruiz Lopez et al. [22] and Paravina et al. [16] but differ from Bayindir et al. [15] and Tabatabaian et al. [21], who both reported that the VC shade 'D3' had the lowest CEP frequency.

While training programs for visual shade matching have been

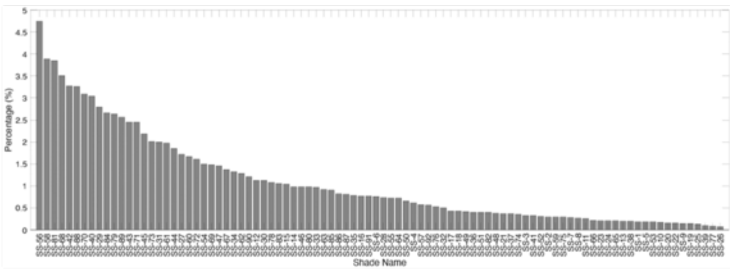

Fig. 7. Percentages of shade frequency for 92 super shades (SS).

proposed [58–61] the present study highlights the persistent challenges in achieving accurate shade matches, even with training. Recent research has also focused on evaluating the accuracy of shade measurement devices [7,9,62–64] and, more recently, intraoral scanners [7,65,66]. However, the results of this study suggest that discrepancies in shade matching may stem more from the coverage error of shade guides than from device accuracy [67].

Although a physical shade guide consisting of 92 discrete shades would be highly impractical, the insights from the present study could prove beneficial in the near future with the rise of digital tools for shade matching [31,68] and new technology like 3D printing [69].

Tooth color appearance is a complex phenomenon [70] and cannot be fully captured by CIELAB values alone. In clinical practice, acceptance or rejection of a restoration often depends on situational factors that cannot be wholly accounted for by visual thresholds alone. For instance, a clinical study by Ballard et al. [57] found that 94 % of patients were at least satisfied or extremely satisfied with a clinical shade-match that was well beyond the clinical acceptability threshold assumed in the present study.

It is also important to recognize that the results of the cardinality computation depend on specific input parameters, such as the definition of alpha-radii and the chosen visual threshold values. Consequently, the results are accurate for color differences computed using Euclidean distance but may not hold for other color difference equations. This is because the volume of the alpha hull, and how many spheres can be packed within it, is determined by the visual thresholds and the color difference equation used, which in turn define the diameter of each sphere. However, even with variations in these parameters, the overall finding remains consistent: a significantly larger number of shade tabs is needed for an ideal shade guide than is currently available.

5. Conclusion

To the best of our knowledge, the present study comprises the largest gamut of natural tooth colors ever published. Unfortunately, the results show that the likelihood of selecting a shade that is either clinically imperceptible or at least acceptable is one in four for the VC shade guide (25 %) and nearly one in three for the 3D-Master shade guide (31 %). On the other hand, a physical shade guide to achieve almost complete coverage is estimated to require 92 discrete shade tabs. These findings highlight the inherent challenges when trying to select the right shade during daily clinical practice.

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Appendix A4

Hein, S., Masannek, M., Westland, S., Spies, B. C., Wrbas, K. T., and Nold, J. (2024). A novel approach for the replacement of accuracy and precision measurements with the visual instrument agreement scale (VIAS) in evaluating the performance of four intraoral scanners and one shade measurement device. Journal of Dentistry. [Online]. 151, p.105458. Available from: https://doi.org/10.1016/j.jdent.2024.105458

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A novel approach for the replacement of accuracy and precision measurements with the visual instrument agreement scale (*VIAS*) in evaluating the performance of four intraoral scanners and one shade measurement device

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A R T I C L E I N F O

Keywords:
Tooth color measurement
Visual-instrumental agreement scale (*VIAS*)
Intraoral scanners
Accuray and precission
STRESS index
Psychophysics

A B S T R A C T

Objectives: The terms 'accuracy' and 'precision' are tightly defined in color science but are often used ambiguously in dental research. This study introduces the visual instrument agreement scale (*VIAS*), a new method for determining visual-instrumental agreement in dental colorimetry by comparing visually perceived and measured color differences.
Materials and methods: In-vivo tooth color measurements were taken from 16 participants using four intraoral scanners (Primescan, Medit i700, Carestream CS3700, Trios 3) and one spectrophotometer (Vita Easyshade V). Visual shade assessment was also performed by one expert observer using the 3D Master shade guide. Statistical significance testing was conducted using the *STRESS* index to calculate *VIAS*, and the *F*-statistic was used to evaluate device performance.
Results: Carestream CS3700 achieved the highest visual-instrumental agreement with a *VIAS* score of 82 %, performing significantly better than the other devices. Primescan, Medit i700, and Trios 3 showed scores of 76 %, 75 %, and 72 %, respectively, with no significant differences between them. Vita Easyshade V scored 57 %, performing significantly worse than the other devices.
Conclusions: The overall performance of the intraoral scanners was strong, with Carestream CS3700 approaching excellent performance. The *VIAS* method offers a practical, color science-based framework for evaluating visual-instrumental agreement and can be easily replicated using the freely available toolbox.
Clinical significance: Intraoral scanners performed surprisingly better than a spectrophotometer specifically designed for tooth color measurement and which is often regarded as the gold standard. Additionally, *VIAS* offers a new, scientifically grounded approach for testing visual-instrumental agreement in dental colorimetry.

1. Introduction

There is a growing interest in dental research to assess the accuracy and precision of shade measurement devices [1,2], including, more recently, intraoral scanners (IOS) [3]. These devices play and increasingly important role in restorative dentistry and claim the ability to measure tooth shades as well [4,5].

However, it is important to recognize that in the medical field, the terms "accuracy" and "precision" are often used interchangeably, which can create confusion. For example, there is no semantic difference between a marginal fit that is described as "precise" or "accurate"; both terms imply that the restoration fits well. This lack of distinction does

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not pose problems in many areas of dentistry but can lead to significant misunderstandings in color-related research.

In color science, "accuracy" and "precision" have tightly defined meanings. The failure to clearly differentiate between these terms can cause considerable confusion when assessing the performance of shade measurement devices.

Colorimetric accuracy is measured by calibration against recognized standards (Fig. 1). National standardization laboratories, using advanced instruments and meticulous procedures, typically conduct the measurement of these standards. Each standard is accompanied by a certificate that outlines the estimated measurement uncertainty [6].

Precision, on the other hand, refers to the closeness of agreement between repeat test results obtained under specific conditions [7]. It is typically measured through repeatability and reproducibility. Repeatability evaluates an instrument's ability to consistently produce the same measurements under the same conditions, while reproducibility tests whether the results remain consistent when some condition—such as the operator or the instrument—has changed [8].

It is tempting to nominate a device as the reference (or "gold standard") simply because it is labeled as a 'spectrophotometer', assuming that other spectrophotometers will measure the same tooth samples in much the same way. However, this assumption is false, as illustrated in Fig. 2, which shows the color measurements of 26 teeth taken with several different devices, all of which are labeled as 'spectrophotometers'. Which of these represents the 'true' values?

In situations where standard instrumental methods may not fully capture the perceptual aspects of color differences, psychophysical experiments are employed. These experiments rely on human observers to assess visually perceived differences between samples by applying visual scaling techniques [9,10].

One commonly used technique for psychophysical experiments is the "grey scale method" [11]. In this method, an observer is presented with a test sample pair and asked to assess the perceived color difference relative to a grey scale. The grey scale consists of achromatic samples of varying lightness but identical shape and size to the test samples. The observer selects the grey pair that most closely matches the magnitude of the test pair's color difference.

In this setup, the color difference between the measured CIELAB values of the test pair is referred to as the computed color difference ΔE. The color difference judged by the observer using the grey scale is referred to as the visual color difference ΔV [12,13].

The computed and visual color differences can be used to calculate the standardized residual sum of squares (*STRESS*) index, which is employed to determine the level of agreement between visual and instrumental measurements [14]. The *STRESS* index is currently

Fig. 1. A set of 12 color standards (Lucideon tiles) typically serves as benchmarks for evaluating the precision and accuracy of color measurements in color science.

regarded as the gold standard in color science and is primarily used to evaluate the performance of color difference equations based on data from psychophysical experiments like the grey scale method [15–17].

The aim of the present study is to provide dental researchers with a novel approach for determining visual-instrumental agreement using the visual instrument agreement scale (*VIAS*), grounded in the principles of color science. This study utilizes *in-vivo* clinical data obtained from four intraoral scanners and one shade measurement device. The null hypothesis was that there is no difference in visual-instrumental agreement, as analyzed via the *STRESS* index and *VIAS*, between the tested devices.

2. Materials and methods

2.1. Selection of participants

In preparation for this study, an application for proportional ethical review was submitted and subsequently granted approved by the local Ethics Committee of the Medical Faculty (Ethical approval number EK-Freiburg 21-1169) and was conducted in accordance with good clinical practice and the Declaration of Helsinki. The study included 16 participants, both female and male, all under the age of 35, with natural, unrestored teeth. Throughout the study, the teeth investigated were tooth 21 (the left maxillary central incisor), tooth 23 (the left maxillary canine), and tooth 26 (the first left maxillary molar). To protect participants' personal data, all information was collected anonymously. Full access to the data sets was restricted to the project management team, ensuring that patients could not be directly identified.

2.2. Included devices

IOS devices' ability to measure tooth color is a topic of growing interest among researchers and practitioners. The Vita Easyshade, frequently cited as a reference device in dental research, is often regarded as the gold standard. Table 1 lists the devices included in this study, comprising four intraoral scanners (IOS) and the Vita Easyshade V.

2.3. Visual shade assessment

Visual shade assessment was conducted by a single expert observer, with dual training in dental technology and clinical dentistry, and experience in both fields. The shade selection was performed using a new 3D Master shade guide. For each assessment, the patient was seated in an upright position directly in front of the observer. All assessments took place in the same clinic during regular working hours, with suitable lighting environment for shade assessment. The clinic featured large north-facing windows that provided ample natural light, supplemented by color-corrected ceiling lighting and with the walls painted white.

2.4. Instrumental shade measurement

Instrumental shade measurements were conducted by the same operator over several days, with each measurement session following a consistent sequence. The order of measurement was as follows: Easyshade, Primescan, Medit, Carestream, and finally Trios.

For Easyshade, the labial and buccal tooth color was measured in three regions: the incisal, middle, and cervical areas. The average of these three regions was used for analysis.

Following the Easyshade measurements, scans were performed for each device on the entire maxilla of the patient. Each full measurement sequence was completed in under two minutes [18]. To further prevent color changes due to dehydration, patients were provided with a cup of water at room temperature to rinse their mouths and rehydrate their teeth after each measurement.

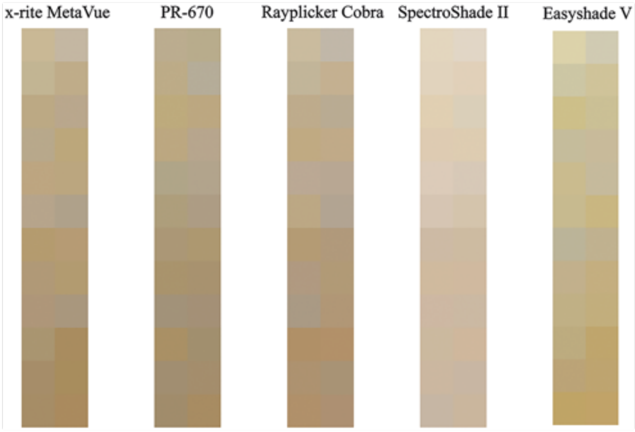

Fig. 2. sRGB visual representations of the color measurements of 26 teeth taken with various spectrophotometers. Despite their identical classification, each device produces different results. Which of these represents the "true" values?.

Table 1
Device models, manufacturer locations, and abbreviations used in the study.

Device Name	Manufacturer	Location	Abbreviation
Primescan	Dentsply Sirona	Bensheim, Germany	'Primescan'
Medit i700	Medit	Seoul, South Korea	'Medit'
CS3700	Carestream LLC	Atlanta, USA	'Carestream'
Trios 3	3Shape	Copenhagen, Denmark	'Trios'
Easyshade V	Vita Zahnfabrik	Bad Säckingen, Germany	'Easyshade'

2.5. Processing of spectral data

The spectral data from Easyshade was processed using a dedicated software package provided by the manufacturer (ES_Helper, version 1.0.11081.369, Vita Zahnfabrik, Germany). The software connects to the device via Bluetooth and provides access to spectral data ranging from 400 to 700 nm in 10 nm intervals, corresponding to the measured tooth color.

In addition to the measurements of tooth color, the physical shade tabs of the same 3D Master shade guide that was used for visual assessment were also measured to obtain their spectral data. Both sets of spectral data were converted to CIELAB coordinates using Illuminant D65 and the CIE 1931 standard colorimetric observer [19], ensuring consistent data processing across all measurements. The software also identified the nearest 3D Master Shade for measured tooth color.

2.6. Processing of IOS data

Intraoral scans were collected in file formats compatible with the open-source software MeshLab software (www.meshlab.net, version 2023.12). Scans from Primescan and Medit were saved in the Wavefront OBJ file format along with MTL files, which define the light-reflecting properties of surfaces for computer rendering. Scans from Carestream and Trios were saved in the Polygon File Format (PLY).

Each scan was imported into MeshLab, where the scans were 3D rotated to obtain a full labial/buccal view of the teeth to be measured. In the vertices panel, 'Shading' was set to 'None,' and 'Color' was set to "Vert." The built-in 'snapshot' feature of MeshLab was used to export each view with a solid black background as a PNG file, which was then saved to the appropriate output folder.

In addition to the scans, the nearest 3D Master shade provided by each IOS software was recorded. Furthermore, each shade tab from the same 3D Master shade guide used for visual assessment was measured with each IOS and the data was processed in the same way as described above.

2.7. Data evaluation

A dedicated MATLAB routine was used to import each PNG file and apply the polygon function to manually capture the average sRGB values from the labial and buccal surfaces of the teeth to be measured (Fig. 3). The collected sRGB data were then converted to XYZ, and subsequently to CIELAB, for Illuminant D65 and the CIE 1931 standard colorimetric observer [19]. This process was carried out using a specialized color toolbox in MATLAB (R2023b; MathWorks, Natick, MA, USA).

The resulting data included the average tooth color from each IOS and the Easyshade device. Additionally, the nearest shade suggested by the Easyshade or by the IOS software was recorded, along with the CIELAB coordinates for the 3D Master shade guide for each device.

2.8. Calculation of the STRESS index and VIAS

As explained in Fig. 4, for each tooth measured (21, 23, and 26), CIELAB values were obtained for both, the natural tooth color and the nearest shade tab selected by the visual observer for each device. Using these CIELAB values, the CIE 1976 color difference between the target color (L_1, a_1, and b_1), and the observer-selected shade tab (L_2, a_2, and b_2), was computed, referred to as ΔV:

$$\Delta V = \sqrt{(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2}$$

Similarly, the CIELAB values for the nearest shade suggested by the device software (IOS or Easyshade) were used to calculate ΔE, which represents the computed color difference between the actual tooth color and the device-recommended shade according to the CIE 1976 color difference equation, where L_3, a_3, and b_3 correspond to the CIELAB values measured by the device:

$$\Delta E = \sqrt{(L_1 - L_3)^2 + (a_1 - a_3)^2 + (b_1 - b_3)^2}$$

The computation of the *STRESS* index was aided by a free toolbox, available for download at www.saschahein.co.uk/downloads. This toolbox is compatible with MATLAB, Python, and Excel, and comes with comprehensive explanations and examples for testing. It simplifies the

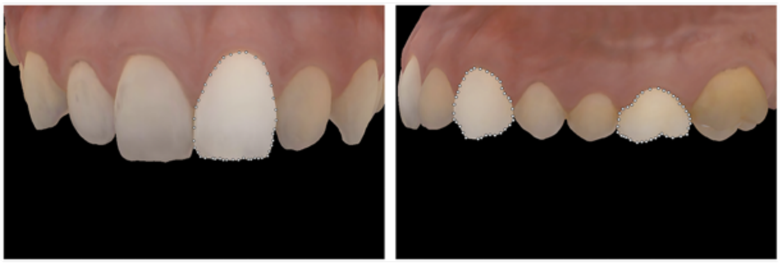

Fig. 3. Example of an intraoral scan (Trios) imported into MeshLab software, with shading set to 'off' and exported as PNG files using the 'snapshot' function. These two PNGs were then opened in MATLAB, where the polygon function was applied to capture the average color coordinates of teeth 21, 23, and 26 for further evaluation.

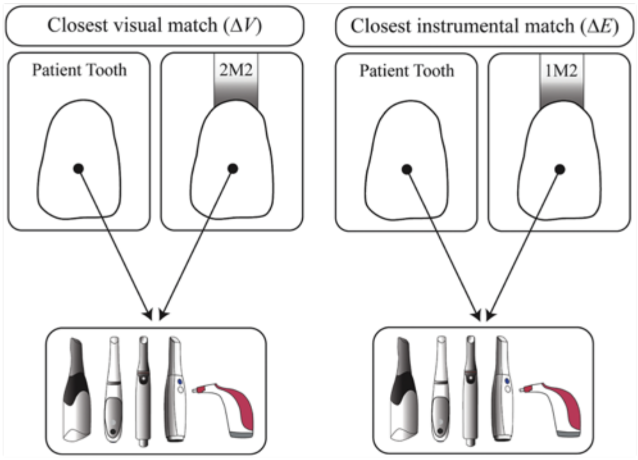

Fig. 4. Computation of *VIAS* with an example. In this scenario, the visual observer has selected '2M2' as the closest visual match, while the instrument has determined that '1M2' represents the smallest computed color difference. For each device, three CIELAB measurements are required: one for the target tooth, one for the shade tab selected by the observer, and one for the shade tab selected by the device. The computed color difference between the patient's shade and the observer-selected shade tab is referred to as 'ΔV', while the computed color difference between the patient's shade and the device-selected shade tab is 'ΔE'. These values serve as the input for calculating the *STRESS* index and subsequently for *VIAS*.

process, allowing users to focus on the analysis rather than manual computations.

The *STRESS* index was computed to quantify the agreement between the visual shade selection and the device's computed selection:

$$STRESS = 100\left(\frac{\sum_i(\Delta E_i - F_1\Delta V_i)^2}{\sum_i F_i^2 \Delta V_i^2}\right)^{1/2} \text{ and } F = \frac{\sum_i \Delta E_i^2}{\sum_i \Delta E_i \Delta V_i}$$

Finally, *VIAS* was simply computed as:

$$VIAS\ (\%) = 100 - STRESS$$

2.9. *Computation of F-statistic for evaluation of individual device performance*

To evaluate the performance of different devices, the *F*-statistic was computed using the *STRESS* index. The *F*-value was calculated as follows:

$$F = \frac{STRESS^2_{Device\ A}}{STRESS^2_{Device\ B}}$$

This *F*-value was then compared against a critical threshold ($F < F_C$ or $F > 1/F_C$) based on the two-tailed *F*-distribution with a 95 % confidence interval and degrees of freedom ($N-1$, $N-1$), where *N* represents the sample size of visually scaled and measured sample pairs (i.e., $N = 3 \times 16 = 48$)

In the present case, $F_C = 1.623$ and $1/F_C = 0.616$. If the *F*-value exceeded the critical threshold F_C, the null hypothesis was rejected, indicating that device A performed significantly better than device B. Similarly, if the *F*-value falls below the critical value of 1/FC the null hypothesis was also rejected, indicating that device A performed significantly worse than device B. Lastly, if the *F*-value falls between Fc and 1/FC it was assumed that there was no significant difference between device A and device B.

3. Results

3.1. *STRESS index and VIAS scores*

The *STRESS* index values and *VIAS* percentages for each device are shown in Table 2, with *STRESS* values ranging from 18 to 43 and *VIAS*

Table 2
STRESS index and *VIAS* each device.

Device	*STRESS*	*VIAS* (%)
Carestream	18	82
Trios	24	76
Primescan	25	75
Medit	28	72
Easyshade	43	57

from 57 % to 82 %.

3.2. Individual device performance

Table 3 presents the *F*-test results for analyzing individual device performance.. Carestream performed significantly better than all other tested devices, while Trios, Primescan and Medit showed no significant differences. Easyshade performed significantly worse than the other devices.

4. Discussion

The primary aim of the present study was to provide dental researchers with a new approach for determining visual-instrumental agreement, grounded in the principles of color science. This approach draws inspiration from methods traditionally used in other fields, such as the grey scale method, which originated in color fastness testing in the textile industry [20], where it is used to describe changes in staining through visual comparison with a grey scale [21]. Since color fastness testing is typically carried out on fabrics that cover a wide range of colors, using a grey scale is a sensible choice, though not strictly necessary. For this study, the grey scale method was distilled to its fundamental principle: relating the instrumental color difference between a pair of samples to the visually perceived color difference between another pair, selected by an observer for the closest match using traditional shade tabs, thus omitting the need for a grey scale. This approach replaces the "gold standard" device with the expert observer and provides a statistical measure of relative device performance using the *STRESS* index and *VIAS*.

In the present study, the results led to the rejection of the null hypothesis, as there were significant differences among tested devices. As shown in Table 3, the performance of Carestream was significantly better than all other devices, while no significant differences were found between Trios, Primescan, and Medit. Surprisingly, Easyshade performed significantly worse than the other tested devices, despite being frequently mentioned in dental research [1]. The results for *VIAS* are generally consistent with a recent multi-center study [14] that also used the *STRESS* index, though it employed a different visual scaling technique known as ‘magnitude estimation’, commonly used in psychophysical research. Such congruency between different psychophysical experiments is ideally expected [22,23]. Performance values for *VIAS* between 70 and 80 % are generally considered to be excellent as demonstrated in other studies which were rigorously controlled [17]. While the theoretical maximum is 95 %, this is rarely achievable in practice and remains a purely theoretical limit [24].

Domain-dependent semantic differences, along with the lack of clear definitions for accuracy and precision in the context of dental colorimetry, have led to considerable confusion in the dental literature. Far too many studies to mention have mistakenly conflated accuracy with what is better described as 'inter-device agreement', while others have used ‘accuracy’, ‘precision’, ‘reliability’, and ‘reproducibility’ interchangeably [1,3].

The idea of obtaining a measure of device accuracy instrumentally for objective assessment is, of course, tempting. The afromentioned reference standards (Fig. 1) were designed for this purpose – to analyze color measurement precision and accuracy [25,26]. However, such measurements are highly technical and sensitive to environmental factors, such as temperature [8]. Addiontally, the reference values provided by national standardizing laboratories are limited to specific CIE-recommended illumination geometries [27], which are rarely matched by dental shade measurement devices for clinical use [28–30].

For these reasons, using a psychophysical approach, as demonstrated in the present study, may be the most feasible option for obtaining a measure of device performance that relates to clinical reality. The use of expert observers for such experiments is crucial to avoid introducing noisy data. The inclusion of only one expert observer is, of course, a limitation of the present study. Ideally, a population size of 20 expert observers would provide more robust data [8]. However, the use of a limited number of expert observers in fundamental colorimetric research is not uncommon. MacAdam [31] for instance, derived color discrimination ellipses from a single observer, and these have served as the fundamental basis for defining just noticeable color differences ever since [32]. A further limitation of this study is the use of the *F*-statistic for pairwise comparisons without correction for multiple comparisons, which could influence the experiment-wise error rate; however, this approach aligns with precedent in color science literature [17] and was selected to provide a practical and accessible evaluation method.

Despite these limitations, the methodology presented here offers a straightforward approach for researchers with an interest in dental colorimetry. The freely available toolbox allows access to the required computations, facilitating evaluation of relative device performance grounded in the principles of color science. Knowledge of coding in MATLAB is not essential, as other readily available digital tools, such as Classic Color Meter software (MacIntosh AC, Ricci Adams), can also be used to measure CIELAB values from images containing natural teeth [33–36].

5. Conclusion

This study introduces a new approach to dental colorimetry called *VIAS*. Significant differences were found between the tested devices, with Carestream performing best, while there was no signficiant performance difference between other tested IOS devices. Despite the limitations of the present study, the *VIAS* method provides a practical framework for future research, supported by a freely available toolbox

Table 3
F-test results for device comparisons using ΔE_{ab}. Yellow cells indicate significantly better performance, grey cells indicate significantly worse performance, and blue cells indicate no significant difference.

Device	Carestream	Trios	Primescan	Medit	Easyshade
Carestream	1.0	0.563	0.520	0.415	0.176
Trios	1.778	1.0	0.951	0.758	0.321
Primescan	1.929	1.085	1.0	0.781	0.331
Medit	2.420	1.361	1.256	1.0	0.424
Easyshade	5.707	3.210	3.012	2.401	1.0

for easy replication.

CRediT authorship contribution statement

Sascha Hein: Writing – original draft, Methodology, Investigation, Conceptualization. **Matthias Masannek:** Resources, Project administration, Investigation. **Stephen Westland:** Writing – review & editing, Validation, Supervision, Methodology. **Benedikt C. Spies:** Writing – review & editing, Supervision, Resources. **Karl Thomas Wrbas:** Supervision, Resources, Project administration. **Julian Nold:** Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sascha Hein reports was provided by University of Leeds. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A5

Hein, S., Nold, J., Masannek, M., Westland, S., Spies, B. C., and Wrbas, K. T. (2025). Comparative evaluation of intraoral scanners and a spectrophotometer for percent correct shade identification in clinical dentistry. Clinical Oral Investigations. [Online]. 29(1), pp.39. Available from: https://doi.org/10.1007/s00784-024-06124-0

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RESEARCH

Comparative evaluation of intraoral scanners and a spectrophotometer for percent correct shade identification in clinical dentistry

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Abstract

Objectives The study aimed to assess the percent correct shade identification of four intraoral scanners (IOS) and a spectrophotometer, focusing on how reliably each device selects the correct tooth shade compared to a visual observer's selection. The research question addresses how much clinicians can trust the device-selected shade without visual verification.

Materials and methods Sixteen participants with natural, unrestored teeth were included. The teeth evaluated were tooth 21 (left maxillary central incisor), tooth 23 (left maxillary canine), and tooth 26 (first left maxillary molar). Tooth color was measured using four IOS devices and the Vita Easyshade V in three regions: incisal, middle, and cervical. The nearest 3D Master shade selected by each device was compared to the visual observer's selection. The percent exact match, acceptable match ($> 1.2, \leq 2.7\ \Delta E_{ab}$), and mismatch type A ($< 2.7, \leq 5.4\ \Delta E_{ab}$) were calculated. Statistical analysis was performed using a chi-square test with a 95% confidence level.

Results The overall clinical pass rate was highest for Carestream (78.2%), followed by Easyshade (63.5%), Primescan (51.2%), Trios (39.5%), and Medit (31.3%). Carestream also recorded the highest rate of mismatch type A (47.7%). Significant differences between devices were observed for all categories ($p < 0.05$).

Conclusions Carestream demonstrated the highest overall clinical pass rate, while Medit exhibited the lowest. The study highlights the variability between devices in shade matching performance.

Clinical relevance This study highlights the importance of considering device performance when relying on IOS or spectrophotometers for shade selection without visual assessment, as the reliability can vary significantly across devices.

Keywords Intraoral scanners · Shade matching · Color measurement · Shade guide reliability · Visual-instrumental agreement

Sascha Hein and Julian Nold contributed equally to this work as co-first authors.

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Introduction

Achieving accurate shade matching in dentistry poses a significant challenge for restorative teams [1], with color mismatches frequently leading to esthetic issues [2] and substantial costs [3]. Visual shade selection remains the most widely used method in dentistry; however, it is often subjective and inconsistent [4]. Various observer-related factors, including gender [5–7], experience [8, 9] and color vision deficiencies [10], can significantly affect its reliability. Among environmental factors, the type and quality of lighting in the dental setting play a critical role in the accuracy of visual shade matching [11]. Recent research has highlighted the extensive variability in natural tooth color, identifying 1,173 unique, visually distinguishable shades—a diversity that current shade guides fail to fully encompass [12]. Additional factors such as geographic location, gender, age, and ethnicity have also been shown to influence natural tooth color [13].

Due to these complexities, instrumental shade measurement has garnered increasing interest, prompting a growing focus on evaluating the accuracy and precision of shade measurement devices [14, 15], with recent attention given to intraoral scanners (IOS) [16–19]. These devices are becoming more essential in restorative dentistry, with claims that they can also accurately measure tooth shades [20, 21].

In clinical dentistry, the terms *accuracy* and *precision* are often used interchangeably, though their meanings can differ from how they are understood in color science. For example, an impression is said to be *accurate*, while there may be discussions of *marginal precision* in relation to indirect restorations or tooth anatomy replication [22]. In these contexts, *accuracy* and *precision* often imply a high level of congruency between the desired outcome and what was achieved, leading to their frequent interchangeable use.

However, in color science, these terms are strictly defined, which can lead to confusion in dental colorimetric research. Colorimetric uncertainty is separated between accuracy and precision. Colorimetric accuracy refers to the calculated color difference between the spectral reflectance factors of reference standards, such as a set of 12 ceramic tiles, and the corresponding measurements from a given test device [23–25]. Colorimetric precision on the other hand refers to how consistently a measuring device provides results [26]. It is assessed by calculating the average color differences between 30 recommended repeated measurements of the same reference standards under identical conditions while colorimetric reproducibility measures consistency when certain conditions, such as the operator or sample, are varied [27, 28].

Performing proper assessments of accuracy and precision in the context of instrument profiling is not a trivial task [29, 30] and may not even be feasible for many shade measurement devices used in dentistry. These devices often rely on a mix of measurement technologies combined with illumination geometries outside of those recommended by the *Commission internationale de l'éclairage* (CIE), to facilitate easy operation and meet clinical requirements.

Numerous studies have set out to investigate *supposed* device accuracy [31], often by designating a spectrophotometer, most commonly the Vita Easyshade, as the *gold standard* [32–35], assuming it measures the *true* colorimetric values. The computed color difference between a set of tooth-colored samples measured by a test device and the reference device is frequently misinterpreted as colorimetric accuracy when it would be more accurately described as *inter-device agreement* [36]. Other studies have aimed to count how often a test device's selected shade matched the visual shade selection by an experienced observer, reporting the results as *accuracy* [4, 37]. However, this approach would be more appropriately termed *percent matching shade identification*.

Nevertheless, evaluating the congruency between observer- and instrument-selected shades offers practical insights into how much clinicians can rely on established shade measurement devices and, increasingly, on IOS, especially when visual shade selection was not performed due to the demands of clinical practice.

Therefore, the aim of this study was to evaluate the reliability of shade selection by four contemporary IOS and one spectrophotometer, comparing device performance against an expert visual observer. The primary objective was to assess the clinical reliability of each device in shade selection by gathering data on the clinical pass rate, indicating how much clinicians can depend on the device's shade selection in practice. The null hypothesis was that there is no difference in device performance.

Materials and methods

Study setting

For this study, a proportional ethical review application was submitted and received approval from the local Ethics Committee of the Medical Faculty (Approval number: EK-Freiburg 21-1169). The study followed good clinical practice guidelines and adhered to the principles outlined in the Declaration of Helsinki. A total of 16 participants, male and female, all under the age of 35 and with natural, unrestored teeth, were included. Participants were instructed to maintain high dental hygiene prior to their appointment, which was verified by the dentist to ensure all measurements were performed on clean teeth. The teeth evaluated in this study were tooth 21 (left maxillary central incisor), tooth 23 (left maxillary canine), and tooth 26 (first left maxillary molar). Participant data was collected anonymously to protect their privacy, and only the project management team had access to the full data sets, ensuring no direct patient identification.

Study procedure

The devices examined in this study, listed in Table 1, include four contemporary IOS and the Vita Easyshade V. All devices were operated in accordance with the manufacturers' recommendations, following specified scanning procedures and calibration protocols.

A single expert observer, with seven years of experience as a dental technician and three years of experience as a dentist, conducted the visual shade assessments. The observer utilized a 3D Master shade guide (LOT J017B027IO, VITA Zahnfabrik, Bad Säckingen, Germany) for visual shade selections in three regions: the incisal, middle, and cervical areas of the labial and buccal surfaces. During each assessment, the patient sat upright, facing the observer. The lighting environment was optimized for shade selection, featuring large north-facing windows providing natural light, supplemented by color-corrected ceiling lighting with an average color temperature of 5000 K to 6500 K and an illuminance of 1000 to 1500 lx, depending on the time of day (08:30 to 17:00, summer time). The walls were painted in a neutral light grey to minimize color interference.

Color measurement

Color measurements were performed by the same, trained operator over several days. Each scan captured all teeth in the upper jaw, while the lower jaw was not scanned. Easyshade was used to measure tooth color in the incisal, medial, and cervical areas of the labial and buccal surfaces. Each IOS employed the color measurement mode of its respective system software to obtain shade designations in approximately the same three regions. In both cases, 3D Master shade designations were selected and recorded. Each complete measurement sequence took less than two minutes. To minimize potential color changes from dehydration, patients were asked to rinse their mouths with room temperature water to rehydrate their teeth between measurements.

Table 1 Devices included in the study, consisting of four IOS and Vita Easyshade V, along with corresponding abbreviations for each device

Device Name	Manufacturer	Location	Abbreviation	Software
Primescan	Dentsply Sirona	Bensheim, Germany	'Primescan'	Cerec SW 5.2.10
Medit i700	Medit	Seoul, South Korea	'Medit'	Medit Link 3.1.4
CS3700	Carestream LLC	Atlanta, USA	'Carestream'	Dexis 1.0.10.902
Trios 3	3Shape	Copenhagen, Denmark	'Trios'	Trios A/S 22.1.3
Easyshade V	Vita Zahnfabrik	Bad Säckingen, Germany	'Easyshade'	ES_Helper 1.0.11081.369

Computation of tooth color

The spectral data from Easyshade, covering 400 to 700 nm in 10 nm intervals, was processed using the manufacturer's *ES-Helper* software and converted to the CIELAB color space which is a standardized system developed by the *Commission Internationale de l'Éclairage* (CIE) for describing and quantifying color. It represents color in three coordinates: L^* for lightness, which ranges from 0 (black) to 100 (white); a^* for the green-red axis, with negative values indicating green and positive values indicating red; and b^* for the blue-yellow axis, with negative values indicating blue and positive values indicating yellow. CIELAB coordinates were computed under Illuminant D65 and the CIE 1931 standard colorimetric observer [38]. The same process was applied to the 3D Master shade guide used for visual assessments to ensure consistent data. The choice of file format (OBJ for Primescan and Medit, PLY for Carestream and Trios) was determined by the standard export capabilities of the respective devices. These formats were not selected by preference but reflect the default outputs provided by the devices. Both OBJ and PLY formats are widely used in 3D rendering and they are fully compatible with MeshLab (version 2023.12), the software used to process and visualize the intraoral scans in this study. Scans were 3D-rotated to capture labial/buccal views, ensuring that measurements were consistently taken in the same three regions for both the natural teeth and all shade tabs of the Vita 3D Master shade guide. A custom MATLAB (R2023b; MathWorks, Natick, MA, USA) routine was used to capture average sRGB values from tooth surfaces in each scan, which were converted to XYZ and CIELAB coordinates using MATLAB's color toolbox. The resulting data included the average tooth color from Easyshade and each IOS, as well as the corresponding CIELAB values for the nearest shade guide match.

Percent correct shade identification

Using the CIELAB values of the natural target tooth for each region and the nearest device-selected shade tab for the same regions, the extent of the discrepancy between the device's selection and the visually selected shade was calculated in cases where the two differed. This resulted in a total of 315 CIELAB values for comparisons per device.

In this study, the ΔE_{ab} formula was chosen over the more complex ΔE_{00} because a recent multicenter study showed that the basic Euclidean distance provided better visual-instrumental agreement in the CIELAB region relevant to natural tooth colors [39].

Percent correct shade identification was determined in three categories: Exact Match, Acceptable Match, and Mismatch Type A. Exact Match refers to instances where the device selected the same shade as the visual observer, while Acceptable Match indicates a clinically acceptable color difference (>1.2, ≤ 2.7 ΔE_{ab}), between the device-selected shade and the target tooth. Mismatch Type A represents cases where the color difference (<2.7, ≤ 5.4 ΔE_{ab}) was moderately unacceptable but still within a range considered for clinical use. The sum of all percentages across these three categories represents the quality range of shade matches that fall within industry tolerance for dentistry. Based on this, a new compound metric, termed *clinical pass rate*, was developed to evaluate the likelihood of a device achieving clinically acceptable results. The clinical pass rate was assessed against the 50/50% threshold, indicating the likelihood of a device achieving clinically acceptable shade selection.

Chi-square analysis was conducted to evaluate the significance of differences across devices for each of these categories. A 95% confidence level ($p=0.05$) was used.

Results

Results for all three regions for all included teeth and per each device, showing exact match, acceptable match and mismatch type A are shown in Fig. 1. In the incisal region, Easyshade achieved the highest Exact Match rate at 20.3%, followed by Medit at 19.0%, and Trios at 19.7%. Carestream recorded the highest rate for acceptable matches in this region at 13.71%, while Easyshade had 5.1%. For Mismatch Type A in the incisal region, Carestream led with 46.7%, followed by Easyshade at 38.1%. In the middle region, Easyshade also had the highest Exact Match rate at 19.4%, while Carestream had the highest percentage of acceptable matches at 22.5%. Carestream also exhibited the highest rate for Mismatch Type A at 33.0%. For the cervical region, Primescan achieved the highest Exact Match at 17.5%, while Carestream had the most acceptable matches at 21.0%. Carestream also led in Mismatch Type A in this region at 48.6%.

Averaged results across all three regions for all included teeth and per each device, showing Exact Match, Acceptable Match, Mismatch Type A, and overall clinical pass rate for each device are shown in Table 2. These results reflect the average across the three regions and three teeth per patient. Carestream achieved the highest clinical pass rate at 78.2%, followed by Easyshade with 63.5%, Primescan with 51.2%, Trios with 39.5%, and Medit with 31.3%. The Exact Match percentages ranged from 11.3% for Primescan to 22.1% for Trios. For the Acceptable Match rate, Carestream showed the highest percentage at 14.0%, while Medit had no acceptable matches. Mismatch type A was highest for Carestream at 47.7% and lowest for Medit at 10.7%. Differences in the clinical pass rate and across all categories for each device were statistically significant at the 95% confidence level ($p=0.05$).

Discussion

This study aimed to evaluate the shade selection capabilities of various IOS, and one shade measurement device commonly mentioned in clinical research, from a practical perspective, rather than through the often-misinterpreted notion of *device accuracy*. The chosen approach focused on *percent correct shade identification*, grouping results into three clinically relevant categories: when a device's selected shade either matched the observer's selection, offered a clinically acceptable match, or was at least a moderately unacceptable match (Type A). To gauge clinical relevance, the sum of these categories presents a single measure referred to as the *clinical pass rate*.

Device performance differed significantly, as demonstrated by the chi-square test results across all categories. To interpret these findings, it is important to consider that historically in psychophysical studies designed to estimate visual thresholds, a 50% cutoff is often used as a standard [40]. Applying this concept to the present study, devices with a clinical pass rate at or above 50% should therefore be considered more reliable for shade selection, than those falling below this mark.

Carestream, with a clinical pass rate of 78.2%, clearly outperformed the other devices, positioning it as the most reliable option. It consistently provided clinically passable results, whether through exact matches or acceptable shade differences. Easyshade, which achieved a 63.5% pass rate, also performed well.

In contrast, both Primescan and Trios hovered near or below the 50% threshold, with Primescan just meeting the cutoff at 51.2%. This raises questions about the reliability of these devices when used without visual confirmation of shade selection. Medit, with a clinical pass rate of only 31.3%, demonstrated the lowest performance, indicating it may require alternative use strategies in clinical practice.

The visual ranking used in this study is grounded in established visual thresholds for clinical dentistry [41]. However, in practice, the acceptance or rejection of clinical

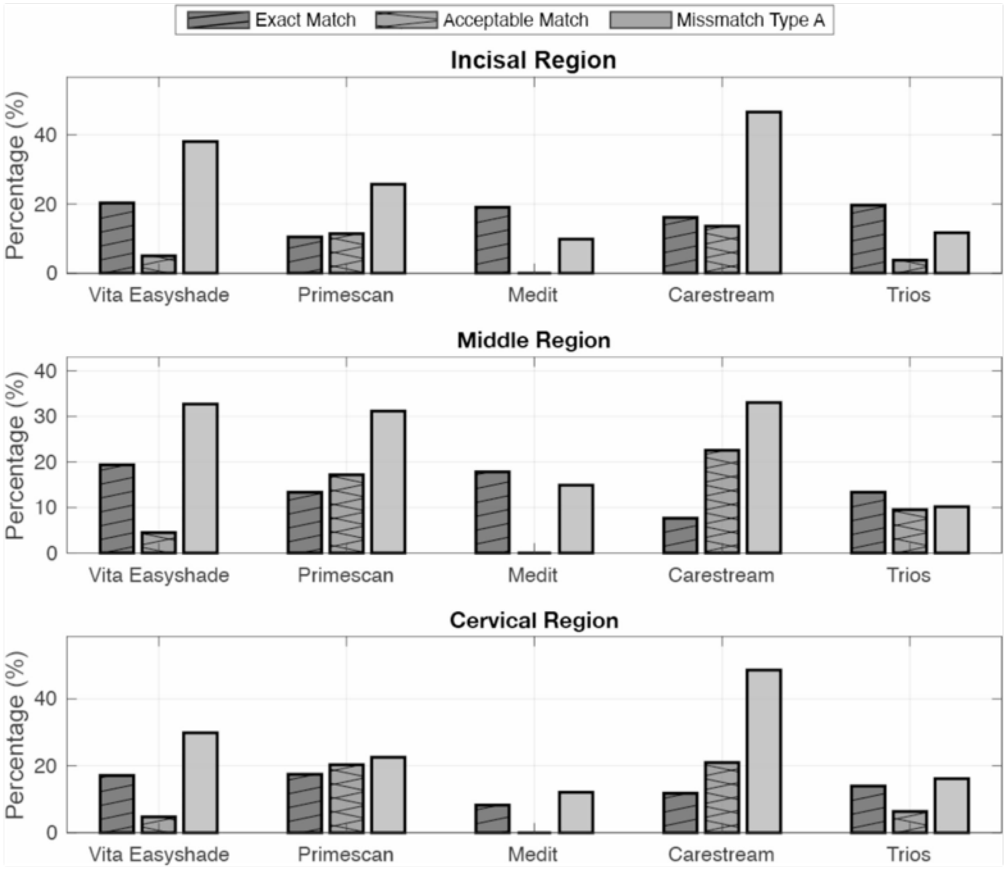

Fig. 1 Percentages for all devices across incisal, middle, and cervical regions, displaying results of exact matches, acceptable matches (> 1.2, ≤ 2.7 ΔE_{ab}), and Mismatch Type A (< 2.7, ≤ 5.4 ΔE_{ab}). Results are shown for each device: Easyshade, Primescan, Medit, Carestream, and Trios

Table 2 Percentages of exact matches, acceptable matches (> 1.2, ≤ 2.7 ΔE_{ab}), and mismatches type A (< 2.7, ≤ 5.4 ΔE_{ab}) for each device, averaged across the cervical, middle and incisal regions. Clinical pass rate represents the sum of these categories, indicating likelihood of clinically agreeable shade selection by device. Chi-square test with 95% confidence level ($p = 0.05$) was used to evaluate statistical significance

Device	Exact match	Acceptable match	Mismatch Type A	Clinical Pass Rate
Carestream	16.6%	14.0%	47.7%	78.2%
Easyshade	20.3%	5.1%	38.1%	63.5%
Primescan	11.3%	12.3%	27.6%	51.2%
Trios	22.1%	4.3%	13.2%	39.5%
Medit	20.6%	0%	10.7%	31.3%
χ^2	12.04	58.65	123.66	97.18
$p = 0.05$	$p < 0.0171$	$p < 0.000$	$p < 0.000$	$p < 0.0001$

restorations often depends on situational factors that cannot be entirely accounted for by visual thresholds. For instance, a clinical study by Ballard et al. [42] found that 94% of patients were either satisfied or extremely satisfied with an average shade match of 6.5 ΔE_{ab} thus exceeding the upper limit for clinical mismatch type A notably. Taking such findings into account, the inclusion of the Mismatch Type A category as part of the clinical pass rate can be justified with confidence.

As mentioned, there is growing interest in the shade selection capabilities of IOS devices [14, 17–19, 43]. In dental research, colorimetric accuracy has been defined as an instrument's ability to provide color measurements identical to those of a reference device [44], though there is no consensus on what that reference should be. Some authors have proposed a radio-spectrometer for this purpose [43], while most dental researchers have designated the Vita Easyshade as their reference standard, likely due to its widespread availability and user-friendly operation. However, a recent multi-center study demonstrated that device performance was overshadowed by the choice of the color difference equation used [12]. Another study showed that color measurements from different devices labeled as spectrophotometers, when used on the same tooth samples, yielded incomparable CIELAB data [45]. For these reasons, the current study opted to use an expert observer as the reference instead of a color measurement device. Variations in methodologies across studies, coupled with ongoing confusion regarding the terms *accuracy* and *precision*, further complicate direct comparisons with the results of the present research.

This research employed a unique methodology aimed at providing insights that are practically relevant to the average dental practitioner, demonstrating that the shade selection abilities of certain IOS devices are comparable to, or even better than, those of a popular shade measurement device, and can therefore be reasonably trusted.

A key limitation of this study is the inclusion of only one expert observer, as a larger sample size of around 20 expert observers would have provided more robust and reliable results. Additionally, the intraoral scanners (IOSs) included in this study were not the latest generations of their respective models. The results might differ with newer generations, which could potentially offer improved performance.

Despite these limitations, the results of the present study demonstrate that IOS devices can indeed be reliable for shade selection, effectively meeting the demands of daily clinical practice.

Conclusions

Within the limitations of this study, it can be concluded that IOS and traditional shade measurement devices show varying degrees of reliability for shade selection. The clinical pass rate, as used in this research, provides a practical metric for assessing device performance. Carestream exhibited the highest clinical pass rate followed by Easyshade, suggesting that these devices can be reasonably trusted in clinical practice. Other devices performed at or below the 50% mark, indicating that their use for shade selection should be considered more carefully. Despite these findings, it remains advisable to visually check the shade wherever possible, as visual assessment provides an additional layer of reliability.

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Author contributions J.N. and K.T.W. conceived the ideas; J.N. and M.M. collected the data; S.H. and S.W. analyzed the data; S.H. led the writing; J.N., S.W., B.C.S. and K.T.W. revised and approved the manuscript; S.H., B.C.S. and K.T.W. provided the resources; K.T.W. supervised the research.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethical Approval This study was conducted according to the Declaration of Helsinki and was approved by the Ethics Committee of the Medical Faculty of Albert-Ludwigs University Freiburg (Approval number: EK-Freiburg 21-1169; approval date: 17.08.2021).

Informed consent All participants provided written informed consent prior to their participation in the study. Details that might disclose their identity were excluded.

Competing interests The authors declare no competing interests.

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Appendix A6

Hein, S., Zangl, M., Graf, T., Vach, K., Güth, J-F., M., and Westland, S. (2025). Evaluating visual thresholds and color metrics in dental research: An exploratory study. Dental Materials. [Online]. Available from: https://doi.org/10.1016/j.dental.2025.04.006

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Evaluating visual thresholds and color metrics in dental research: An exploratory study

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ABSTRACT

Objectives: This study aimed to evaluate perceptibility (PT) and acceptability thresholds (AT) for multiple color measurement devices and assess the performance of three color difference equations (ΔE^*_{ab}, ΔE_{00}, and ΔE_{94}) using a visual dataset from expert observers.
Methods: A visual dataset previously published was extended by adding the x-rite MetaVue spectrophotometer and ΔE_{94} to the analysis. Visual scaling was performed on 26 sample pairs of teeth using magnitude estimation. Observers answered PT and AT questions to determine thresholds. Threshold estimation was conducted using a model-free method, and device performance was analyzed using the standardized residual sum of squares (*STRESS*) index and visual instrument agreement scale (*VIAS*).
Results: The PT and AT thresholds varied across devices and color difference equations. For ΔE_{00}, *STRESS* values ranged from 23 to 32 (mean 29, sd 2.9), with *VIAS* scores between 68 % and 77 % (mean 71 %, sd 2.9). ΔE_{94} showed higher *STRESS* values (24–42, mean 34, sd 5.5) and lower *VIAS* scores (58–76 %, mean 66 %, sd 5.5). ΔE^*_{ab} demonstrated excellent visual-instrumental agreement with *STRESS* values from 18 to 36 (mean 24, sd 5.9) and lower *VIAS* scores (82–64 %, mean 76 %, sd 5.9) outperforming ΔE_{94} and ΔE_{00}. The x-rite MetaVue achieved excellent results under controlled conditions but it is unsuitable for clinical research due to its design.
Significance: This study highlights the variability in PT and AT across devices, suggesting the need for device-specific thresholds. It also demonstrates the effectiveness of ΔE^*_{ab} in dental colorimetry compared to more complex color difference metrics

1. Introduction

Color technology in industry and business has traditionally focused on quality assessment, with particular emphasis on determining whether a pair of samples match [1]. Similarly, in dental research, tooth color assessment is a frequent subject of investigation [2–6], reflecting its critical role in patient satisfaction [7]. Shade matching a single anterior tooth with a restoration is often crucial, but differences in esthetic expectations, rising demands, and the challenges of accurate color determination frequently result in esthetic failures [8].

Instrumental measurements should align with visual perception, ensuring that calculated color differences reflect those observed by individuals [9]. Ideally, a restoration should perfectly and unconditionally match its natural counterpart, but the complexity of tooth color appearance [10] can make this an unattainable ideal. To address this, there are two general types of visual assessments—perceptibility and acceptability—applicable not only in clinical dentistry but across all industries involved in color management [11,12]. Industry-specific needs are addressed through dedicated psychophysical experiments designed to estimate appropriate thresholds. A sigmoidal transformation is applied to predict the computed color difference at which 50 % of the expert observer population can perceive a color difference between a

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test sample pair [13]. For this so-called *50/50 perceptibility threshold* (PT), it is not uncommon for sample pairs with color differences only slightly above or equal to the PT to be judged as unacceptable, particularly when whitish-pale samples are visually evaluated by expert observers [14]. In many industries this can create significant practical challenges, as such PT values are typically small and often exceed production tolerances. To address this, a so-called *commercial factor* is often introduced to establish a more practical *50/50 acceptability threshold* (AT) [15].

PT and AT thresholds for use in dentistry were established by Paravina et al. [16] using flat, uniformly colored (monochromatic) ceramic samples visually scaled by a mixed population, including dental practitioners, technicians, auxiliaries, students, and laypeople. Samples were measured with a spectroradiometer under consistent viewing conditions, and color differences were calculated using the CIE 1976 Euclidean formula (ΔE^*_{ab}) and the more modern CIEDE2000 (ΔE_{00}) metric, following CIE recommendations for small color differences [17]. The average PT and AT values for both metrics, PT (1.2 ΔE^*_{ab} / 0.8 ΔE_{00}) and AT (2.7 ΔE^*_{ab} / 1.8 ΔE_{00}), were subsequently adopted by the International Organization for Standardization (ISO/TR 28642:2016, Dentistry – Guidance on Colour Measurement) [18] and have since become a benchmark for numerous scientific investigations, where they tended to be applied regardless of the instrument or illumination geometry used [2,19]. However, these thresholds have often been applied without considering the potential impact of differences in instrumentation and measurement geometry [20,21].

Instrumental shade measurement in dentistry has seen renewed interest with the introduction of new devices and increasing scientific inquiry into their clinical and research applications [22–24]. Recent efforts have focused on estimating visual-instrumental agreement using the standardized residual sum of squares (*STRESS*) index and evaluated through the recently termed *Visual Instrument Agreement Scale* (*VIAS*) [25]. A multi-center study demonstrated that device performance in *VIAS* assessments was strongly influenced by the choice of color difference equation [26]. One device, the 'optishade' (Smile Line, Switzerland), uniquely employs the ΔE_{94} metric, an unusual choice given that it has been largely superseded by ΔE_{00} in general color science applications. However, its increasing popularity among dental practitioners, due to its ease of use in clinical settings, raises the question of whether ΔE_{94} remains a viable alternative for tooth color measurement. Moreover, reliable PT and AT thresholds for ΔE_{94} have not yet been established, and its visual-instrumental agreement remains unexplored. Investigating its suitability is therefore important, particularly if it offers comparable or superior performance to ΔE_{00} in the specific context of tooth color measurement.

Another device, the x-rite 'MetaVue' imaging spectrophotometer, has been highlighted in the literature [27] for its suitability for measuring diffusely scattering media without causing edge loss [28]. However, its effectiveness in dental research remains unverified, warranting further investigation. Establishing robust PT and AT thresholds is critical, as CIELAB values are well known to be device-dependent [3, 29]. The human eye remains the final arbiter in determining whether a restoration is acceptable based on its color match. Nevertheless, visual thresholds serve as essential benchmarks for standardizing instrumental color measurements, ensuring reproducibility and facilitating effective communication between clinicians and dental laboratories.

Therefore, the aim of this exploratory study was to shed light on whether the PT and AT values recommended for color measurement in dentistry are universally applicable across different devices and illumination geometries, whether expert thresholds differ from general thresholds, potentially indicating the effects of a commercial factor, and to what extent ΔE_{94} PT and AT thresholds align with or differ from ΔE_{00}, given that the latter metric evolved from the former. Additionally, the study aimed to evaluate whether ΔE_{94} is justified by superior *STRESS* and *VIAS* performance compared to other metrics and to investigate the suitability of the MetaVue spectrophotometer for dental color measurement.

2. Material and methods

The present study utilizes a visual dataset previously acquired; details about how tooth colors were measured and how the visual experiment was conducted have been previously published [26]. Only an abridged version of the methodology is presented here, with additional elements unique to this study highlighted, including the inclusion of one extra device and one additional color difference equation.

2.1. Selection of expert observers and sites

Ethical approval (LTDESN-196) was obtained, allowing recruitment of 154 expert observers, comprising dental practitioners and dental technicians with experience in restorative dentistry. Observers passed the Ishihara test for color vision deficiency and were recruited across 16 professional settings, including dental schools, dental laboratories, and private practices.

2.2. Visual scaling technique

To examine visual color differences (ΔV) between pairs of teeth, the magnitude estimation (ME) technique was applied, where observers assessed color differences between maxillary central incisors. They were asked to rate the color match on a scale from 0 % to 100 %, with 0 % indicating the worst possible match and 100 % indicating a perfect match. Observers were also asked two specific questions to determine PT and AT:

1. *"Can you see a color difference between the two maxillary centrals?"*
2. *"Would you accept this color difference if this were your patient?"*

2.3. Visually scaled samples and experimental setup

Previous studies on visual scaling of tooth-colored samples often used simplified samples, such as monochromatic ceramic discs [30] or other configurations, designed to minimize the influence of parametric effects [31]. In this study, a different approach was taken by employing custom-made, hyper-realistic phantom models that closely resemble the appearance of natural teeth, aiming to create a lifelike visual context for observers. Four color centers within the CIELAB color space were identified, representing one base shade, with 5–7 exchangeable teeth per model, resulting in a total of 26 visually scaled sample pairs with controlled variations in hue and chroma, all with color differences under 5 ΔE^*_{ab} units. Observations were conducted at a distance of 35–50 cm against a neutral grey background under simulated daylight at 6500 K.

2.4. Instrumental measurement of sample pairs

Color measurements were obtained using devices frequently cited in dental literature, listed in Table 1. An additional device, the x-rite MetaVue, was included due to recent positive references in the literature [27]. Sample pairs were mostly measured with devices designed for dentistry, with each device using a consistent measurement protocol and illumination geometry.

2.5. Computation of inter-instrument variability

To evaluate inter-instrument variability in color measurements, pairwise subtractions of color differences were performed between the tested instruments. Color differences were computed under Illuminant D65 for the CIE 1931 standard colorimetric observer, using the CIE D65 reference white (X = 95.047, Y = 100.000, Z = 108.883). Three color difference equations were employed: ΔE^*_{ab}, ΔE_{00}, and, additionally, ΔE_{94}, as it is used by the Optishade dental colorimeter which has

Table 1
Color measurement devices investigated in this study, including device name, manufacturer, geographical location of manufacturer, and type of device.

Device Name	Manufacturer	Location	Type
SpectroShade Micro II (SSM II)	Spectroshade USA	Oxnard, CA, USA	Multispectral camera
SpectraScan PR−670 (PR−670)	Photo Research Inc.	Syracuse, NY, USA	Spectroradiometer
Rayplicker Cobra (RPC)	Borea	France	Multispectral camera
Optishade (OS)	Smile Line	Switzerland	Calibrated camera
eLAB & Nikon D7500 (eLAB)	Emulation	Germany	Calibrated camera
Vita Easy Shade V (ES-V)	Vita Zahnfabrik	Germany	Spectrophotometer
MetaVue (MetaVue)	X-Rite Inc. USA	Grand Rapids, MI, USA	Imaging spectrophotometer

recently gained attention in dental research [24,32,33]. For instruments i and j, the pairwise difference was calculated as:

$$\Delta E_{difference,ij} = \Delta E_i - \Delta E_j$$

where $\Delta E_{\text{difference, ij}}$ represents the variability in color differences between instruments i and j, and ΔE_i and ΔE_j denotes the color differences computed for instruments i and j, respectively. This calculation was repeated for all pairwise comparisons across the instruments for each color difference equation ΔE^*_{ab}, ΔE_{00}, and ΔE_{94}.

2.6. Computation of visual thresholds

Visual thresholds were determined based on observer responses to the PT and AT questions. The computation of thresholds used a nonparametric, Model-Free Estimation Technique developed by Zychaluk & Foster [34], which uses local linear fitting. This approach does not assume a specific parametric model for the psychometric function but rather relies on a smoothness assumption, providing threshold estimates that adapt to the response distribution [35]. This method is particularly effective as it mitigates potential biases from model misspecifications, yielding robust and consistent threshold values.

2.7. Statistical analysis

Data evaluation was conducted using MATLAB (R2024b) with a specialized color science toolbox, and statistical testing was performed using STATA (Version 17.0, College Station, TX, USA) with a significance level of 5 %. Linear mixed models, incorporating sample pair as a random effect, were applied to test for inter-instrument variability across devices for each of the three color difference (ΔE_{00}, ΔE_{94}, and ΔE^*_{ab}). The following pairwise comparisons were not corrected for multiple testing due to the exploratory nature of the study. Both, the *STRESS* index and *VIAS* were used to evaluate device performance. Small *STRESS* values indicate high visual-instrumental agreement, while *VIAS* is calculated as 100 - *STRESS*, meaning that higher *VIAS* values correspond to greater visual-instrumental agreement.

3. Results

3.1. Inter-instrument variability

The results for inter-instrument variability, calculated using the ΔE_{00}, ΔE_{94}, and ΔE^*_{ab} color difference equations, are shown in Figs. 1, 2, and 3, respectively. Among the 21 different device pair comparisons, 12 combinations exhibited significant color differences ($p < 0.05$) for both the ΔE_{00} and ΔE_{94} color difference equations. For the ΔE^*_{ab} equation, six device pairs demonstrated statistically significant differences. Individual color differences between all devices for each of three color

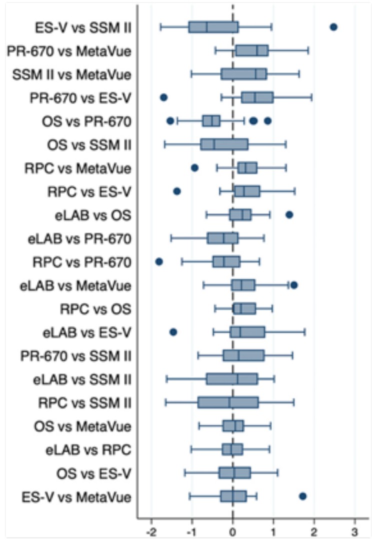

Fig. 1. Boxplot showing pairwise comparisons of inter-instrument variability calculated using the ΔE_{00} color difference equation. Each box represents the ΔE_{00} differences between the first and second named device, sorted by increasing absolute median values from bottom to top. Dots represent outliers. The dashed line indicates no difference between devices. Among the 21 device pair comparisons, 12 pairs showed statistically significant differences ($p < 0.05$).

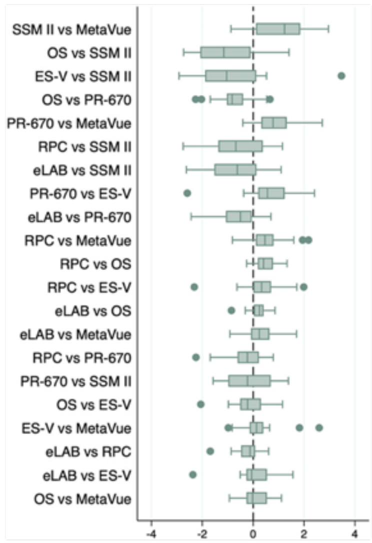

Fig. 2. Boxplot showing pairwise comparisons of inter-instrument variability calculated using the ΔE_{94} color difference equation. Each box represents the ΔE_{94} differences between the first and second named device, sorted by increasing absolute median values from bottom to top. Dots represent outliers. The dashed line indicates no difference between devices. Out of 21 device pair comparisons, 12 pairs exhibited statistically significant differences ($p < 0.05$).

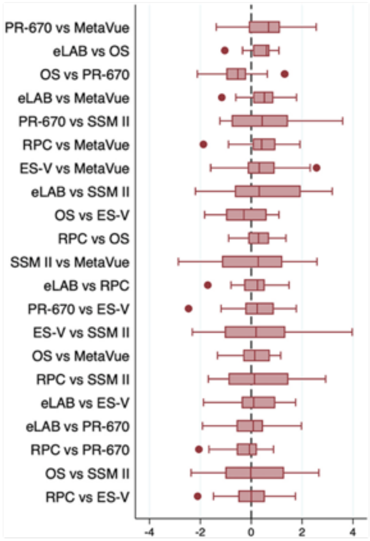

Fig. 3. Boxplot showing pairwise comparisons of inter-instrument variability calculated using the ΔE^{*}_{ab} color difference equation. Each box represents the ΔE^{*}_{ab} differences between the first and second named device, sorted by increasing absolute median values from bottom to top. Dots represent outliers. The dashed line indicates no difference between devices. Six out of 21 device pairs showed statistically significant differences ($p < 0.05$).

difference equations are included in appendix A.

Since visual thresholds calculated by model-free estimation, are sensitive to variations of ΔE^{*} values per device and color difference equation, equivalence class partitioning was applied. This approach grouped devices into clusters with no significant differences in color differences among members as shown in Fig. 4.

3.2. Visual thresholds

The results for the 50/50 PT and AT for each device, calculated using the ΔE_{00}, ΔE_{94}, and ΔE^{*}_{ab} color difference equations, are summarized in Tables 2, 3, and 4, respectively. These tables also include associated statistical metrics, including Standard Error (SE), the 95 % confidence interval (CI) low and high values, as well as the average values and standard deviations across all devices. Results are reported by equivalence class groups, with the mean for each group, the grand mean, and standard deviation (SD) provided. The average PT values were 0.8 for ΔE_{00}, 0.9 for ΔE_{94}, and 1.2 for ΔE^{*}_{ab}, while the AT values were 1.8 for both ΔE_{00} and ΔE_{94}, and 2.8 for ΔE^{*}_{ab}. Variations in PT and AT values were observed across different devices and color difference equations.

3.3. *STRESS* index and *VIAS* score

The results for the *STRESS* index, *VIAS* and *R*-squared for each color difference equation (ΔE_{00}, ΔE_{94}, and ΔE^{*}_{ab}) are presented in Tables 5, 6, and 7, respectively. Each table also includes the average values across all devices and their standard deviations. Individual device performances are detailed in Tables B1, B2, and B3 in the appendix.

4. Discussion

This exploratory study aimed to evaluate the applicability of PT and AT thresholds across devices with differing designs and illumination geometries, the potential influence of a commercial factor on expert thresholds, and the relationship between ΔE_{94} and ΔE_{00} thresholds. Additionally, it assessed whether ΔE_{94} offers superior *STRESS* and *VIAS* performance and the suitability of the MetaVue spectrophotometer in dental research.

The established PT and AT thresholds were derived from psychophysical experiments that employed the Takagi-Sugeno-Kang (TSK) Fuzzy Approximation technique [16]. The experimental setup, designed to provide a controlled and repeatable testing environment, utilized flat, square ceramic samples to represent teeth and an opaque pink barrier to approximate the presence of gingiva. While this approach offers a structured framework for assessing color difference perception, it represents a highly simplified model of the anatomical and optical complexities found in the oral cavity. In contrast, the present study employed highly realistic phantom models to better replicate clinical conditions and included expert observers exclusively, whereas previous studies incorporated a mixed population.

The present study employed the Model-Free Estimation Technique by Zychaluk & Foster [34,35], a non-parametric method that approximates psychometric functions using local linear fitting with kernel smoothing, adapting dynamically to data through cross-validation. This approach was chosen for its statistical rigor and open accessibility, as it

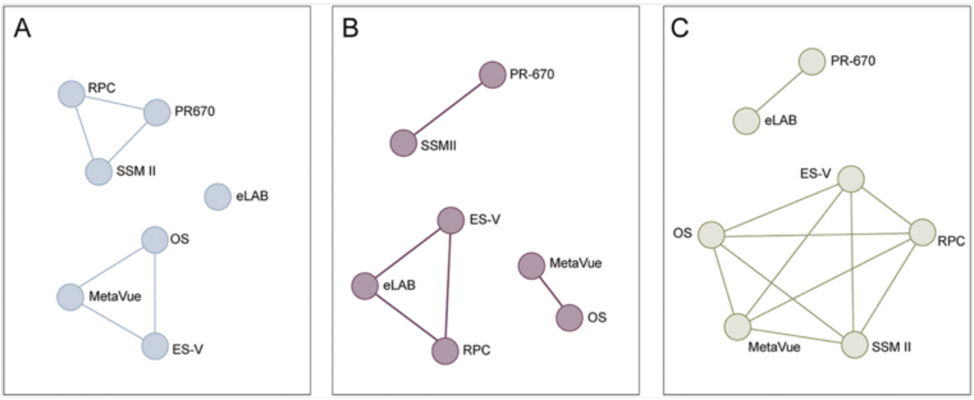

Fig. 4. Equivalence class plots for ΔE_{00} (A), ΔE_{94} (B), and ΔE^{*}_{ab} (C). Each connected component represents devices with no significant differences among them.

Table 2
Summary of 50/50 PT and AT values for each device using the ΔE_{00} color difference equation. Statistical metrics include Standard Error (SE), 95 % confidence interval (CI) low and high values, average values, and standard deviations across all devices. Results are reported by equivalence class groups, with the mean for each group, the grand mean, and standard deviation (SD) also provided.

Device	PT(ΔE_{00})	SE	95 % CI low	95 % CI high	AT(ΔE_{00})	SE	95 % CI low	95 % CI high
ES-V	0.9	0.021	0.849	0.933	1.6	0.021	1.628	1.706
MetaVue	0.8	0.028	0.713	0.82	1.7	0.021	1.643	1.731
OS	0.6	0.028	0.596	0.729	1.7	0.030	1.681	1.800
Group Mean	0.8				1.7			
RPC	0.7	0.05	0.55	0.742	1.8	0.033	1.855	1.972
PR−670	0.8	0.055	0.69	0.904	2.1	0.036	2.040	2.192
SSM II	0.9	0.001	0.911	0.911	1.8	0.054	1.627	1.867
Group Mean	0.9				1.9			
eLAB	0.7	0.039	0.612	0.778	1.9	0.025	1.814	1.920
Grand Mean	0.8				1.8			
sd	0.111				0.166			

Table 3
Summary of 50/50 PT and AT values for each device using the ΔE_{94} color difference equation. See Table 2 for detailed metrics and grouping information.

Device	PT(ΔE_{94})	SE	95 % CI low	95 % CI high	AT(ΔE_{94})	SE	95 % CI low	95 % CI high
RPC	0.9	0.039	0.814	0.955	1.8	0.034	1.865	1.989
eLAB	0.6	0.048	0.511	0.703	1.8	0.026	1.775	1.882
ES-V	1.0	0.018	1.004	1.072	1.7	0.022	1.725	1.806
Group Mean	0.8				1.8			
PR−670	0.8	0.031	0.751	0.864	2.1	0.052	2.153	2.319
SSM II	1.3	0.001	1.255	1.255	1.7	0.126	1.407	1.970
Group Mean	1.1				1.9			
OS	0.7	0.023	0.612	0.694	1.5	0.026	1.545	1.648
MetaVue	0.7	0.027	0.711	0.814	1.7	0.025	1.669	1.757
Group Mean	0.7				1.6			
Grand Mean	0.9				1.8			
sd	0.230				0.183			

Table 4
Summary of 50/50 PT and AT values for each device using the ΔE^*_{ab} color difference equation. See Table 2 for detailed metrics and grouping information.

Device	PT(ΔE^*_{ab})	SE	95 % CI low	95 % CI high	AT(ΔE^*_{ab})	SE	95 % CI low	95 % CI high
OS	0.9	0.044	0.875	1.046	2.8	0.036	2.711	2.859
SSM II	1.3	0.000	1.345	1.345	2.5	0.072	2.320	2.594
ES-V	1.4	0.042	1.337	1.504	2.7	0.030	2.715	2.824
MetaVue	1.2	0.001	1.158	1.158	2.6	0.038	2.545	2.680
RPC	1.0	0.075	0.855	1.123	2.8	0.047	2.822	3.009
Group Mean	1.2				2.7			
eLAB	1.1	0.054	1.032	1.242	3.1	0.043	3.007	3.152
PR−670	1.2	0.074	1.041	1.336	3.2	0.047	3.105	3.296
Group Mean	1.2				3.1			
Grand Mean	1.2				2.8			
sd	0.173				0.251			

Table 5
STRESS index, *VIAS* scores, and R^2 values for each device using the ΔE_{00} color difference equation, with devices listed in order of *STRESS* values from low to high. The table includes mean and standard deviation (SD) values for all devices, providing an overview of performance across devices in terms of agreement and variance.

Device	*STRESS*	*VIAS*	R^2
MetaVue	23	77	0.7
ES-V	26	74	0.7
OS	29	71	0.6
eLAB	30	70	0.6
PR−670	30	70	0.5
RPC	30	70	0.6
SSM II	32	68	0.5
Mean	29	71	0.6
SD	2.9	2.9	0.1

Table 6
STRESS index, *VIAS* scores, and R^2 values for each device using the ΔE_{94} color difference equation. See Table 5 for detailed metrics and ordering information.

Device	*STRESS*	*VIAS*	R^2
MetaVue	24	76	0.7
eLAB	33	67	0.5
ES-V	33	67	0.5
OS	34	66	0.5
PR−670	34	66	0.4
RPC	37	63	0.4
SSM II	42	58	0.2
Mean	34	66	0.5
SD	5.5	5.5	0.2

can be implemented using freely available software such as MATLAB. In contrast, TSK Fuzzy Approximation relies on fuzzy logic with Gaussian membership functions and rule-based inference. While the TSK approach offers interpretability through linguistic rules, it requires careful selection of membership functions, whereas the Model-Free

Table 7
STRESS index, *VIAS* scores, and R^2 values for each device using the ΔE^*_{ab} color difference equation. See Table 5 for detailed metrics and ordering information.

Device	*STRESS*	*VIAS*	R^2
eLAB	18	82	0.8
MetaVue	20	80	0.8
OS	22	78	0.8
RPC	24	76	0.7
PR–670	25	75	0.7
ES-V	25	75	0.7
SSM II	36	64	0.3
Mean	24	76	0.7
SD	5.9	5.9	0.2

Estimation Technique is purely statistical, making it particularly well-suited for psychometric function estimation. While computational differences may introduce small numerical variations, the overall results are expected to be comparable. This is reflected in the present study, where the average PT and AT values align closely with those reported by Paravina et al., further supporting the robustness of both estimation techniques and indicating their comparable performance.

In highly controlled psychophysical experiments, expert observers, such as colorists or quality control assessors, are often preferred because their trained visual acuity and experience result in lower inter- and intra-observer variability, producing more robust data and minimizing measurement noise [36–39]. However, individual quality assessments, even by experts, are subject to error, as demonstrated in other industries where visual pass/fail decisions play a critical role. Studies on professional shade passers in large-scale production environments have shown that, on average, 17 % of visual judgments were incorrect, evenly split between false acceptances and false rejections. The consequences of such misjudgments include unnecessary remakes, increased production costs, and reputational damage [39]. While aggregated expert assessment can significantly reduce visual misjudgments, it is impractical for routine application. The most effective solution is instrumental color measurement, guided by thresholds derived from aggregated expert assessments [40].

Similarly, dental practitioners must independently assess the color match of restorations without the benefit of aggregated expert judgments, introducing uncertainty and increasing the risk of unnecessary remakes or acceptance of suboptimal restorations. Visual thresholds based on expert assessments help mitigate this risk by providing an objective benchmark for decision-making. A considerable body of research on visual threshold estimation in dentistry has been reviewed by Paravina et al. [41], revealing substantial variation in reported thresholds across different devices, and research methodologies (PT_{mean} = 1.6 ΔE^*_{ab} (SD 0.7); AT_{mean} = 3.2 ΔE^*_{ab} (SD 1.0)). The majority of these studies relied on non-expert observers to ensure practical execution and to simulate a general patient population (i.e., laypersons). The resulting higher PT and AT values suggest a commercial factor, as non-expert observers tend to be less critical in their assessments [30,42, 43]. This effect was also observed in the original work by Paravina et al. [16], where dentists and dental technicians demonstrated notably lower thresholds compared to dental students, auxiliaries, and laypersons.

In addition, a robust visual dataset obtained from expert observers is essential for detecting device-dependent threshold differences, which are likely to be small and easily obscured by noise in the data. Statistical testing revealed frequent and significant inter-device variability in PT and AT values, depending on the device and the color difference metric used, differences that may have otherwise been missed with a more variable observer population.

To better understand these variations, equivalence class partitioning was applied to group devices with no significant inter-device variability. Within these groups, PT and AT values remained relatively consistent, supporting the idea that thresholds can be applied uniformly within a group. However, differences between groups highlight the need for device-specific or group-specific thresholds, suggesting that a single set of values cannot be uniformly applied across all devices without accounting for their design, measurement geometry, and equivalence class groupings

The use of ΔE_{94}, a metric that has been superseded by ΔE_{00} [17], may be seen as an unusual choice, which sparked interest in investigating its effectiveness. While the findings do not align with the conclusions of Rizzi et al. [44], which suggested that ΔE_{94} performs better than ΔE_{00} in aligning with visual perception, the broader notion that simpler color difference metrics may perform better for tooth colors is supported. In this study, ΔE_{94} did not outperform ΔE_{00}, which is consistent with the historical development of ΔE_{00} as an evolution of ΔE_{94} to address discrepancies in regions of CIELAB beyond the gamut of natural tooth colors [45]. Both metrics produced nearly identical results for visual thresholds but ΔE_{00} outperformed ΔE_{94} notebaly as evaluated by *STRESS* and *VIAS* metrics.

The findings reaffirm the effectiveness and computational simplicity of ΔE^*_{ab}, which delivered superior results without the added complexity of more modern equations. This can be attributed to the location of natural tooth colors within a region of CIELAB [46] where color difference ellipsoids are small and spherical, as demonstrated by Luo and Riggs [47], and where the assumption of perceptual uniformity reasonably holds.

Another relatively new device mentioned in scientific research, the x-rite MetaVue, demonstrated excellent performance, as indicated by *STRESS* and *VIAS* results. However, while this instrument may be beneficial for in-vitro investigations, it is not suitable for clinical research due to its design.

The present study acknowledges the importance of device-specific thresholds and recommends replacing the common practice of applying a single set of values uniformly across all color measurement devices, even though these differences may appear small. While the study aimed to simulate real-life clinical conditions using hyper-realistic phantom models, the results require clinical validation. Although the use of expert observers was intended to minimize intra- and inter-observer variability, future research should investigate the impact of lay observers to assess potential commercial factor effects. Further work is also needed to compare the performance of TSK fuzzy approximation against the Model-Free Estimation Technique, which would require open-source access to specific TSK fuzzy parameters (e.g., membership functions) to better elucidate visual color difference perception in dentistry.

5. Conclusions

Within its limitations, the findings of this study indicate that the recommended PT and AT thresholds should not be universally applied across all color measurement devices and illumination geometries due to significant inter-device variability. Instead, the results support the implementation of device-specific thresholds to improve the accuracy and consistency of instrumental shade assessment in dentistry. While ΔE_{94} and ΔE_{00} produced similar visual thresholds, the latter demonstrated superior performance in *STRESS* and *VIAS* evaluations and should therefore be preferred. However, the study further highlights the robustness and computational efficiency of ΔE^*_{ab}, which aligned with approximate perceptual uniformity within the gamut of natural tooth colors and outperformed the more complex color difference equations in this specific application.

Moreover, the x-rite MetaVue spectrophotometer was found to be well-suited for in-vitro investigations, though its design limitations restrict its applicability in clinical settings. These findings emphasize the necessity of refining current industry practices by integrating computationally validated thresholds that account for differences in device design and measurement geometries. Future research should focus on the clinical validation of these results, particularly by incorporating lay observers to assess potential commercial factor effects and by further comparing the Model-Free Estimation Technique by Zychaluk & Foster with model-based approaches such as TSK fuzzy approximation to enhance the understanding of visual color difference perception in dentistry.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests that could have appeared to influence the work reported in this paper.

Appendix

This study utilized a visual dataset that was acquired in a previous investigation, parts of which are reproduced here for comprehensive comparison. The dataset served as the foundation for computing the *STRESS* index and *VIAS* to evaluate visual-instrumental agreement, following methods detailed in a prior publication.

Table A.1
Computed ΔE_{00} color differences for each of the 26 sample pairs across all included devices. Notable differences are evident, illustrating variability in color measurement results between devices

Sample pair	eLAB	RPC	OS	PR-670	ES-V	SSM II	MetaVue
1	5.7993	5.1145	4.9738	5.2817	4.2863	5.1607	4.4357
2	5.7124	5.2935	4.3235	5.5734	4.5731	5.6640	4.2091
3	0.6769	0.5496	0.9854	0.7054	0.7495	1.5569	0.9394
4	5.1396	4.2402	4.2293	4.5712	3.3746	4.7821	4.0511
5	3.1146	3.3728	2.7620	3.2522	2.3192	2.8977	3.1929
6	1.7351	1.3821	1.3476	1.9878	1.6813	2.7046	1.6255
7	2.7908	2.5404	2.3321	2.8665	2.6416	3.4049	2.0590
8	3.0158	3.1483	2.4584	3.2110	3.0047	2.5512	2.5356
9	0.3412	0.7811	0.2306	1.2834	0.7492	1.8974	1.0598
10	2.3611	1.5842	1.8605	3.3958	1.4605	3.2340	2.5208
11	0.9264	1.4472	0.8770	2.1163	1.3038	2.5498	0.9209
12	2.0706	2.2313	2.1687	2.5665	2.5482	2.6381	2.1105
13	1.3320	1.5988	1.7634	2.8479	1.3384	2.5626	0.9962
14	3.9374	4.1600	4.0285	4.5700	4.0539	3.1043	3.8976
15	2.4020	2.4928	2.6851	2.1668	3.8640	1.3868	2.1439
16	1.8721	2.8963	2.5198	2.9715	1.5385	2.2601	1.5922
17	2.7720	2.6651	2.4745	2.9301	2.3778	1.9711	2.9894
18	1.9717	2.5081	1.7354	2.3127	2.0159	1.4302	2.2343
19	2.5571	3.2791	2.3573	2.7071	2.6551	1.7817	2.5809
20	2.4699	3.0043	2.5858	2.8215	1.4842	3.1297	1.8135
21	2.0099	1.8975	2.1025	1.2441	1.5245	1.3802	1.3133
22	3.3893	3.5745	3.1552	3.7484	2.9017	2.7722	3.0561
23	1.0965	1.0889	0.4281	0.6634	0.8815	0.9108	0.6829
24	2.7008	2.5540	2.6016	2.1080	1.9001	2.1441	2.5352
25	2.3915	2.3713	2.0574	3.4209	2.4062	2.5097	2.2542
26	1.9078	1.6357	1.4857	2.1882	1.2528	1.9537	1.3553

Table A.2
Computed color differences for ΔE_{94} per ech device and sample pair

Sample pair	eLAB	RPC	OS	PR-670	ES-V	SSM II	MetaVue
1	6.5481	5.9645	5.7114	6.1068	4.9848	6.9260	5.1224
2	5.8585	6.3294	4.9984	6.0209	5.9739	7.1127	4.1531
3	0.7046	0.6839	0.9060	0.7615	1.0324	2.0313	1.1674
4	4.4296	4.0346	3.8232	4.0309	2.9063	5.0078	3.2362
5	2.5621	2.9926	2.2156	2.7709	2.0063	2.6146	2.8320
6	1.6993	1.4016	1.2910	2.1879	2.0375	3.6456	1.7971
7	2.5382	2.4869	2.1742	2.8550	2.5469	4.4316	1.9016
8	3.1554	3.3740	2.5803	3.5663	3.3673	3.2287	2.7986
9	0.2825	0.9319	0.2630	1.5220	0.7916	2.6211	1.1998
10	2.1870	1.5812	1.7966	3.8305	1.4193	4.3322	2.3964
11	0.9590	1.3426	0.8504	2.5213	1.2872	3.5829	0.9829
12	1.9807	2.1363	1.9522	2.6734	2.4248	3.5046	2.0299
13	1.2054	1.9567	1.3843	3.6472	1.4698	3.4616	0.9305
14	3.5640	4.0352	3.5981	4.6324	3.7230	3.2485	3.5917
15	2.5820	2.6369	2.8932	2.3628	4.9527	1.4834	2.3574
16	2.0070	3.6935	2.8621	3.7006	1.7061	3.0118	1.7502
17	2.6021	2.5245	2.3293	3.1644	2.7704	2.2464	2.8035
18	1.9739	2.2252	1.6633	2.4904	2.1873	1.7678	2.0587
19	2.4038	3.1965	2.2604	2.9185	2.6490	2.1848	2.4164
20	2.8831	3.7508	2.7442	3.4671	2.0334	4.3339	2.1532
21	1.9594	2.0511	1.9189	1.2600	1.6329	1.5117	1.1965
22	3.6377	3.8006	3.4183	4.2519	3.1008	3.5091	3.3149
23	1.3258	1.4109	0.5513	0.7511	1.0608	1.2550	0.7107

(continued on next page)

Table A.2 (*continued*)

Sample pair	eLAB	RPC	OS	PR-670	ES-V	SSM II	MetaVue
24	2.5184	2.3995	2.3521	2.2687	2.0507	2.4608	2.3514
25	2.3875	2.4066	2.0658	3.7549	2.3792	3.3165	2.1097
26	2.1120	1.9754	1.4191	2.5850	1.2376	2.7817	1.3165

Table A.3
Computed color differences for ΔE_{00} per ech device and sample pair

Sample pair	eLAB	RPC	OS	PR-670	ES-V	SSM II	MetaVue
1	7.6983	6.8673	6.9823	6.8920	6.3592	7.1384	5.9194
2	6.3632	6.6378	5.2745	6.4280	6.2644	7.3033	4.7189
3	1.0492	0.7874	1.3910	0.8252	1.0572	2.0589	1.1942
4	5.0042	4.3428	4.2220	4.4407	3.3299	5.2352	3.6793
5	4.1193	4.7170	3.5164	4.4957	3.4724	3.2601	4.7246
6	3.1470	2.5179	2.3670	2.7723	2.8407	3.7530	2.3386
7	5.2910	4.9679	4.6610	4.8637	6.0503	4.7185	3.7342
8	5.6231	5.5893	4.6941	5.1005	5.8283	3.6509	4.0984
9	0.4434	0.9695	0.2739	1.5826	1.5630	2.6388	1.5994
10	4.5090	3.0232	3.9122	5.0819	3.3104	4.5775	4.9034
11	1.7390	1.9339	1.4942	2.7451	2.4397	3.6205	1.5207
12	4.3893	4.0212	4.1006	4.5881	5.5051	3.8544	3.9574
13	1.8209	2.1448	1.7812	3.7375	2.0075	3.5177	1.1820
14	7.5001	7.2388	6.9739	7.9086	7.8728	4.3157	7.1800
15	4.0725	3.8419	4.1152	3.4826	5.9480	1.9787	3.3807
16	2.5308	4.2391	3.5711	4.2790	2.6857	3.1723	2.6225
17	5.4094	4.5978	4.4105	4.9486	4.0646	2.8838	5.4938
18	3.1913	3.0332	2.5783	3.2597	2.9500	2.0391	2.8805
19	4.9532	5.2792	4.2793	4.4933	4.6328	2.7258	4.5968
20	3.0027	3.7974	2.9339	3.6087	2.0602	4.3776	2.2029
21	3.0677	2.7495	3.3604	2.0531	2.9730	1.6763	2.2013
22	6.0001	5.6125	5.3456	6.0873	5.4813	4.0582	5.2080
23	1.3858	1.4353	0.5523	1.0640	1.5155	1.3446	1.1585
24	5.2523	4.1533	4.5962	3.2772	3.5073	2.7950	4.6525
25	3.2821	3.3481	2.8918	5.0102	4.1586	3.5710	3.2055
26	2.8870	2.3580	2.8147	2.6510	1.9443	2.7955	1.7953

The *STRESS* index quantified the agreement between the visual shade selection and the computed selection by the devices, calculated as:

$$STRESS = 100\left(\frac{\sum_i (\Delta E_i - F_1 \Delta V_i)^2}{\sum_i F_i^2 \Delta V_i^2}\right)^{1/2} \text{ and } F = \frac{\sum_i \Delta E_i^2}{\sum_i \Delta E_i \Delta V_i}$$

The VIAS score was derived directly from the *STRESS* index using the formula:

$$VIAS(\%) = 100 - STRESS$$

To compare device performance, the F-statistic was computed using the STRESS values for different devices as follows:

$$F = \frac{STRESS^2_{DeviceA}}{STRESS^2_{DeviceB}}$$

The *F*-value was then compared against a critical threshold ($F < F_C$ or $F > 1/F_C$) determined by a two-tailed *F*-distribution with a 95 % confidence interval and degrees of freedom ($N-1, N-1$), where $N = 26$ in this study. In this case, $F_C = 1.955$ and $1/F_C = 0.512$. If the *F*-value exceeded F_C or fell below $1/F_C$, the null hypothesis of no significant difference between the devices was rejected. If the *F*-value fell between these thresholds, no significant difference was assumed.

Yellow cells indicate instances where an equation performs significantly better than another, blue cells denote no significant performance difference, and grey cells signify significantly poorer performance compared to the corresponding equation in the row.

Table B.1
Individual device performance for ΔE_{00}

Device	MetaVue	ES-V	OS	eLAB	PR-670	RPC	SSM II
MetaVue	1.0	0.798	0.642	0.600	0.600	0.600	0.527
ES-V	1.308	1.0	0.823	0.769	0.769	0.769	0.676
OS	1.565	1.225	1.0	0.920	0.920	0.920	0.809
eLAB	1.666	1.303	1.048	1.0	0.979	0.979	0.860
PR-670	1.695	1.327	1.066	0.996	1.0	0.996	0.876
RPC	1.716	1.343	1.080	1.009	1.009	1.0	0.887
SSM II	1.936	1.515	1.218	1.138	1.138	1.138	1.0

Table B.2
Individual device performance for ΔE_{97}

Device	MetaVue	eLAB	ES-V	OS	PR-670	RPC	SSM II
MetaVue	1.0	0.514	0.514	0.485	0.485	0.409	0.318
eLAB	1.870	1.0	0.989	0.932	0.932	0.787	0.611
ES-V	1.903	1.007	1.0	0.948	0.948	0.801	0.621
OS	1.957	1.035	1.035	1.0	0.975	0.823	0.639
PR-670	1.979	1.047	1.047	0.986	1.0	0.833	0.646
RPC	2.362	1.250	1.250	1.177	1.177	1.0	0.771
SSM II	3.082	1.630	1.630	1.536	1.536	1.297	1.006

Table B.3
Individual device performance for ΔE^*_{ab}

Device	eLAB	MetaVue	OS	RPC	PR-670	ES-V	SSM II
eLAB	1.0	0.793	0.656	0.551	0.508	0.508	0.245
MetaVue	1.271	1.0	0.851	0.715	0.659	0.659	0.318
OS	1.452	1.176	1.0	0.817	0.753	0.753	0.363
RPC	1.724	1.397	1.154	1.0	0.894	0.894	0.431
PR-670	1.854	1.502	1.241	1.043	1.0	0.961	0.464
ES-V	1.857	1.504	1.243	1.045	0.963	1.0	0.464
SSM II	4.094	3.316	2.740	2.303	2.122	2.12	1.0

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