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Hong Kong

CIC 33 COLOR & imaging CONFERENCE

Color Science and Engineering Systems, Technologies, and Applications

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FINAL PROGRAM AND PROCEEDINGS

The papers in this volume represent the program of CIC33: The 33rd Color and Imaging Conference held October 27–31, 2025 in Hong Kong.

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WELCOME CIC33!

Welcome to the 33rd Color and Imaging Conference (CIC33)! It is with great pleasure that we gather in Asia for the first time since the conference's inception in 1992, and in the dynamic and culturally rich city of Hong Kong. This milestone reflects the growing global reach and influence of our community, and we are thrilled to welcome participants from all corners of the world. We are deeply grateful for the strong support from a wide range of companies, whose sponsorships and exhibitions have helped make this event possible.

Since 2017, I have attended every CIC, whether online or in person, and I am inspired by the depth and breadth of the programs and discussions, which consistently address practical challenges and advance the frontiers of color and imaging science. The collaborative spirit and innovative ideas shared at CIC have always been a source of motivation for me. It is truly an honor to serve as the general chair of the conference, alongside Prof. Ronnier Luo, a distinguished researcher and leader in our field. Together with the dedicated organizing committee, we have worked hard to create a memorable and impactful week for all attendees here in Hong Kong.

This year's conference program is designed to offer something for everyone, from newcomers to seasoned experts. CIC33 begins with a series of short courses on Monday and Tuesday, covering a wide spectrum of topics. These range from foundational subjects such as Color Science Research and Application, to advanced areas like High Dynamic Range (HDR) Imaging: Capture, Standards, Display, and Color Management. On Tuesday, we also host four workshops, providing a platform for focused presentations and lively discussions on selected topics that are shaping the future of our field.

The heart of the conference—the technical sessions—take place Wednesday to Friday. Our program chairs, Paul Hubel, Jan Morovic, and Takahiko Horiuchi, have curated an outstanding lineup of oral presentations and interactive (poster) papers, showcasing the latest research and developments. We are honored to feature three keynote speakers from China, Japan, and South Korea, each bringing unique perspectives and expertise:

- Mingxue Wang, Huawei, "Recent Development and Challenges of Smartphone Digital Imaging"
- Shoji Tominaga, Nagano University and Norwegian University of Science and Technology, "Colorimetry and Image Reproduction of Fluorescent Objects"
- Hyeon-Jeong Suk, Korea Advanced Institute of Science and Technology, "Skin Color in Culture and Technology"

In addition, we are delighted to present an evening talk by Reuben Wu, photographer and visual artist, who shares his insights on "Light as Language: The Creative Use of HDR in Photography." These talks promise to spark new ideas and foster meaningful dialogue among participants.

Beyond the technical program, CIC33 offers ample opportunities for networking and social interaction. Our conference reception is held aboard a boat, allowing you to experience the stunning night views of Victoria Harbor while enjoying an extensive international buffet. This unique setting provides a relaxed atmosphere to connect with colleagues, exchange ideas, and celebrate our shared passion for color and imaging.

We hope that CIC33 not only deepens your knowledge and expands your professional network, but also leaves you with lasting memories of Hong Kong's vibrant culture and hospitality. Thank you for joining us for this special occasion. I look forward to meeting each of you, and wish you an inspiring and enjoyable conference experience.

—Minchen (Tommy) Wei
CIC33 General Chair

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COURSE AND WORKSHOP PROGRAM

MONDAY 27 OCTOBER 2025

SHORT COURSES

SC01: Color Science Research and Application
Instructors: Ming Ronnier Luo, Zhejiang University, and Minchen (Tommy) Wei, The Hong Kong Polytechnic University

SC02: Multimodal AI Essentials: Language, Vision, and Technical Use Cases
Instructors: Orange Gao, Shida Yu, and Nanqi Gong, Amazon

SC03: Creating Perceptual Experiments with Unity and VR
Instructor: Richard Murray, York University

SC10: Camera Phone Image Quality
Instructor: Jonathan B. Phillips, Society for Imaging Science and Technology

SC15: High Dynamic Range (HDR) Imaging: Capture, Standards, Display, and Color Management
Instructors: Nicolas Bonnier, Paul Hubel, and Luke Wallis, Apple Inc.

TUESDAY 28 OCTOBER 2025

SHORT COURSES

SC11: Underwater Colorimetry
Instructor: Derya Akkaynak, University of Haifa & IUI Eilat

SC12: Human Color Vision and Visual Processing and the Effects of Individual Differences
Instructor: Andrew Stockman, University College London and Zhejiang University

SC13: Camera Color Characterization: Theory and Practice
Instructor: Eric Walowit, consultant

WORKSHOPS

WORKSHOP 1: Display Color Consistency and Individual Differences in Color Sensitivity
Conveners: Francisco Imai and Shahram Peyvandi, Apple Inc. (US)
Confirmed talks and speakers:
- Physiologically-based Color Matching Functions: *Andrew Stockman, University College London (UCL) (UK) and Zhejiang University (China)*
- Color Reproduction Across Media: *Ming Ronnier Luo, Zhejiang University (China), Leeds University (UK), and National Taiwan University of Science and Technology (NTUST) (Taiwan)*
- HDR Color Reproduction and Impact of CMFs on Color Consistency: *Minchen (Tommy) Wei, The Hong Kong Polytechnic University (Hong Kong)*
- Individual Differences in CMFs that Lead to Inconsistent Colours on Different Displays: *Andy Rider, University College London (UK)*
- Improve Consistency of White Point Across Displays with Varied Primary Spectra: *Shining Ma, Beijing Institute of Technology (China)*
- Spectral Definition of Display Primaries: *Yuteng Zhu, Apple Inc. (China)*
- Optimal Color Matching Functions for Display and Color Consistency: *Yanjun Li, Apple Inc. (US)*
- CIE Technical Committee on Optimal CMF for Consistency Color on Electronic Displays: *Francisco Imai, Apple Inc. (US)*

WORKSHOP 2: Facial Appearance Measurement, Perception, and Applications
Convener: Yan Lu, University of Leeds (UK)
Confirmed speakers:
- Kumiko Kikuchi, SHISEIDO Global Innovation Center (Japan)
- Yoko Mizokami, Chiba University (Japan)
- Norimichi Tsumura, Chiba University (Japan)
- Changjun Li, University of Leeds (UK)
- Yan Lu, University of Leeds (UK)
- Théo Phan Van Song, L'Oréal (France)

WORKSHOP 3: New ICC Features in Real World Applications
Convener: Max Derhak, Onyx Graphics, ICC co-chair (US)
Confirmed speakers:
- Chris Bai, BenQ Corporation (Taiwan)
- Nicolas Bonnier, Apple Inc. (US)
- Phil Green, NTNU (Norway)
- Luke Wallis, Apple Inc. (US)

WORKSHOP 4: AR/MR/VR Color Perception and Rendering
Conveners: Jiangtao Kuang, Meta, Inc. (US), and Kaida Xiao, University of Leeds (UK)
Confirmed speakers:
- Shining Ma, Beijing Institute of Technology (China)
- Pei-Li Sun, National Taiwan University of Science and Technology (Taiwan)
- Minchen (Tommy) Wei, The Hong Kong Polytechnic University (Hong Kong)

18:15 – 19:45
WELCOME RECEPTION
Join colleagues at Dan Ryan's Chicago Grill for drinks and bar food to kick off the week.

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TECHNICAL PROGRAM: SCHEDULE AND ABSTRACTS

WEDNESDAY 29 OCTOBER 2025

WELCOME AND OPENING KEYNOTE

Session Chair: Minchen (Tommy) Wei, The Hong Kong Polytechnic University (Hong Kong)

9:00 – 10:00

Recent Development and Challenges of Smartphone Digital Imaging, *Mingxue Wang, Huawei Technologies Co., Ltd.* *

The rapid evolution of digital imaging has transformed smartphones into versatile tools for visual creation and display. Great efforts have been made on improving user experiences, including capturing, editing, transmission, and display. In particular, photography and HDR display are the two most outstanding examples. Unique photography technologies enhance low-light performance, long-distance capturing, and personalized editing, all of which are achieved with the rapid development of artificial intelligence (AI), better understanding about human perception, and user experiences. On the other hand, the realization of HDR VIVID, an HDR video/image technology released by the UHD World Association (UWA), on smartphones, allows the user to see more realistic images, richer colors, deeper shadows and details, and more highlights. Looking forward, there are still many challenges awaiting better solutions, such as color reproduction under complex illumination conditions, consistency across devices, and controllability of generated color images.

METAMERISM

Session Chair: Eric Kirchner, Zhejiang University (China)

10:00 – 10:40

10:00 **Recovering Stable Metamers Under a Varying Illumination,** *Violet Mayne and Graham Finlayson, University of East Anglia (UK)* **1**

It is impossible to recover the actual reflectance that induces a given colour response: as many spectra—called metamers—will integrate to the same response values. For some applications it suffices to recover a good single metamer (satisfying a criterion such that it is the smoothest amongst all metamers). However, when the same surface is viewed under different lights—generating different RGBs—the corresponding reflectances recovered by Smoothest Reflectance estimation (SR) are not all the same. Indeed, there can be a large spectral variation. Recent work has demonstrated that more stable—illuminant insensitive—metamers can be produced by Colour Corrected Smoothest Reflectance estimation (CCSR): where camera RGBs are colour corrected to a canonical reflectance light with respect to which metamers are recovered. In this paper, we examine the relationship between the spectral sensitivities of the camera and both SR and CCSR metamer recovery. Empirically, the variation in recovered metamers for the worst camera for the SR method is found to be 2.5 times larger than the best camera using CCSR. We argue that the stability of metamer recovery in general (for either SR or CCSR) is linked to the extent that accurate colour correction is possible.

10:20 **Deterministic Metamer Mismatch Body Computation,** *Alexander Forsythe[1,2] and Brian Funt[1]; [1]Simon Fraser University (Canada) and [2]Academy of Motion Picture Arts and Sciences (US)* **A-1**

Metamer mismatching poses a significant challenge for accurate color reproduction, as objects that match under one illuminant can diverge under another. The widely used algorithm for computing Metamer Mismatch Bodies (MMBs), proposed by Logvinenko et al., suffers from run-to-run variability due to its reliance on random direction vectors for boundary searches. This can result in sparsely sampled boundary regions. The stochastic nature of the algorithm introduces uncertainty into computed metrics, such as the Metamer Mismatching Color Rendering Index (MMCRI), which depend on the Logvinenko method, thereby complicating interpretation and comparison.

We propose a deterministic framework that eliminates this variability by replacing random seeding with a Sobol low-discrepancy sequence. This approach ensures uniform initial coverage of the feasible reflectance space. To further improve the distribution and maintain determinism, a Gray code transformation is applied to the Sobol sequence. A boundary-seeking nonlinear optimizer then refines these seeds to trace the MMB surface. In tests, the new method yields identical MMBs on every run, eliminating run-to-run variability, and shows a small but statistically significant reduction in average runtime (≈2% faster on this dataset). The resulting repeatable output makes the approach suitable for critical applications such as sensor design, color-correction lookup tables, and tolerance analysis. This work provides a more reliable foundation for MMB-based analyses, addressing the reproducibility challenges inherent in existing methods based on randomized sampling.

10:40 – 11:20 COFFEE BREAK / EXHIBITS OPEN

SKIN COLOR

Session Chair: Maryam Azimi, Apple Inc. (US)

11:20 – 12:20

11:20 **LUT-based Skin Spectrum Estimation System,** *Fangjia Du and Minchen Wei, The Hong Kong Polytechnic University (Hong Kong)* **7**

The measurement of diffuse skin reflectance spectrum has important applications, but require accurate and fast measurements. In this study, we proposed several methods for reconstructing the diffuse skin reflectance spectrum using several existing datasets. These methods can reconstruct the spectrum of an area by only capturing the images under several LED illuminations, instead of using comprehensive systems. A comprehensive system is being built to collect a ground-truth dataset, and also used to test the performance of the proposed methods.

*No proceedings paper or extended abstract associated with talk.

11:40 **Skin Color Preference Under Multi-scene Demand,** *Beijia Qin, Yuechen Zhu, and Ming Ronnier Luo, Zhejiang University (China)* **13**
This study discusses how scenes and model's appearance, gender and makeup status influence the preference facial skin tone of Chinese models for Chinese observers. This research also explores how the models' preference differ from the stranger observers. The results show that the makeup status can affect the scope of the preference area. The preference centers exhibit a trend of higher lightness and smaller hue angles than original ones. In all scenes except indoor scenes, a higher CCT correlates with a greater inclination angle of the ellipsoid projection on the a*-b* plane, a narrower ellipsoid range, and a smaller hue angle of the ellipsoid center. Apart from the in-lab scenario, higher scene color temperatures are associated with a larger chroma increment and a smaller hue increment in the preference centers relative to the original image skin tones. Also, the chroma of the preference centers of indoor and in-lab scenes is lower than that of the original images, distinguishing them from other scenes. The models' preference is influenced by their actual skin color to a larger extent.

EXHIBITORS

12:00 **Preferred Skin Color Reproduction Under Mixed Illumination,** *Liqing Wang, Ming Ronnier Luo, and Yuechen Zhu, Zhejiang University (China)* **19**
Skin tone reproduction has long been a challenge in image processing due to illumination by multiple sources in real–world conditions. This paper describes an algorithm to achieve preferred skin tone reproduction. The work comprises two pivotal components including to develop: 1) a CCT-SPQ/D optimization model via controlled experiments to reveal the mapping relationships between correlated color temperature (CCT) and skin preference quality (SPQ) and chromatic adaptation degree (D), and 2) a novel white balance correction algorithm for skin regions under mixed illumination, which integrates local processing and spatial filtering with color temperature adaptive enhancement via the aforementioned model. Finally, a preference assessment experiment was conducted to demonstrate the superiority of the algorithm proposed.

2-MINUTE EXHIBITOR PREVIEWS

Session Chair: Ján Morovic, HP Inc. (UK)

12:20 – 12:35

Exhibitors Colorspace Co. Ltd., Shanhai LumiChrome Intelligent Technology Co. Ltd., Jilin Qiushi Spectrum Data Tech. Ltd., Beijing Seetrum Technology Co., Ltd., Spectricity, and Thousand Lights Lighting (Changzhou) Limited share information about their products/services in short previews.

TWO-MINUTE INTERACTIVE PAPER PREVIEWS I

Session Chairs: Yuechen Zhu, OPPO, and Yuteng Zhu, Apple (China)

12:35 – 12:50

Relaxation Effect of Virtual Trees in Passthrough Space by Head Mounted Display, *Daiki Kiyohara and Norimichi Tsumura, Chiba University (Japan)* **A-4**
Stress is a growing concern in modern society, and exposure to natural environments has been shown to alleviate it. However, urban living often limits access to nature. This study explores the use of passthrough virtual reality (VR) to simulate natural elements in real-world settings. Passthrough VR refers to a mixed-reality approach in which cameras mounted on the outside of a head-mounted display capture the user's real environment in real time, allowing virtual objects to be superimposed onto it. We developed a passthrough VR environment and displayed virtual trees over the user's actual surroundings. Twelve male participants were tested with and without virtual trees. RMSSD rose significantly in the tree condition ($p < 0.05$), reflecting enhanced relaxation.

Testing the Acceptability Prediction of Color Difference Models using the Multiple Illumination Scenarios (MIS) Dataset, *Zhiyu Chen[1], Chenyu Wang[1], Qiang Xu[2], and Qiang Liu[1]; [1]Wuhan University and [2]Honor Device Co., Ltd. (China)* **25**
With the rapid advancement of mobile imaging and the increasing demand for perceptually accurate white balance (WB) algorithms, the need for a comprehensive dataset providing perceptual acceptability assessments across diverse illumination conditions has arisen. To address this gap, we constructed the Multiple Illumination Scenarios (MIS) dataset, which spans both pure colors and complex objects under single and multiple illuminant conditions. Observer-based acceptability ratings were collected and analyzed across 3,465 trials, revealing heightened sensitivity to chromatic deviations in regions of low lightness and chroma. Additionally, spatial and illuminance factors were found to modulate color acceptability judgments in multi-illuminant scenarios. Based on these findings, we proposed two new metrics to improve the performance of current color difference models: one weighted by color appearance attributes and another that incorporates spatial and illuminance factors. Evaluation results demonstrated that our proposed metrics showed improved correlation with perceptual judgments across all tested color difference models. By incorporating more realistic datasets and integrating alternative WB error evaluation metrics, we aim to advance research into the prediction of WB error acceptability under complex lighting environments.

Modeling Perceived Brightness in HDR Displays, *Farnaz Agahian and Dale Stolitzka, Samsung Display America Lab (US)* **31**
This article presents an enhanced mathematical framework that builds on the existing XCR model to more fully account for the increase in perceive display brightness as saturation rises. By integrating modifications to the CIECAM16, our toolkit allows for intuitive graphical exploration of color appearance attributes across a display's full gamut.

Psychophysical Colour Calibration of Multiple VR/MR Head-mounted Displays via Instrument-free Methods, *Jinbi Jiang and Stephen Westland, University of Leeds (UK)* **A-6**
Accurate colour reproduction in immersive environments is a long-standing problem for both researchers and developers working with virtual-reality (VR) and mixed-reality (MR) head-mounted displays (HMDs). Recent studies document how difficult it is to apply conventional calibration workflows to near-eye optics and real-time renderers. Hardware obstacles include complex lens pipelines that distort radiometric measurements and luminance imbalance between left- and right-eye panels. MR headsets add two further complications: perceived colour depends on both the display and the front-facing cameras that capture the physical scene, and transparent wave-guide optics (e.g., HoloLens 2) have subtle iridescence. On the software side, inside game engines, post-processing tone mapping, automatic exposure, lighting models and colour-space settings further decouple RGB values from on-screen output. Moreover, practical measurement is nontrivial—MR headsets and spectroradiometers must be precisely aligned with angle and distance controlled. These issues also result in instrument-based measurements of HMD being unable to achieve the same level of accuracy as when measuring 2D monitors. Relatively few studies have examined perceptual calibration in HMDs, what remains under-explored is how material shaders, lighting configurations and the choice of lit versus unlit rendering affect perceptual calibration, and whether 2-D results extrapolate robustly to genuine 3-D scenes. This project addresses the limitations of instrument-based calibration by developing a visual method for calibrating MR devices. Rather than claiming higher accuracy than instruments, our goal is to provide a complementary, user-centred pathway that is more stable and uniform across rendering modes and scenes. We introduce a repeatable perceptual matching method on HMDs that pairs rendered and no-rendering conditions to capture how users experience luminance. We also propose a perception-based colour-space conversion routine that links engine input signals to perceived luminance/colour via interpolation. These elements constitute a practical framework that complements instrument-only workflows by improving repeatability and harmonisation in MR colour characterisation.

An Effective Workflow for Colour Style Transfer, *Nanlin Xu[1], Lihao Xu[2], Miaosen Zhou[1], Liangwei Chen[1], and Ming Ronnier Luo[1]; [1]Zhejiang University and [2]Hangzhou Dianzi University (China)* **35**
To perform colour rendition in digital images for different atmosphere styles is becoming important for effectively communicating visual information. While different camera brands often possess their unique feature styles, precisely reproducing and evaluating colour style effects across diverse camera systems remains significant challenge such as fast mapping and effective evaluation between the source and target styles.

To address this issue, a workflow of colour style transfer has been developed. To begin with, multi-device image database including many images was built, comprising 1550 sRGB images, for which each includes two colour charts for calibration, and proposed transfer method using a 3DLUT precisely transfers colour styles, achieving a remarkably low ΔE_{00} of 1.09 in colour charts tests. Subjective evaluation with 10 volunteers showed a perceptible small visual difference, indicating the effect of workflow achieved satisfactory performance.

To overcome the limitations of subjective testing, a Siamese network-based EfficientNet Visual Difference Evaluation Model (EVDM) was introduced, which utilized a lightweight EfficientNet, achieved Pearson correlation coefficients of 0.90 (training), 0.88 (validation), and 0.92 (overall), significantly outperforming sophisticated baseline methods based on CIEDE2000 methods (max 0.76). This demonstrates EVDM's superior fitting, generalization, and consistency with human perception.

An Adaptive Model for Predicting Visual Comfort of Displays Accounting for Luminance Contrast in Various Ambient Light Conditions, *Zhenzhen Li and Ming Ronnier Luo, Zhejiang University (China).* **41**
The ubiquitous use of mobile devices has underscored the importance of evaluating display visual comfort to reduce eye strain and fatigue. This developed and tested visual comfort model for display visual comfort, taking into account key factors such as ambient illuminance, display luminance, text-background luminance contrast. The VC_{ALL} model was built based on three psychophysical experimental datasets: Neutral Colour Combination (NC), Coloured Colour Combination (CC), and Neutral Colour Combination with Dim Ambient Light (NCD), which involved 103 participants spanning various age groups. Two new experiments were conducted to verify the model' performance. One is to use the model to access displays' visual comfort, using an LCD and a QD_mini-LED, comparing with the results from various other testing methods. The other experiment was conducted to verify the performance of $VC_{reverse}$ by computing optimal text-background luminance combinations for any display under varying ambient light.

Three Dimensional Non-local Anisotropic Diffusion, *Ali Alsam and Hans Jakob Rivertz, Norwegian University of Science and Technology (Norway)* **46**
We present a novel anisotropic diffusion algorithm for noise reduction in Magnetic Resonance Imaging (MRI). The method integrates two key concepts: (1) diffusion is explicitly constrained to avoid increases in local image gradients, thereby preserving edges and fine structural details; and (2) a sequence of filters with exponentially increasing radii is applied, each maintaining a fixed number of non-zero coefficients. These filters allow the algorithm to evaluate whether pixels distant from the target location can contribute to smoothing without degrading local gradients. As a result, the method aims to balance between preserving local details and averaging global similarities.

In contrast to traditional denoising techniques based on local filtering or total variation minimization, the proposed algorithm enables controlled non-local diffusion and naturally extends to three-dimensional voxel arrays, making it well-suited for volumetric MRI data. The framework also permits the integration of additional geometric constraints, such as curvature, further enhancing its ability to preserve anatomical structures and surfaces.

The effectiveness of the proposed method is demonstrated on real MRI data from a macaque monkey. The experimental results indicate PSNR values comparable to those of our previous approach, while providing substantially better suppression of low-frequency noise, absence of visible artifacts, and faithful preservation of critical image features.

12:50 – 14:00 LUNCH ON OWN

ICC

Session Chair: Jinbi Jiang, University of Leeds (UK)

14:00 – 15:20

14:00 **Transforming Cone Fundamentals to Color Matching Functions for Use by iccMAX-based Color Management,** *Max Derhak, Onyx Graphics Inc. (US)* **52**

The use of the 1939 standard colorimetric observer for modern display calibration and color management has proven to be problematic in that it doesn't adequately predict the color matching of actual human observers. Recent research has resulted in the ability to identify physiologically based Cone Fundamental (CF) curves that more accurately predict individual color matching. However, the challenge still remains of adapting CF curves for the use of imagery and color specification based on the 2-degree 1931 standard observer. The use of iccMAX based color management requires well defined relationships between custom observers and the 2-degree 1931 standard observer to be provided.

In this paper, mathematical relationships and principles between cone fundamentals and color matching functions relative to viewing primary lights are outlined. Methods of conversion between cone fundamentals and color matching functions are explored and compared along with the proposed use of Wpt based material adjustment transforms to create color matching functions that provide backwards compatibility with legacy standard observer colorimetry.

14:20 **Toward Perceptolute Rendering of Media with Different Amounts of Optical Brightening Agents,** *Moritz J. Feil, Andreas Kraushaar, and Donatela Saric, Fogra Forschungsinstitut für Medientechnologien e. V. (Germany)* **58**

The established media relative and ICC-absolute colorimetric intents have been demonstrated to result in unsatisfactory visual matches when comparing prints on substrates with strongly differing amounts of optical brightening agents (OBA). This paper aims to contribute twofold toward the solution of this problem. First, a step toward a colour transformation is taken, which enables the most satisfying reproduction of pictures, printed on substrates with low amounts of optical brightening agents, on substrates with large amounts of OBAs. This is done on the basis of previous findings, which indicate that such a transform should consist of an absolute transform for colours with low lightness and a perceptual transform for colours of medium to high lightness. It is therefore, proposed that a new term be adopted for this colour transformation: perceptolute. In this paper, the previous findings are extended experimentally by investigating the progression of the perceptual part of the transform, via a colour matching experiment for exemplary achromatic colours. Secondly, since the fluorescence of OBA containing substrates strongly depends on the present UV amount, a practical tool to evaluate the UV amount in a given indoor lighting situation will be described. It is called "UV-Checker".

14:40 **Investigating Soft-proofing Performance using Individual Color Matching Functions,** *Yu-Kai Hong and Chris Yi-Ho Bai, BenQ Corp. (Taiwan)* **64**

CCFL displays have long been favored in professional applications for their spectral stability and neutral grayscale rendering. In contrast, LED-backlit monitors dominate the current market for their higher efficiency and wider color gamuts. Despite identical calibration settings, spectral differences between the two technologies often lead to significant perceptual mismatches, posing challenges in color-critical workflows such as soft proofing.

To investigate individual differences in color perception, we conducted a large-scale psychophysical experiment involving 45 observers. Each observer used custom software to adjust seven color images (white, red, green, blue, cyan, magenta, and yellow) to visually match corresponding printed targets. White image adjustments were performed using RGB gain controls, while chromatic images were adjusted using HSL sliders.

From these adjustments, individual color matching functions were derived for each observer. ΔE_{2000} values were computed to assess spectral curve differences between individuals and across groups. K-means clustering was applied to classify observer patterns. Results showed that individual color matching functions consistently outperformed the CIE 2° Standard Observer in terms of perceptual accuracy, except for magenta and yellow. Interestingly, several K-means cluster-based color matching functions also delivered good performance representing individual color matching functions.

Spectral differences across groups were visible directly through color matching functions comparisons, validating the effectiveness of clustering and supporting the use of perceptual group modeling.

This study demonstrates that incorporating individual color matching functions can significantly improve cross-media color matching. Observer-specific models built on K-means categories offer a scalable, perceptually based approach to user-aware color management.

15:00 **ICC Profile-driven Adaptive GCR for High-fidelity Facsimile Reproduction of Music Manuscripts,** *Marcin Dąbrowski, Warsaw University of Technology (Poland)* **70**

The faithful reproduction of historical art and music manuscripts lies at the intersection of color science, printing technology, and artistic interpretation. In such projects, the printed facsimile must be visually indistinguishable from the original, both to the trained eye and to the casual observer. This paper presents a methodology for creating dedicated ICC profiles for high-fidelity facsimile printing, developed through over a decade of reproducing Fryderyk Chopin's manuscripts. The approach is based on adaptive Gray Component Replacement (GCR), selectively tuned to different tonal and chromatic regions to preserve fine details, control local contrast, and mitigate issues such as show-through caused by the transparency of original paper. By mapping GCR levels according to the specific visual characteristics of each work, the method allows for targeted control over critical features such as ink density, edge sharpness, and tonal transitions. The process also accounts for substrate variability, press condition, and metameric effects under different illuminants. Results demonstrate that adaptive GCR, combined with context-driven communication between technical and artistic stakeholders, enables reproductions that maintain the visual fidelity, texture, and emotional impact of the original works.

15:20 – 16:00 COFFEE BREAK / EXHIBITS OPEN

COLOR CONSTANCY

Session Chair: Andreas Kraushaar, Fogra Forschungsinstitut für Medientechnologien e. V. (Germany)

16:00 – 17:40

16:00 **Facial-centric Color Constancy Dataset to Improve Scenario-specific White Balance Algorithms,** *Yuyang Liu and Minchen Wei, The Hong Kong Polytechnic University (Hong Kong)* **75**

Eliminating the color cast of the illuminant is a critical step in modern image processing systems, which has been addressed with a great number of illuminant estimation algorithms. The algorithms are found not effective for some specific contexts and applications, which leads to the development of scenarios-specific algorithms leveraging domain-specific cues. This paper investigated how facial cues help illuminant estimation. A total of 1299 images were captured under various dual-illuminant conditions, including real-world environments and lab settings. Modifications were made on existing methods by considering the facial information, which resulted in better performance.

16:20 **Integration of RGB Image and ALS for Color Constancy,** *Ruikai He and Minchen Wei, The Hong Kong Polytechnic University (Hong Kong)* **80**

Illuminant estimation plays a key role in computational color constancy, which typically relies on RGB images alone. In recent years, smartphones are commonly equipped with an ambient light sensor (ALS) next to the rear camera, which records low-resolution spectral information. This paper proposes several methods to estimate the illuminant using both RGB images and ALS signals, which are based on the state-of-the-art learning-based methods without significantly increasing computational cost. The proposed methods are found to result in better performance, in comparison to those only rely on RGB images.

16:40 **Color Adjustment of Brand Logos for Dark Mode Display,** *Byeongjin Kim, Giyun Lee, and Hyeon-Jeong Suk, KAIST (Republic of Korea)* **86**

We investigated how to optimally adjust brand logo colors for dark mode displays without compromising their original color identity. Through analyzing manual color adjustments of logos placed on black backgrounds (N=31), we figured out that designers tend to light up the dark-colored logo, while pale down the colors of bright logo. A tendency similar to that of their adjustments converging in a specific direction was obtained, so we derived a surface model that represents the direction in which original colors tend to shift. This model incorporates the L*, C*, and h* attributes to guide the computational adjustment process. This study offers a structured method for adapting logo colors to contemporary display contexts, effectively linking algorithmic solutions with design intuition.

17:00 **Learning-free Cross-sensor Color Constancy Using Optimal Nonsingular Matrices,** *Liangwei Chen and Minchen Wei, The Hong Kong Polytechnic University (Hong Kong), and Ming Ronnier Luo, Zhejiang University (China)* **90**

Automatic white balance (AWB) plays a crucial role in digital imaging, with modern learning-based methods achieving better performance. These methods, however, require extensive training data captured by a specific sensor, which cannot be directly deployed other sensors due to the different spectral sensitivity functions. This paper presents a novel cross-sensor adaptation method based on 3×3 color transformation matrices. By leveraging least-squares optimization and a Mahalanobis distance strategy, our approach constructs sensor-specific mapping matrices using 24-patch ColorChecker data. The results derived using the NUS dataset demonstrate that the proposed method has much smaller angular errors without requiring additional data collection or complicated network tuning.

17:20 **Enhancing Local Automatic White Balance with Multi-spectral Imaging,** *Johannes Keustermans, Robbe Van Beers, Jeroen Hermans, Alex Borgoo, and Michael Jacobs, Spectricity NV (Belgium)* **95**

Accurate white balancing (WB) remains a critical challenge in image signal processing. Particularly white point estimation for scenes with limited or ambiguous color information can lead to color casts and degraded visual quality. Moreover, many every-day scenes contain multiple relevant illuminants, further complicating illuminant estimation. Estimating multiple white points in a scene exacerbates the challenge and traditional RGB-based WB algorithms struggle with the limited information available for localized regions of a scene. We introduce a novel approach leveraging compact multi-spectral camera technology to improve local WB performance. By capturing additional, narrow-band spectral information beyond the RGB channels, our method provides more accurate white point estimation. We present comparative results demonstrating the advantages of multi-spectral sensing over conventional approaches, highlighting its potential to enable more intelligent and adaptive imaging pipelines in mobile, automotive, and industrial applications. Our approach is based on a relatively simple neural network, trained on simulated multi-spectral measurements. We developed a data collection protocol to establish a medium-sized validation dataset for which we report white point angles and color accuracy (DE2000) values. Our study includes a performance benchmark against a state-of-the art deep learning-based algorithm for our new validation set and the publicly available Large Scale Multi-Illuminant (LSMI) dataset. From the results we observe that our network performs on par with the state-of-the-art algorithm on the LSMI dataset and outperforms the state-of-the-art algorithm on our validation dataset. Furthermore, the multi-spectral based network outperforms the RGB based network.

17:40 – 19:30 DINNER ON OWN

EVENING TALK

Session Chair: Paul Hubel, Apple Inc. (US)

19:30 – 20:30

Light as Language: The Creative Use of HDR in Photography, *Reuben Wu, photographer and visual artist* *

Photography has always existed in dialogue with technology, but progress in imaging often raises as many creative questions as it answers. As tools for capturing and reproducing light become more sophisticated, the artist's challenge is no longer simply to record reality, but to interpret it. High Dynamic Range (HDR) imaging introduces new expressive possibilities, expanding how light, color, and atmosphere can be experienced within a photograph.

This talk reflects on the evolving relationship between imagination and precision in contemporary photography. Through Wu's illuminated landscape work, he explores how emerging imaging capabilities can transform perception, deepen emotional impact, and redefine what visual fidelity means in an artistic context.

*No proceedings paper or extended abstract associated with talk.

THURSDAY 30 OCTOBER 2025

THURSDAY KEYNOTE

Session Chair: Ming Ronnier Luo, Zhejiang University (China)
9:00 – 10:00

TALK SPONSORED BY

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Colorimetry and Image Reproduction of Fluorescent Objects, *Shoji Tominaga, Norwegian University of Science and Technology (NTNU), and Nagano University (Japan)* *

Fluorescence improves the appearance of many object surfaces, which has led to fluorescent materials being commonly integrated into everyday objects today. While methods for measuring the color of non-fluorescent objects are established and colorimetric devices are widely available, fluorescent objects exhibit not only reflection, but also luminescence, so there are no easy methods or devices available to measure it. As such, reproducing fluorescent color images is difficult.

This talk presents a method for estimating the Donaldson matrix from image data of fluorescent objects captured with a spectral camera. This matrix can be described by three components: spectral reflectance, emission, and excitation. Also presented is a technique for appearance synthesis of fluorescent objects with a mutual illumination effect. This technique improves the spatial resolution of measurements using a spectral camera. Furthermore, it makes it possible to reproduce fluorescent colors under arbitrary lighting conditions and generate realistic images of fluorescent objects if their shape is known. Natural objects exist in addition to man-made ones that emit fluorescence. Finally, this talk shows a method for estimating fluorescence emission spectra from plant grain and leaves.

ILLUMINATION

Session Chair: Edward Yu-Kai Hong, BenQ Corp. (Taiwan)
10:00 – 10:40

10:00 **An Adaptive Per-patch Weighted Regression for Target-based Color Correction of sRGB Images under Uncontrolled Outdoor Illumination,** *Asel Esra Özyılmaz, Norwegian University of Science and Technology (Norway); Damien Muselet and Alain Trémeau, Jean Monnet University (France); and Mathis Cordier, Cindy Torres, Olivier Robert, Cyril Dambrine, and Ali Boudjedra, Vilmorin - Mikado / Limagrain Vegetable Seeds (France)* . . . **101**

Color-accurate digital imaging is critical for agricultural phenotyping, but the scientific literature predominantly assumes the availability of linear RAW sensor data. In some commercial workflows, only standard 8-bit sRGB JPEG images are available, which poses a significant challenge due to their non-linear encoding and information loss from in-camera processing. This paper presents a robust color correction pipeline designed specifically for such non-linear images captured in uncontrolled outdoor environments.

Our core contribution is a novel, per-patch adaptive weighting scheme for least-squares color correction. Instead of deriving a single global correction, our method generates a unique transformation for each patch on an in-frame ColorChecker. This is achieved through a leave-one-out approach where, for each target patch, a model is trained on the remaining 23 patches. Crucially, this training is guided by a weighting matrix customized for the target patch. This adaptive process allows a simple linear model to outperform more complex polynomials. Through systematic evaluation on an unseen test set, we demonstrate this method reduces the mean color error ΔE_{00} from 11.23 to 3.79, providing a practical and effective solution for real-world agricultural imaging.

*No proceedings paper or extended abstract associated with talk.

10:20 **Improving the Color Accuracy of Lighting Estimation Models,** *Zitian Zhang[1], Joshua Urban Davis[2], Jeanne Phuong Anh Vu[2], Jiangtao Kuang[2], and Jean-Francois Lalonde[1]; [1]Université Laval (Canada) and [2]Meta (US)* **106**

Advances in high dynamic range (HDR) lighting estimation from a single image have opened new possibilities for augmented reality (AR) applications. Predicting complex lighting environments from a single input image allows for the realistic rendering and compositing of virtual objects. In this work, we investigate the color robustness of such methods—an often overlooked yet critical factor for achieving visual realism. While most evaluations conflate color with other lighting attributes (e.g., intensity, direction), we isolate color as the primary variable of interest. Rather than introducing a new lighting estimation algorithm, we explore whether simple adaptation techniques can enhance the color accuracy of existing models. Using a novel HDR dataset featuring diverse lighting colors, we systematically evaluate several adaptation strategies. Our results show that preprocessing the input image with a pre-trained white balance network improves color robustness, outperforming other strategies across all tested scenarios. Notably, this approach requires no retraining of the lighting estimation model. We further validate the generality of this finding by applying the technique to three state-of-the-art lighting estimation methods from recent literature. Our project webpage is available at: https://lvsn.github.io coloraccuracy.

10:40 – 11:20 COFFEE BREAK / EXHIBITS OPEN

COLOR VISION & NAMING

Session Chair: Begoña Acha, Universidad de Sevilla (Spain)
11:20 – 13:00

11:20 **Validation Experiment for Individual Observer Color Matching Functions,** *Jiaye Li[1,2] and Kevin Smet[1]; [1]KU Leuven University (Belgium) and [2]Université de Lyon (France)* **113**

Color matching functions (CMFs) form the foundation of colorimetric calculations. Among color-normal observers, individual differences in visual perception lead to substantial variability in CMFs. While this variability was historically less critical due to the broad spectral characteristics of most stimuli, it has become increasingly important with the growing use of narrowband spectral sources in wide-gamut displays and lighting technologies. As a result, individual observer CMFs have become an important topic of study. Li et al. introduced modifications to Asano's Individual Colorimetric Observer Model (AICOM+), including the adoption of the 2012 CIE ocular media model and the removal of LMS normalization prior to CMF conversion. A rapid approach for estimating individual observer CMFs—a reduced model with fewer parameters—was also developed to avoid overfitting while maintaining high predictive accuracy. These individualized CMFs were previously validated using achromatic matches.

In the present study, the colorimetric accuracy of the individual observer CMFs derived from both the full AICOM+ model and its reduced version was validated, using a rating-based experimental method with the same setup. Nine observers, randomly selected from the original cohort, participated. Their individual CMFs were compared to the CIE 2015 10° CMFs using the rating data. The reduced AICOM+ model yielded more accurate predictions than both the full model and the CIE 2015 10° CMFs for 7 out of 9 observers. Future work will apply recent improvements to individual observer models to evaluate potential further gains in predictive accuracy.

11:40 **Robert W. G. Hunt Best Paper Award A New Perspective on Color Vision Deficiency Diagnosis: Individual Color Matching Functions and Illuminations to Improve Color Discrimination,** *Siyuan Song, Hong Yang, and Ming Ronnier Luo, Zhejiang University (China)* **119**

In this study, a comprehensive test on 20 observers with color vision deficiencies was performed, including the standard Ishihara color vision test, the Farnsworth Panel D-15 test, and the anomaloscope test. In addition, a visual tricolorimeter to measure the individual color matching functions (ICMFs) of these observers was employed. The results showed that, except for the D-15 test, which exhibited some false negatives, the outcomes of the other three tests were completely consistent. This indicates the potential of ICMFs in diagnosing color vision deficiencies. Furthermore, the color discrimination abilities of these observers were tested under four specific light sources. The findings suggest that the vision for both Protan and Deutan observers can be significantly improved by one type of light source, especially for the Deutan observers.

12:00 **The Changes of Memory Colours Under Different Environmental Conditions,** *Yixuan Lou, Yuechen Zhu, and Ming Ronnier Luo, Zhejiang University (China)* **125**

This study investigates the sky and grass memory colours. Experiment was conducted to perform preferred and naturalness judgements by 21 subjects on images having sky and grass contents according to different environmental conditions. Thirty-three scene images were selected from 7 world wide websites. Thirty-one images were generated surrounding the original image. Each image was assessed in terms of naturalness and preference using the force choice method. The results were used to construct model to obtain memory colour centers, to compare the results between preferred and natural perceptions, and to model colour changes over environmental conditions. A model was developed to predict sky memory colour according to the cloud information in each image.

12:20 **The Colonisation of Colour Categories: How European Colour Concepts Have Invaded Polynesian Languages,** *Neil Dodgson, Victoria Chen, Tia Neha, and Meimuna Zahido, Victoria University of Wellington (New Zealand)* **130**

Berlin and Kay propose that there are basic colour terms in any language. These terms split the range of all colours into categories and different languages may have different categories. A meeting of cultures can lead to changes in how a language categorises colour. Across Polynesia, today, we see educational material that purports to teach colour in the indigenous languages, but that categorises colour into the Western European categories, using loan words or repurposed indigenous words to describe colour categories that did not exist in that language prior to colonisation. We describe an ongoing project that tracks changes in language use in Polynesian languages, both before and after colonisation. We present our initial findings.

12:40 **Ghiblification and Color Richness in Material Appearance: How Human Observers and Image Quality Metrics Perceive Them?,** *Mobina Mobini, Olga Cherepkova, and Davit Gigilashvili, NTNU (Norway)* **136**

Distortions introduced during the reproduction of digital images can lead to substantial changes in their color composition. The motivations for altering images range from practical purposes, such as image compression and color quantization to reduce file size, to more aesthetic applications like style transfer using generative AI. In this work, we investigate how the reproduction of color images affects material appearance, in particular, the perception of gloss and translucency. We applied different image quality distortions to natural images of glossy and translucent objects. Additionally, we Ghiblified them—a recent viral social media phenomenon of mimicking the Japanese anime style using generative AI style transfer. Afterward, we conducted a series of user studies to evaluate the fidelity of gloss and translucency reproduction. The experimental results represent how the reproductions are perceived by image quality metrics and open up a new direction for material appearance studies.

13:00 – 14:15 LUNCH ON OWN

DISPLAYS

Session Chair: Norimichi Tsumura, Chiba University (Japan)
14:15 – 15:15

14:15 **Spectral Definition of Standard Color Space Primaries for Display,** *Yuteng Zhu, Yanjun Li, Po-Chieh Hung, Adria Fores Herranz, Tyler Pruitt, Yanming Li, Francisco Imai, Will Wu, and Shahram Peyvandi, Apple Inc. (US)* **142**

To calibrate a display, a standard color gamut is defined by the target chromaticity coordinates of RGB primaries in CIE 1931 color space, e.g. DCI-P3 and Rec.709. Due to lack of spectral information of such standard target gamut primaries, transformation of target color gamut from CIE 1931 color space to another color space associated with a different observer (defined by a different set of CMFs) is not possible. In this paper, we introduce a novel method for transforming target primary colors from CIE 1931 color space into a new target color space with improved color appearance consistency for typical observers. Our approach represents each primary with a simple spectral definition across the visible range. Results demonstrate that this spectral definition significantly reduces inter-observer variation, thereby offering a practical solution to cross-observer display color space transformation.

14:35 **Optimizing Mobile Display Perception in Dim-light Environments: Observer-driven Adjustments of Backlight Luminance and Image Lightness and Chroma,** *Xinye Shi, Ming Ronnier Luo, and Yuechen Zhu, Zhejiang University (China)* **147**

Adjustment of the backlight luminance of mobile phones in dim lighting has been challenging due to the setting of low lighting levels. The present experiment is aimed to reveal the suitable brightness for viewing images under six low lighting conditions (0, 0.5, 1, 2, 3, 4, 5, 10, 25, 50 lux).

Twenty participants adapted to each light level in ascending order. For each level, they adjusted: 1) backlight luminance for comfortable viewing on a white background image with black text, and 2) the lightness and chroma of a test image for optimal appearance on color images. The results reveal distinct trends. Firstly, preferred backlight luminance increases non-linearly with rising ambient illuminance. Secondly preferred image lightness and chroma gains both exhibit a small but consistent increase with rising ambient illuminance. Finally, the magnitude of these preferred gains for both lightness and chroma showed a negative correlation with the average lightness and chroma of the original images. These findings offer new insights into how observers adapt displays under near-dark to low-light (mesopic) conditions and provide practical guidance for refining display adaptation algorithms.

14:55 **Does D65 Illuminant or D65 Chromaticities Produce Neutral White Appearance?,** *Yuetong Shen and Minchen Wei, The Hong Kong Polytechnic University (Hong Kong)* **153**
D65 plays a critical role in color reproduction, specification, and characterization. Displays commonly use D65 chromaticities as the white point, but many studies shown that a stimulus produced by displays having a slightly higher CCT was perceived to produce neutral white appearance. Moreover, our two recent studies found that LCD/OLED displays need to produce a stimulus having a slightly higher CCT to match the appearance of a high quality D65 illuminant that was produced by a 14 channel spectrally tunable LED device. We hypothesize that a higher CCT required by displays to produce a neutral white appearance was caused by the CIE 1931 Color Matching Functions and a D65 illuminant can indeed produce a neutral white appearance. In this study, we use the 14 channel LED device to produce a series of high quality daylight simulators. The observers generally selected the stimulus having a CCT between 6346 and 6906 K to produce the neutral white appearance. When using an LCD display to match the color appearance of the selected stimulus, the average CCT was between 7209 and 7943 K. Such a finding suggests the importance of color matching functions in display specification and calibration.

TWO-MINUTE INTERACTIVE PAPER PREVIEWS II

Session Chairs: Yuecheng Zhu, Zhejiang University, and Yuteng Zhu, Apple (China)
15:15 – 15:30

A Pilot Study Investigating How Individuals with Varying Sensory Characteristics Perform in Virtual Reality Environments,
Mina Shamohammadi, Chihiro Hiramatsu, Kana Miayazato, Hiroyuki Matsuguma, Naoto Nakamura, and Naoko Takahashi, Kyushu University (Japan). **156**
Diversity in visual perception, particularly due to age and color vision types, has been widely studied in fields such as cognitive psychology and human-computer interaction. Variations in color perception, such as those arising from dichromatic or trichromatic vision, can significantly influence object-finding tasks and overall performance in virtual environments. Recent studies suggest that while Virtual Reality (VR) environments can be designed with universal accessibility, understanding how individuals process visual cues in these environments remains underexplored.

This study investigates how individuals with diverse visual perception perform object-finding tasks in a VR environment. As part of a pilot study, participants completed tasks in two types of VR environments: one rendered in full color and the other in grayscale. The aim was to explore how different visual settings might support future research involving a more diverse participant group. While preliminary results indicated better performance in the color environment across participants, the primary focus was to assess the suitability of the experimental design and environment setup for investigating sensory interactions in VR.

By understanding how visual differences affect performance, designers can create more inclusive virtual spaces for uses like education, gaming, and training. This interdisciplinary approach, combining elements of psychology, sensory studies, and technology design, suggests a more inclusive framework for addressing diversity in VR environments. By systematically analyzing visual perception, the study not only advances academic understanding but also provides a practical roadmap for implementing inclusive VR solutions across industries.

A Pigment-based Spectral Imaging Sensor Approach for AWB: Outperforming Flagship Smartphones in Challenging Scenes,
Zhilei Huang[1], Jiawei Yang[2], Hong Zhang[1], and Xinle Guo[1]; [1]Beijing Seetrum Technology Co. and [2]Tsinghua University (China) **A-8**
We propose a camera-independent illuminant estimation algorithm for Auto White Balance (AWB) base on pigment-based spectral imaging sensors, achieving over 30% accuracy improvement compared to flagship smartphone solutions, especially in traditional challenging scenes such as single-color dominated scenes and non-white-dominant scenes. We use quantitative metrics including error angle $\Delta\theta$ and color difference ΔE_{00} for AWB evaluation, demonstrating superior performance across 382 real scenes with an average error angle of 3.26° and an average ΔE_{00} of 3.77. The results show great application potential of spectral imaging sensors for AWB in consumer electronic imaging devices such as smartphones.

Modeling the Relationship between Haze and Attenuation Coefficient from Image-based Measurements of Translucent Liquids,
Lu Xu[1], Davit Gigilashvili[1], and Jean-Baptiste Thomas[1,2]; [1]Norwegian University of Science and Technology (Norway) and [2]Université Bourgogne Europe (France) **161**
This study focuses on exploring the relationship between haze and the intrinsic optical properties of translucent materials through image-based measurements conducted in a real-world setting. The research adopts water-based samples mixed with milk and black tea, enabling the investigation of materials with varying absorption and scattering properties. We quantify haze using an image-based measurement system and estimate lateral attenuation coefficient with a translucency meter device. A linear regression model was established, relating haze to the logarithm of the product of sample thickness and the effective lateral attenuation coefficient. This finding contributes to advancing the understanding the appearance of translucent materials and has potential industrial applications.

Smartphone Color Quantification from a Clinical Perspective: Accuracy and Precision, *Yifan Zhang and Terence S Leung, University College London (UK)* **167**
Smartphones, with their built-in cameras, are increasingly employed in clinical applications, e.g., screening patients for jaundice or anemia. In these applications, the color values of the target are converted into a biomarker using a regression or AI model. This paper investigated the accuracy and precision of x and y chromaticity values influenced by image noise and environmental factors, which could affect diagnostic performance. Accuracy was represented by the mean xy error distance (MED), and precision by the standard deviation (SD) of the xy chromaticity measurements. Using a Samsung S22 smartphone to take photos of the same color patch in 9 positions over 20°, we found that even for the same target, taking a photo from different angles caused the xy chromaticity values to change. However, the accuracy could be maintained by averaging these color measurements. The xy chromaticity measurements could also be affected by a neighboring color object and its impact on accuracy depended on the colors of the neighboring object and the target. We also investigated the scenarios with 3D graphics software Blender and found similar trends. Understanding factors influencing the accuracy and precision of color quantification can lead to improvements of smartphone imaging-based diagnostic techniques.

JIST-First The Lower the Bumps, the Higher the Translucency: How Editing Perceived Bumpiness Affects Material Appearance,
Seyedeh Kimia Arfaie Oghani, Davit Gigilashvili, and Mobina Mobini, Norwegian University of Science and Technology (Norway), and Midori Tanaka and Takahiko Horiuchi, Chiba University (Japan) **see JIST 69(5)/** DOI: 10.2352/J.ImagingSci.Technol.2025.69.5.050401
A recent work proposed a methodology to effectively enhance or suppress perceived bumpiness in digital images. We hypothesized that this manipulation may affect perceived translucency due to similarity in affected image cues. In this work, we test this hypothesis experimentally. We conducted psychophysical experiments and found a correlation between perceived bumpiness and perceived translucency in processed images. This not only may have implications when digitally editing the bumpiness of a given material but also can be taken advantage of as a translucency editing tool unless the method produces artifacts. To check this, we evaluated the naturalness and quality of the processed images using subjective user study and objective image quality metrics, respectively.

3D CG HEVC Images Attention Mechanism Based on Vision Transformer, *Norifumi Kawabata, Kanazawa University (Japan)* . . . **173**
When creating media content, it is important to understand in advance where people focus their attention and what they are interested in when viewing images. Thus far, we have measured the area using saliency maps to determine the relationship between picture coding and gaze points. However, as an evaluation metric, it is not enough to consider factors other than area, and the accuracy was not enough. Therefore, we thought that we could achieve higher accuracy it estimating areas of interest by using the knowledge of Vision Transformer, which was developed in the field of computer vision based on natural language processing. In this study, we experimentally examined the evaluation of regions of interest in images by performing region of interest estimation using the attention mechanism of Vision Transformer on HEVC encoded 3D CG images and then analyzing the images.

HDR Printing, How to Produce and Display Extreme Contrast Levels,
Reiner Fageth, CEWE Stiftung & Co. KGaA, and Dietmar Wueller, Image Engineering GmbH & Co. KG (Germany) **A-10**
The maximum density that can be achieved with today's printing technologies on reflective material is about 2.4. This results in a contrast range of 250:1. Applying a specialized coating increases the maximum density to around 3, but does not improve the ability to differentiate detail between densities 2.4 and 3.

To achieve larger dynamic ranges, backlit transparencies are essential. However, even with these, the dynamic range of available materials is limited to a maximum density of approximately 3, which equals a displayable contrast range of up to 1000:1 and is classified as SDR.

Higher contrast levels require multi-layer technology in conjunction with a bright, uniform light box. It is necessary to determine how to generate the required tone curve and manage colors to achieve the desired result. ICC color management is referenced to diffuse white and is therefore not defined for real HDR applications. Another challenge is registering multiple layers with each other, especially when they are applied to both sides of the same substrate.

INTERACTIVE PAPER SESSION / EXHIBITS OPEN

15:30 – 17:00
Discuss the Interactive (poster) Papers with their authors and help select the CIC33 Cactus Award winner. Exhibits are also open during this time.

HONG KONG HARBOUR CRUISE AND BUFFET DINNER

19:00 – 22:00
Join colleagues for dinner and a lovely cruise of Hong Kong Harbour.

FRIDAY 31 OCTOBER 2025

CLOSING KEYNOTE AND CIC AWARDS

Session Chair: Paul Hubel, Apple Inc. (US)
9:00 – 10:00

TALK SPONSORED BY

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Skin Color in Culture and Technology, *Hyeon-Jeong Suk, Korea Advanced Institute of Science and Technology (KAIST) (Republic of Korea)**
Human skin color lies along a narrow pathway from dark brown to light beige within the wide gamut of human vision. Despite this limited range, even subtle variations carry disproportionate weight—affecting perceptions of beauty, social class, and identity. These interpretations are not fixed; they evolve across cultures and historical periods.

In Asia, lighter skin was historically associated with status and attractiveness, while today's trends emphasize authenticity and diversity. Reflecting this shift, cosmetic brands now release anywhere from 15 to more than 200 foundation shades, enabling individuals to express identity as well as appearance. Makeup thus becomes not only a cosmetic tool but also a means of self-definition.

Recent advances in color science and digital technology are accelerating this transformation. Imaging systems, AI-driven analysis, and smartphone applications can measure and recommend skin tones beyond the limits of the eye. Digital-first brands are leading the way with personalized services. Yet an essential question remains: Should skin color be captured with maximal precision, or tuned to reflect self-perception and context?

From the mirror to social media, from stage presence to XR avatars, each version of the "self" reveals a different shade—bridging science, culture, and technology.

SAMPLING

Session Chair: Farnaz Agahian, Samsung Display America Lab (US)
10:00 – 10:40

10:00 **ΔE–uniformity–tuned Color Sets,** *Ján Morovic, HP Inc. (UK), and Peter Morovic, HP Inc. (Spain)* **179**
Color charts are used in many color imaging contexts to sample a color space or the effects of a color transformation. A rich variety of approaches exist here for determining the set of colors contained in a color chart and the specific choices of colors and their cardinality both then impact the goodness of the color imaging processes that use them. A key example here are the color charts used for building ICC color profiles. Such charts are often variations on uniform samplings in either an RGB or a CMYK device color space. At the same time, the accuracy of an ICC profile is judged in terms of color difference (ΔEs), and a chart that is uniformly distributed in those terms would be advantageous. This paper presents an approach to explicitly tuning color charts for uniformity in arbitrary color spaces and for arbitrary color difference metrics, using computational optimization over a hexagonally close packed mesh. Results show a substantial improvement in the uniformity of ΔE differences between each chart color and its neighbors.

*No proceedings paper or extended abstract associated with talk.

10:20 **An Empirical Evaluation of Down- and Up-sampling in Jacobi Retinex,** *Afsaneh Karami and Graham Finlayson, University of East Anglia (UK)* **184**

The McCann99 Retinex is a particular algorithmic implementation of Retinex theory. Retinex algorithms attempt to compress the dynamic range of an input image to make an output which can be displayed and has a pleasing rendition. The McCann99 Retinex algorithm employs a multi-grid structure, processing the image in a pyramidal manner from coarse to fine resolutions. This hierarchical approach is designed to enhance computational efficiency and accelerate convergence. In recent work, the structure of the McCann99 Retinex has—by appealing to classical work in numerical analysis—been modified to be a per pyramid level Jacobi iteration and as such is not only faster, but aligns Retinex with other theories of early visual processing (including centre-surround operators and path-based theories).

In this paper, we conduct a complementary systematic investigation into how images are down- and up-sampled as part of the multi-grid computation. The McCann99 and Jacobi Retinex algorithms use a simple box-filter approach, which means that down-sampled image data must be aliased. We investigate a set of other commonly used sampling methods, including bilinear, bicubic, Lanczos2 and 3, sinc with rectangular, Hamming and Kaiser windows. We are interested in using image quality metrics to determine whether substituting a different sampling approach into the Jacobi Retinex leads to better quality outputs being generated. Our investigation leads us to an interesting conclusion: while more complex down- and up-sampling algorithms can improve image quality, the simple box method performs well. If image quality is the primary concern, sinc is found to be the best method for down- and up-sampling. However, it requires an appropriate window function to taper the truncation and avoid ringing artefacts.

10:40 – 11:20 COFFEE BREAK

GENERATIVE AI

Session Chair: Zhilei Huang, Beijing Seetrum Technology Co., Ltd. (China)

11:20 – 12:40

11:20 **LLMs Speak LAB,** *Ján Morovic, HP Inc. (UK), and Peter Morovic, HP Inc. (Spain)* **191**

Large Language Models (LLMs) are advanced neural networks designed to interpret and generate human-like text thanks to their structure and to having been trained on vast amounts of data. They can perform a wide range of natural language processing tasks, including text generation, translation, summarization, and question-answering, and are the engines of conversational AI platforms like ChatGPT, Gemini or Claude. A key feature of such LLMs is their inference of a subsequent piece of text from preceding pieces of text. As such, their computational structure lends itself to making other, similar sequential inferences. While the acquisition of color measurements may at first seem far removed from the domain of LLMs, it too can be thought of as a sequential process, consisting of the measurement of a sequence of stimuli, and therefore open to sequential inference. The present paper introduces an adaptation of LLMs to color data, and more broadly to sensor data, and their application to generating measurements from a preceding sequence, based on pre–training transformers with sensor data sequences. Promising first results are shared that point to low color differences when models are prompted with similar magnitude data to those being constructed using generative AI (GenAI).

11:40 **Color Encoding in Latent Space of Stable Diffusion Models,** *Guillem Arias, Ariadna Solà, Martí Armengod, and Maria Vanrell, Universitat Autònoma de Barcelona (Spain)* **197**

Recent advances in diffusion-based generative models have achieved remarkable visual fidelity, yet a detailed understanding of how specific perceptual attributes—such as color and shape—are internally represented remains limited. This work explores how color is encoded in a generative model through a systematic analysis of the latent representations in Stable Diffusion. Through controlled synthetic datasets, principal component analysis (PCA) and similarity metrics, we reveal that color information is encoded along circular, opponent axes predominantly captured in latent channels $\rightarrow c_3$ and $\rightarrow c_4$, whereas intensity and shape are primarily represented in channels $\rightarrow c_1$ and $\rightarrow c_2$. Our findings indicate that the latent space of Stable Diffusion exhibits an interpretable structure aligned with a efficient coding representation. These insights provide a foundation for future work in model understanding, editing applications, and the design of more disentangled generative frameworks.

12:00 **JIST-First Automatic Image Colorization with Semantic Segmentation and Multipath Deep Networks,** *Jie-Sen Wang[1], Hung-Chung Li[2], and Pei-Li Sun[1]; [1]National Taiwan University of Science and Technology and [2]National Chung Hsing University (Taiwan)* . . . . **see JIST 69(5)/**
DOI: 10.2352/J.ImagingSci.Technol.2025.69.5.050402

A fully automated colorization model that integrates image segmentation features to enhance both the accuracy and diversity of colorization is proposed. In the model, a multipath architecture is employed, with each path designed to address a specific objective in processing grayscale input images. The context path utilizes a pretrained ResNet50 model to identify object classes while the spatial path determines the locations of these objects. ResNet50 is a 50-layer deep convolutional neural network (CNN) that uses skip connections to address the challenges of training deep models. It is widely applied in image classification and feature extraction. The outputs from both paths are subsequently fused and fed into the colorization network to ensure precise representation of image structures and to prevent color spillover across object boundaries. The colorization network is designed to handle high-resolution inputs, enabling accurate colorization of small objects and enhancing overall color diversity. The proposed model demonstrates robust performance even when training with small datasets. Comparative evaluations with CNN-based and diffusion-based classification approaches show that the proposed model significantly improves colorization quality.

12:20 **Language-based Color ISP Tuning,** *Owen Mayer[1], Shohei Noguchi[2], Alexander Berestov[1], and Jiro Takatori[2]; [1]Sony Corporation of America (US) and [2]Sony Corporation (Japan)* **203**

We propose a method for tuning the parameters of a color adjustment Image Signal Processor (ISP) algorithmic "block" using language prompts. This enables the user to impart a particular visual style to the ISP-processed image simply by describing it through a text prompt. To do this, we first implement the ISP block in a differentiable manner. Then, we define an objective function using an off-the-shelf, pretrained vision-language-model (VLM) such that the objective is minimized when the ISP-processed-image is most visually similar to the input language prompt. Finally, we optimize the ISP parameters using gradient descent. Experimental results demonstrate tuning of ISP parameters with different language prompts, and compare the performance of different pretrained VLMs and optimization strategies.

12:40 – 14:00 LUNCH ON OWN

HDR

Session Chair: Eric Walowit, consultant (US)

14:00 – 15:20

14:00 **HDR Image Reconstruction from Saturated LDR Images of Dielectric Objects,** *Shoji Tominaga, Norwegian University of Science and Technology (Norway) and Nagano University (Japan), and Takahiko Horiuchi, Chiba University (Japan)* . . . **209**

This paper presents a method for reconstructing the original high dynamic range (HDR) image from a saturated low dynamic range (LDR) image with missing physical information, specifically for single dielectric objects. A deep neural network approach is employed to map an 8-bit LDR image directly to its corresponding HDR representation. We begin by analyzing the reflection and saturation characteristics of dielectric materials and then construct an HDR image database using a diverse set of dielectric objects. Each HDR image is clipped to generate a set of 8-bit LDR images. All HDR-LDR image pairs are normalized to a fixed resolution and used for training and validation. A deep convolutional neural network (CNN) is designed in the form of an autoencoder architecture with skip connections. The entire network is implemented using MATLAB's machine learning toolbox, with the ADAM optimizer employed for training. The performance of the proposed method is evaluated using a separate validation set. Comparative experiments with existing methods demonstrate that our approach achieves significantly higher reconstruction accuracy and better histogram fitting.

14:20 **HDR Image Visual Matching and Tone Mapping based on CAM16-UCS,** *Miaosen Zhou and Ming Ronnier Luo, Zhejiang University (China)* **215**

A controlled experimental setup used multichannel LED lighting to create HDR scenes. Ten observers performed visual matching tasks between real illuminated scenes and HDR display content across eight lighting conditions. $J_za_zb_z$, CIECAM16, and CAM16-UCS were evaluated, analysis using STRESS metrics showed CAM16-UCS achieved the best performance for both lightness and colorfulness predictions. Based on these findings, a tone mapping operator was developed utilizing CAM16-UCS color space with local adaptation and gamma adjustments derived from experimental data. The results demonstrate that CAM16-UCS provides superior color appearance prediction for HDR content and serves as an effective foundation for tone mapping applications.

14:40 **Very Simple Tone Curves,** *James Bennett and Graham Finlayson, University of East Anglia (UK)* **221**

Tone mapping algorithms are used to compress dynamic range, make image details more conspicuous and generally enhance the image for preference. Global tone mapping manipulates the brightnesses of pixels by applying a single function - or tone curve - to every pixel in the image. Tone curve generation algorithms often constrain the shape of their tone curves and it has been argued that tone curves should be simple, meaning they have one or zero inflexion points. In this work, we investigate whether tone curves should be simplified even further. We present our method which finds the zero inflexion tone curve - which we call a Very Simple (VS) curve - that best approximates a potentially complex tone curve. For the MIT-Adobe FiveK dataset, comprising 25,000 expert tone adjustments, we calculate the best VS approximations and find these curves produce visually similar images compared with more complex counterparts.

15:00 **High Dynamic Range – The Last Frontier of Digital Imaging,** *Guoping Qiu, The University of Nottingham (UK and China)* *

Despite decades of research and significant investment, digital imaging technology still struggles in certain real-world scenarios—such as capturing a photo at an evening gathering in a dimly lit restaurant—where either shadows appear completely dark or bright areas become oversaturated, losing vital details. Even with modern HDR (High Dynamic Range) features now standard in smartphones, these issues often persist. And yet, the human eye can perceive detail across both shadowed and brightly lit areas in such scenes with ease.

This talk explores the fundamental reason behind this discrepancy: the inherent limitations of digital sensors in handling high dynamic range light intensities. Professor Qiu will revisit the HDR problem from first principles, arguing that it remains one of the most critical—and often misunderstood—challenges in digital imaging. He will critique common misconceptions in recent literature, particularly those relying on deep learning-based "black-box" approaches to low-light enhancement. Through theoretical insights and practical demonstrations, the talk will make the case that HDR remains the last great frontier in the evolution of digital photograph.

15:20 – 16:00 COFFEE BREAK

MATERIAL APPEARANCE

Session Chair: Davit Gigilashvili, NTNU (Norway)

16:00 – 17:00

16:00 **Color Co-occurrence Matrix based on Color Appearance Model CIECAM16. Application to Dermatological Images,** *Begoña Acha and Carmen Serrano, Universidad de Sevilla (Spain)* **227**

New color texture features have been designed based on second-order statistics features that are calculated from a new color co-occurrence matrix (CCM). These CCM features have three main novel design aspects. First, they incorporate perceptual color differences in their computation. Second, the second-order probability distributions are based on the CIECAM16 color appearance model and its derived Uniform Color Space (CIECAM16-UCS). Third, to avoid high-dimensional and sparse cooccurrence matrices, low-dimensional CCMs are calculated using perceptual clustering for color quantization. The ability of these new CCM metrics to analyze colored textures has been validated in two experiments using biomedical color texture images: Basal Cell Carcinoma (BCC) dermoscopic pattern detection and hemangioma depth estimation from color photographs. Both experiments demonstrated that the proposed CCM features outperformed other texture analysis methods.

16:20 **How Color Influences Gloss and Gloss Influences Sparkle and Graininess in Metallic Coatings,** *Eric Kirchner, Zhejiang University (China)* **232**

Three main aspects of the appearance of metallic coatings are color, gloss and texture (including graininess and sparkle). All three aspects can now be objectively measured using instruments according to ASTM and other international standards. However, there is no reason why these three aspects would be independent from each other. Indeed, it is known for more than a century that variations in color influence the perception of gloss. Here, we present the first systematic investigation

*No proceedings paper or extended abstract associated with talk.

on the influence of gloss variations on the occurrence of sparkle and graininess.

We created a new, dedicated set of 462 solid and metallic paint samples, with systematic variations in color and gloss. We measured multi-angle reflectance properties for all samples. Our results confirm that color strongly influences measured gloss values, especially for metallic coatings. We also show that there is a substantial influence from glossiness to the measured graininess and sparkle properties. For example, by applying a matte clearcoat instead of a more common high-gloss clearcoat on top of a metallic basecoat, the measured graininess reduces by 0.6±0.3 units and the sparkle grade at 15° by 3.3±1.7 units. This is in line with visual assessments on matte car paints: matte metallic paints hardly show sparkle. A physical explanation for these trends is presented.

16:40 **JPI-first Can Gloss and Translucency Be Captured in an Explainable Low-dimensional Space?,** *Hassan Askary, Muhammad Hamza Zafar, and Davit Gigilashvili, Norwegian University of Science and Technology (Norway)* . . . . . **see JPI 8/**
DOI: 10.2352/J.Percept.Imaging.2025.8.000404
One central challenge in modeling material appearance perception is the creation of an explainable and navigable representation space. In this study, we address this by training a StyleGAN2-ADA deep generative model on a large-scale, physically based rendered dataset containing translucent and glossy objects with varying intrinsic optical parameters. The resulting latent vectors are analyzed through dimensionality reduction, and their perceptual validity is assessed via psychophysical experiments. Furthermore, we evaluate the generalization capabilities of StyleGAN2-ADA on unseen materials. We also explore inverse mapping techniques from latent vectors reduced by principal component analysis back to original optical parameters, highlighting both the potential and the limitations of generative models for explicit, parameter-based image synthesis. A comprehensive analysis provides significant insights into the latent structure of gloss and translucency perception and advances the practical application of generative models for controlled material appearance generation.

CLOSING REMARKS AND BEST STUDENT PAPER AWARD

Minchen (Tommy) Wei, The Hong Kong Polytechnic University (Hong Kong) and Ming Ronnier Luo, Zhejiang University (China)

17:00 – 17:10
The conference concludes with closing remarks from the chairs and the presentation of the Best Student Paper Award.

NOTES

CIC33 APPENDIX A EXTENDED ABSTRACTS

NOTES

Deterministic Metamer Mismatch Body Computation

Alexander G. Forsythe[1,2,], Brian Funt[1]*
[1] *Simon Fraser University, Vancouver, Canada*
[2] *Academy of Motion Picture Arts and Sciences, Hollywood, California*
[*] *Corresponding Author*

Abstract

Metamer mismatching poses a significant challenge for accurate color reproduction, as objects that match under one illuminant can diverge under another. The widely used algorithm for computing Metamer Mismatch Bodies (MMBs), proposed by Logvinenko et al., suffers from run-to-run variability due to its reliance on random direction vectors for boundary searches. This can result in sparsely sampled boundary regions. The stochastic nature of the algorithm introduces uncertainty into computed metrics, such as the Metamer Mismatching Color Rendering Index (MMCRI), which depend on the Logvinenko method, thereby complicating interpretation and comparison.

We propose a deterministic framework that eliminates this variability by replacing random seeding with a Sobol low-discrepancy sequence. This approach ensures uniform initial coverage of the feasible reflectance space. To further improve the distribution and maintain determinism, a Gray code transformation is applied to the Sobol sequence. A boundary-seeking nonlinear optimizer then refines these seeds to trace the MMB surface. In tests, the new method yields identical MMBs on every run, eliminating run-to-run variability, and shows a small but statistically significant reduction in average runtime (≈2 % faster on this dataset). The resulting repeatable output makes the approach suitable for critical applications such as sensor design, color-correction lookup tables, and tolerance analysis. This work provides a more reliable foundation for MMB-based analyses, addressing the reproducibility challenges inherent in existing methods based on randomized sampling.

Reproducibility Challenges in MMB Estimation

Metamerism is a phenomenon where two objects with distinct spectral reflectance functions produce identical color responses under a given illuminant [13, 3, 24]. However, a change in light source can reveal their underlying spectral differences, leading to visible color differences, a phenomenon known as metamer mismatching [13, 17, 2]. The Metamer Mismatch Body (MMB) is defined as the set of all possible resulting color signals that occur under a new light source for all objects that were metameric under the original one [13, 11, 4, 2]. In simpler terms, the MMB describes all the different colors an object might appear when the lighting changes, even though it matched another object under the original light. This three dimensional volume is a valuable construct for assessing the robustness of object color across lighting conditions, with practical applications in lighting design, material manufacturing, and digital imaging [13, 2]. MMBs are typically estimated by generating a set of reflectance functions metameric to a reference illuminant and target tristimulus value, then computing their tristimulus values under a second illuminant [17, 15, 25]. The convex hull of this point cloud estimates the MMB [17, 15]. Logvinenko et al. provided a formal geometric foundation for MMBs, demonstrating that M(z0; Φ,Ψ) is a convex body embedded in tristimulus space [13]. The boundary of the MMB is characterized by μ-optimal reflectances. Such a reflectance produces the target tristimulus value under the reference illuminant that lies on the boundary of the object color solid [13, 12].

Problem Statement and Motivation

Despite their conceptual appeal, current implementations of various MMB algorithms, including those used in MMCRI calculations, are not deterministic [2, 23, 15, 25]. They rely on randomized transition wavelengths to initialize the optimization process for determining optimal metameric spectra, leading to different outcomes with identical inputs [2, 23]. This stochastic behavior creates an undesirable degree of uncertainty, complicating interpretation and meaningful comparison of results [2, 23]. As Esposito et al. note, “MMCRI as currently documented is not [deterministic], and the metric value produced for a single SPD will change every time the computation is run” [2]. The use of randomized boundary sampling exacerbates this issue, causing non-uniform sampling of the MMB boundary [15, 25, 2]. Some regions may be oversampled, while others are sparsely represented or even missed entirely [6, 18, 20, 8, 16, 9, 13]. This lack of consistency undermines the reliability of the metric in applications where reproducibility is fundamental, such as lighting specification, standards development, or comparative analysis of lighting technologies [2, 23].

Deterministic Sampling for MMB Estimation

To overcome these limitations, a deterministic method for estimating MMBs is proposed. This approach replaces randomized initialization with a Sobol low-discrepancy sequence (LDS) [21, 10], which is known for its uniform coverage and repeatability [22]. To further enhance the distribution and ensure full determinism, a Gray code scrambling is applied to the Sobol sequence [5], promoting more uniform exploration by ensuring minimal changes between successive points [1, 7]. Scrambling is helpful because it eliminates inherent biases [7, 16], allows for practical error estimation to assess the accuracy of results [6, 7, 20, 14], and improves the uniform distribution of points by mitigating poor correlations [8] and filling regions that might otherwise be sparsely represented or missed [6, 8]. This leads to increased convergence rates [6] and enhanced efficiency [6] in computational problems, often yielding smaller discrepancies [7] and improved accuracy due to error cancellation [20]. For this work, Gray code reordering was chosen due to maintain a deterministic sample as compare to scrambling methods using randomization.

The proposed deterministic pipeline offers several significant advantages over conventional random or pseudo-random sampling approaches.

- **Repeatability**: Identical inputs consistently produce identical outputs, which is a fundamental requirement for reproducible research and reliable metric computation. This is inherent to the deterministic nature of Sobol sequences used in Quasi-Monte Carlo methods [8, 10, 1].
- **Coverage**: The combination of Sobol sequences and Gray code scrambling ensures a uniform exploration of the feasible reflectance space, avoiding clustering or directional bias. See Figure 1. For 1000 points, the star-discrepancy [19] of the Sobol + Gray code scrambled set is 0.00789, compared to 0.03045 for uniform random sampling. While regular patterns are visible in 2D projections, these arise from the projection itself and do not reflect the full 5D uniformity which is reflected in the star discrepancy statistic. This numerical evidence highlights the low-discrepancy strengths of Sobol sequences [8, 10], and the use of Gray code in generating these sequences retains their low-discrepancy properties while enabling more efficient point generation by ensuring minimal changes between successive points [1, 7, 22]. The common Matousek-Affine-Owen scrambling method [7] achieves similar star-discrepancy (0.00794) to the Sobol + Gray code method but introduces nondeterminism due to the use of random numbers in the algorithm.
- **Efficiency**: By avoiding redundant computations inherent in random sampling, the Sobol-based initialization accelerates convergence to the boundary points [8, 10, 1]. Quasi-Monte Carlo methods, which utilize low-discrepancy sequences like Sobol, generally achieve a faster and more stable convergence rate than traditional Monte Carlo methods [10, 8]. This was tested by calculating 1000 metamers for 50% gray using random versus Sobol transition starting points. Sobol initialization showed a statistically significant mean runtime reduction of about 3.2 seconds compared to uniform random (95% CI [2.19, 4.18] s; paired $t(1799)$=–6.27, p=4.4 × 10^{-10}), corresponding to a modest but reliable gain of 1.9 %. Figure 2 shows the timing results for both initialization methods.

Conclusion

This paper addresses a limitation in existing stochastic techniques for MMB estimation by introducing a fully deterministic framework. By using Sobol low-discrepancy sequences with Gray code reordering and deterministic optimization, our approach eliminates all sources of non-determinism from MMB estimation. This guarantees identical results for identical inputs, provides uniformly distributed samples, and supports repeatable evaluation of color shifts under illumination change. In addition to eliminating run-to-run variability, timing tests showed a small but statistically significant reduction in average runtime (3.2 s, 1.9 % faster). Together, these properties establish a robust foundation for future MMB-based metrics and applications where consistent and reproducible evaluation is crucial, particularly in areas such as lighting specification, standards development, and comparative analysis.

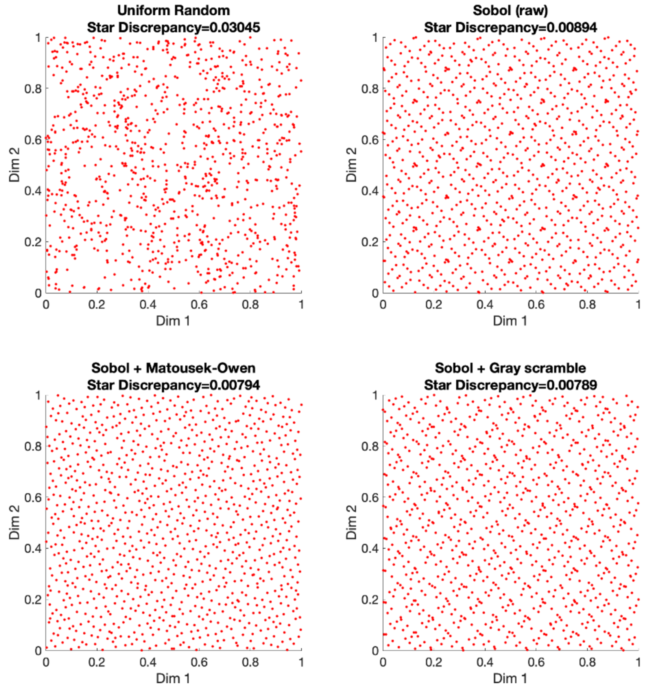

*Figure 1. Two-dimensional (dims 1 vs 2) projections of four 1000-point sets in the five-dimensional unit cube, each annotated with its exact star discrepancy. **Top left**: uniform random sampling (D = 0.03045), showing obvious clusters and voids. **Top right**: raw Sobol sequence (D = 0.00894), with its characteristic lattice motifs. **Bottom left**: Sobol plus Matousek-Affine-Owen scramble (D = 0.00794), a non-deterministic perturbation whose exact pattern will vary run-to-run. **Bottom right**: Sobol plus gray-code scramble (D = 0.00789), which achieves the lowest worst-case gap across all axis-aligned boxes in five dimensions, even though this 2D slice still hints at subtle periodic structure. Note that those visual patterns arise from the projection and do not contradict the gray-code scramble's superior uniformity in the full 5D space. The five dimensions correspond to transition wavelengths that parameterize metameric reflectances in this experiment.*

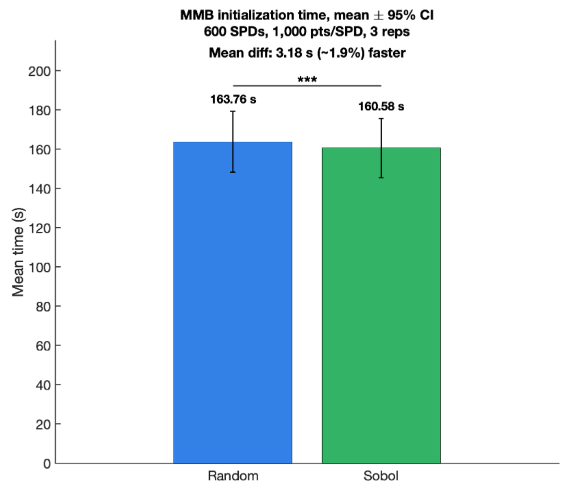

Figure 2. Mean initialization times for 600 SPDs (1000 points each, 3 replicates) using Random versus Sobol + Gray code starting points. Error bars indicate 95% confidence intervals. Sobol initialization was on average 3.2 seconds faster (1.9%), a small but statistically significant improvement (paired t(1799)=–6.27, p=4.4e-10).

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Author Biography

Alex Forsythe is pursuing an interdisciplinary Ph.D. at Simon Fraser University, with a focus on color science applications in cinema. He holds B.S. and M.S. degrees from Rochester Institute of Technology and is Senior Director of Science and Technology at the Academy of Motion Picture Arts and Sciences.

Brian Funt (Ph.D. 1976 Univ. of British Columbia) is Professor Emeritus, School of Computing Science, Simon Fraser University. His research focuses on computational models of colour perception.

Relaxation effect of virtual trees in passthrough space by head mounted display

***Daiki Kiyohara**, Graduate School of Science and Engineering, Chiba University, Chiba, Japan*
***Norimichi Tsumura**, Department of Information and Computer Science, Chiba University, Chiba, Japan*

Abstract
Stress is a growing concern in modern society, and exposure to natural environments has been shown to alleviate it. However, urban living often limits access to nature. This study explores the use of passthrough virtual reality (VR) to simulate natural elements in real-world settings. Passthrough VR refers to a mixed-reality approach in which cameras mounted on the outside of a head-mounted display capture the user's real environment in real time, allowing virtual objects to be superimposed onto it. We developed a passthrough VR environment and displayed virtual trees over the user's actual surroundings. Twelve male participants were tested with and without virtual trees. RMSSD rose significantly in the tree condition (p < 0.05), reflecting enhanced relaxation.

1. Introduction
Stress is a serious issue in modern society, associated with both physical and mental health problems. To prevent these outcomes, effective stress-reduction methods are in high demand. One such method is exposure to natural environments, which has been shown to produce relaxation effects. For example, studies on "forest bathing" (Shinrin-yoku) have demonstrated that time spent in forests can significantly reduce blood pressure and levels of stress hormones [1]. To address this limitation, recent studies have explored the use of virtual reality (VR) to recreate natural environments and reduce stress. While effective in some cases, conventional VR systems typically block the user's view of the real world, causing sensory disconnection and reducing suitability for daily use. As a potential solution, passthrough VR offers a mixed-reality experience by combining the user's actual surroundings with virtual elements. This technology allows users to remain aware of their physical environment while interacting with digitally overlaid content. In this study, we investigate whether the placement of virtual trees within a passthrough VR environment can elicit a relaxation response.

2. Method

2.1 Experimental Procedure
To evaluate the relaxation effect of virtual nature, we developed a passthrough VR environment that displays virtual trees over the real world using the Meta Quest 3 as head mounted display. A within-subject experimental design was employed, in which each participant experienced two conditions: one with no virtual trees (baseline) and one with virtual trees displayed in the passthrough view. Twelve healthy male participants in their twenties took part in the study. To minimize external factors affecting heart rate variability (HRV), participants were instructed to avoid caffeine, alcohol, medication, and intense physical or emotional activity for at least two hours before the experiment. None of the participants reported chronic health conditions or used tobacco products. Each session began with a 10 min resting period during which the participants remained seated. After confirming proper equipment function, the experiment proceeded as follows:

1. Baseline phase: Participants wore the VR headset with passthrough enabled, viewing only the real room environment (Fig.1(a)). HRV was measured for 3 min.
2. Rest phase: The headset was removed, and participants rested for 1 minute.
3. Stimulus phase: Participants wore the headset again, now viewing the same real space with animated virtual trees overlaid (Fig.1(b)). HRV was recorded for 5 min.

Physiological data were recorded using a high-resolution electrocardiograph, and RMSSD was calculated as an indicator of parasympathetic nervous system activity.

(a) without virtual trees (b) with virtual trees overlaid
***Figure 1.** Views through the passthrough VR headset*

2.2 Experimental Environment
The passthrough VR environment was developed using Unity 2022.3.30f1, a real-time rendering and development platform widely used for interactive 3D content. The virtual scene was displayed through the Meta Quest 3 headset (Meta Platforms, Inc.), head mounted display. This headset supports full-color passthrough at a resolution of 1920 × 1080 pixels per eye and a refresh rate of 72 Hz. The rendering resolution was configured at 2064 × 2208 per eye. The virtual trees displayed during the stimulus phase were created using the Animated Trees Package asset, which includes 30 high-fidelity 3D tree models. The trees were animated to simulate natural leaf movement, enhancing visual realism. These virtual elements were overlaid onto the real-world view in real time using Unity's passthrough AR framework. Heart rate data were recorded using the ProComp (Thought Technology Ltd.), a high-precision electrocardiograph system with a sampling rate of 2048 Hz. Three surface electrodes were attached to the left triangle configuration [2]. The data were acquired and visualized using BioGraph INFINITY software (Thought Technology Ltd.), a physiological monitoring and analysis platform designed for high-resolution biosignal processing. The experiments were conducted in a quiet, temperature-controlled laboratory room with minimal external stimuli. Participants sat in a fixed position throughout the session.

3. Result
To assess the effect of virtual trees on relaxation, we compared RMSSD values—the root mean square of successive differences between adjacent R-R intervals, calculated from heart rate data—between two conditions: without trees (baseline) and with virtual trees (stimulus). Fig. 2 shows the average RMSSD across all twelve participants for both conditions.

The mean RMSSD increased from 27.58 ± 10.14 ms (baseline) to 36.33 ± 14.15 ms (with virtual trees). A Shapiro-Wilk test [3] confirmed that the data in both conditions followed a normal distribution (p > 0.05). A paired t-test showed a statistically significant increase in RMSSD when virtual trees were present ($t(11) = -2.20$, $p < 0.05$), indicating an enhancement of parasympathetic nervous system activity and a relaxation response.

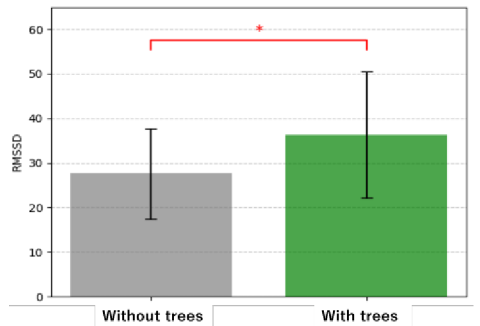

***Figure 2.** Average RMSSD values across all participants*

Figure. 3 illustrates individual RMSSD changes for each participant. Each line represents a participant's RMSSD value in the baseline condition (without trees) and the stimulus condition (with virtual trees). Out of the twelve participants, nine showed an increase in RMSSD during the stimulus phase, while three participants exhibited a decrease. This indicates that although a general trend toward increased parasympathetic activity was observed, individual responses varied.

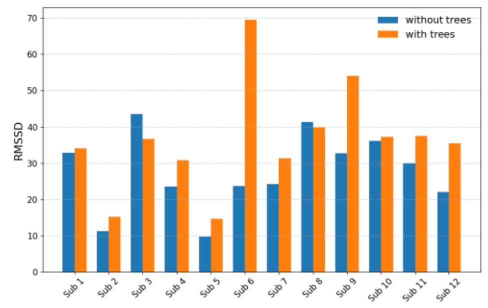

***Figure 3.** Individual RMSSD changes per participant*

The results indicate a significant increase in RMSSD when participants were exposed to virtual trees within a passthrough VR environment. This supports the hypothesis that overlaying natural elements in a mixed-reality space can enhance parasympathetic activity and promote relaxation. One possible explanation for this effect is the biophilia hypothesis, which suggests that humans have an innate tendency to seek connections with natural elements [3]. Even when presented virtually, natural imagery may trigger subconscious calming responses rooted in evolutionary adaptation. However, individual differences were observed, with three participants showing a decrease in RMSSD during the tree-present condition. Post-experiment feedback revealed that some participants experienced discomfort or fatigue from prolonged use of the VR headset. These physical burdens may have counteracted the intended relaxation effect.

For future applications, making headsets lighter and adding head straps could help improve user comfort and enhance the relaxation effect. In addition, incorporating subjective measures, such as questionnaires, could provide a more comprehensive understanding of the user experience beyond physiological indicators like RMSSD. Further exploration of different types of virtual content, such as campfire effects, may help tailor the experience to individual preferences and enhance its calming impact. Varying stimulus duration and order may help refine the design and optimize relaxation conditions.

Conclusion
This study investigated the relaxation effect of displaying virtual trees in a passthrough VR environment. By measuring HRV, we demonstrated that virtual natural elements can elicit a significant increase in parasympathetic activity, suggesting a measurable reduction in stress. These findings support the potential of passthrough VR as a practical tool for stress relief, particularly for individuals in urban settings with limited access to nature. By adding realistic virtual trees to the user's actual surroundings, the system created a new type of digital relaxation experience. This approach allowed users to feel connected to nature while still being aware of their real environment.

For future work, we plan to incorporate subjective evaluations through questionnaires to better understand users' perceived stress and relaxation. Additionally, we aim to improve user comfort by optimizing headset ergonomics and to explore various types of natural virtual content and presentation methods to maximize the calming effect.

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Psychophysical Colour Calibration of Multiple VR/MR Head-Mounted Displays via Instrument-Free Methods

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Extend Abstract

Background and research gap

Accurate colour reproduction in immersive environments is a long-standing problem for both researchers and developers working with virtual-reality (VR) and mixed-reality (MR) head-mounted displays (HMDs). Recent studies document how difficult it is to apply conventional calibration workflows to near-eye optics and real-time renderers [1]. Hardware obstacles include complex lens pipelines that distort radiometric measurements and luminance imbalance between left- and right-eye panels. MR headsets add two further complications: perceived colour depends on both the display and the front-facing cameras that capture the physical scene, and transparent wave-guide optics (e.g., HoloLens 2) have subtle iridescence. On the software side, inside game engines, post-processing tone mapping, automatic exposure, lighting models and colour-space settings further decouple RGB values from on-screen output. Moreover, practical measurement is nontrivial -- MR headsets and spectroradiometers must be precisely aligned with angle and distance controlled. These issues also result in instrument-based measurements of HMD being unable to achieve the same level of accuracy as when measuring 2D monitors. Relatively few studies have examined perceptual calibration in HMDs [2], what remains under-explored is how material shaders, lighting configurations and the choice of lit versus unlit rendering affect perceptual calibration, and whether 2-D results extrapolate robustly to genuine 3-D scenes. This project addresses the limitations of instrument-based calibration by developing a visual method for calibrating MR devices. Rather than claiming higher accuracy than instruments, our goal is to provide a complementary, user-centred pathway that is more stable and uniform across rendering modes and scenes. We introduce a repeatable perceptual matching method on HMDs that pairs rendered and no-rendering conditions to capture how users experience luminance. We also propose a perception-based colour-space conversion routine that links engine input signals to perceived luminance/colour via interpolation. These elements constitute a practical framework that complements instrument-only workflows by improving repeatability and harmonisation in MR colour characterisation.

Experimental design

This experimental Task1 &2 reference the psychophysical methods of Xiao's to VR/MR [3]. The experiment included 4 tasks which use four Unity programs (two 2-D, two 3-D) running in the Universal Render Pipeline (URP). This paper first explains Tasks 1 & 2 for luminance (Y) prediction. URP offers script-level control and mid-tone precision superior to the legacy pipeline while avoiding the heavy, less predictable post-processing stack of HDRP. All post-processing, tone mapping and auto-exposure are disabled so that fragment-shader colour values reach the framebuffer unaltered.

In Tasks 1 & 2 (Y estimation), participants match a target patch/cube to a halftone background (channels R, G, B, grey). Fitted input–output curves yield a psychophysical Y (Figure 1).

Three headsets were used to cover a range of display technologies: HTC VIVE Pro (AMOLED VR), Meta Quest 3 (LCD MR passthrough) and Microsoft HoloLens 2 (see-through LBS). Task 1 uses 2D environments with all lighting removed; colours are drawn via UI canvases that bypass camera lighting; Task 2 uses 3D environments, with uniform point lights (D65, intensity 1 on a 0–10 scale, positioned inside the room to yield similar average light levels) that illuminate the scene. Objects use default lit materials, while the target stimulus also has a custom lit shader to quantify lighting influence. It is worth noting that HoloLens 2 imposes additional technical constraints due to its LBS display properties and reliance on the newly released MRTK3 framework for Unity. Unlike enclosed LCD or LCOS displays with controllable backgrounds, HoloLens 2 uses an optical see-through additive display in which black appears transparent and emitted light is added to the real scene, so calibration should follow an additive model $L_{meas} = \tau L_{ambient} + L_{display}$ with measurements taken under shielding to separate ambient contributions [4]. Its MEMS laser beam-scanning engine injects narrow-band primaries into a diffractive waveguide, which introduces field-dependent colour and luminance non-uniformity and potential speckle, best addressed with per-channel colour matrices and flat-field gain maps rather than a single gamma curve. Additionally, although HoloLens 2 allow some traditional components of XR, it is useless and meaningless for Hololens 2 development as people will not choose to use XR in these headsets. For this, this experiment chooses to work within its specific architecture.

A total of 21 participants were recruited for the study, with screening to exclude individuals with colour vision deficiencies or susceptibility to motion sickness. Each participant completed all four tasks across the three headsets. The Unity-based programs used for Tasks 1 & 2 are identical across the devices, enabling direct comparison of user-matched values under consistent task conditions on different display systems.

Before testing, candidate headsets were screened for inter-ocular luminance variation; only units with $\Delta Lv < 2$ % were used. Each device was characterised with a Konica-Minolta CS-2000 in both Unity gamma and linear colour spaces. Linear mode produced higher accuracy in the grey-scale range. All 3-D programs include a screenshot function; captured frames are later analysed in MATLAB for pixel-level verification.

Results

Tasks 1 and 2 shows luminance (Y) prediction by perceptual methods are the stability across scenes, stable calibration of high-weighting channel and transportability with & without rendered.

Under the no-render baseline, input digital counts (0–255) are written one-to-one to the framebuffer, allowing the preset luminance–code mapping to be compared directly with the CS-2000. Relative to the instrument curves, the perceptual method shows high single-channel consistency on the HTC headset (mean RMSE across R/G/B = 1.7 counts, MaxAE = 6.2 counts). For the MR headsets (Meta Quest 3, HoloLens 2), the mixed channel show closer agreement (Meta: RMSE = 1.6 counts, MaxAE = 3.2 counts; HoloLens: RMSE = 3.5 counts, MaxAE = 6.8 counts). After normalising luminance by per-channel Y_{max} and applying piecewise-linear interpolation (PLCC) to predict luminance, the mixed channel performs best in perceptual and instrument measurement—particularly on HTC and Meta (HTC: RMSE = 0.01, MaxAE = 0.02; Meta: RMSE = 0.05, MaxAE = 0.08). Given the optical see-through characteristics of HoloLens, its perceptual–instrument difference (RMSE = 0.07, MaxAE = 0.10) is somewhat larger than for opaque headsets yet remains acceptable for the present analysis. Overall, perceptual luminance prediction is consistent with instrumental estimates in occluded LCD headsets, and—despite additional optical complexity—remains within a practicable error range on HoloLens.

In rendered scenes, the radiance leaving a surface point is given by the rendering equation, which integrates incident light weighted by the material's scattering function (BRDF/BTDF/BSDF). The pixel colour observed is that linear HDR radiance after the camera and display pipeline - exposure, tone mapping, encoding and display characteristics—so practical mismatches usually arise from this pipeline. Thus, we adopt a controlled setup - the same nominal colour is applied to a cube and analysed by facet - bright (illuminated) versus dark (back-lit), and tone mapping and auto-exposure are disabled. Under our rendering pipeline and lighting/material configuration (URP Lit), we observe a lighting-dependent offset on non-driven channels that is independent of the driven code. For example, in Meta, with inputs (R,0,0), sampled RGB on the bright facet consistently reads (R*,≈56,≈56) and on the dark facet (R*,≈7,≈7) across the full R range (0–255). This case arises from pipeline-level illumination and shading (not a device property) and its magnitude is configuration-dependent. Based on it, we using CS-2000 measurements on experimental Unity materials to white-point correction, all three headsets show a similar pattern; the bright walls white-point shift is small ($\Delta u'v' \approx 0.0016$) relative to the dark walls ($\Delta u'v' \approx 0.020$), and each HMDs' $\Delta u'v'$–luminance trend essentially unchanged after global white-point correction.

For transportability, let A and B as the humanity perceptual datasets (no-render vs rendered), C and D as instrumental datasets (dark- vs bright-walls). After normalising digital counts to [0,1] per channel, the instrument dark-walls curves fall within the perceptual error bar, whereas instrument bright-walls curves sit systematically below perception (mean RMSE ≈ 13 counts). By contrast, A and B are near-identical (mean RMSE ≈ 2.3 counts) in each channels, indicating that no-render perceptual data have high consist with rendered perceptual data. We can use bi-directional mapping perceptual data from the light/dark wall of the rendered dataset (B) into the unrendered dataset (A).

We validated on three headsets how a no-render perceptual data bi-directional map to rendered scenes of per-channel bright and dark luminance. For each device and channel, we treat the no-render perceptual curve as y_s and the rendered curve (bright or dark walls) as y_t, and we evaluate two approaches. The first is multiplicative least squares in the linear-luminance domain, which finds a gain k that minimises $\|ky_s - y_t\|_2$ so the zero point remains fixed and differences are absorbed as an overall scale. The second is a power-law transport that fits $y \approx Ax^{\gamma}$ to source and target; when exponents are similar and gain-only transfer $y' = (A_t / A_s)y_s$ is sufficient, and when they differ a curvature-matching map $y' = sy_s^{\alpha}$ with $\alpha = \gamma_t/\gamma_s$ is used, with s set from the measured bright-to-dark luminance ratio for that channel. Pooled across devices the power-law option yielded lower errors in our data RMSE=0.006–0.015 compared with multiplicative least squares 0.009–0.32 and gain-only 0.014–0.056. Both appoaches are viable and are reported to give practitioners a choice; given the observed curvature differences in rendered scenes we tend to prefer the power-law variant, while retaining the simpler gain-based approach when scale dominates.

This project had additional Tasks 3 & 4 to predict the perceptual matrix. Tasks 1 and 3 are mutually supportive – Task 1 provide γ correction to Task 3, and Task 3 provides matrix calculation to specifical Y. A comprehensive analysis will provide a new, stable and unified method for colour prediction in VR and MR.

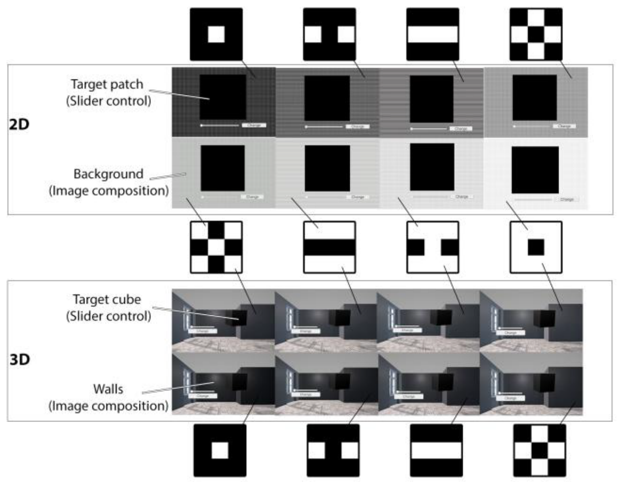

Figure 1. *Task 1(2D) and Task 2(3D) scene presentation (it does not represent the actual display effect in the headsets)*

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A Pigment-based Spectral Imaging Sensor Approach for AWB: Outperforming Flagship Smartphones in Challenging Scenes

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Abstract

We propose a camera-independent illuminant estimation algorithm for Auto White Balance (AWB) base on pigment-based spectral imaging sensors, achieving over 30% accuracy improvement compared to flagship smartphone solutions, especially in traditional challenging scenes such as single-color dominated scenes and non-white-dominant scenes. We use quantitative metrics including error angle $\Delta\theta$ and color difference ΔE_{00} for AWB evaluation, demonstrating superior performance across 382 real scenes with an average error angle of 3.26° and an average ΔE_{00} of 3.77. The results show great application potential of spectral imaging sensors for AWB in consumer electronic imaging devices such as smartphones.

Introduction

The human visual system dynamically adapts to ambient color temperatures, enabling the perception of white objects as white under varying light sources (e.g., candlelight, incandescent bulbs, or daylight)—a phenomenon known as color constancy. White Balance (WB) technology emulates this biological capability by adjusting color components in images to ensure accurate white representation under different illuminants, thereby preserving overall color fidelity. Compared with manual white balance, modern devices predominantly employ AWB, making color accuracy accessible to non-expert users.

Existing AWB algorithms [1] are broadly classified as:

1. Static Statistical Methods, including gray-world assumption [2], white-patch assumption [3], shades of gray [4], gray edge method [5], grayness index method [6], etc.
2. Learning-Based Methods, including CCC [7], FFCC [8], FC4 [9], etc.
3. Hybrid architectures (statistical and learning)

These methods dominate smartphone AWB but struggle in some particular scenarios including: monochrome scenes (e.g., large green fields → erroneous gray-point detection), misleading colors (e.g., yellow/cyan patches misclassified as light sources) and mixed illuminants (e.g., concert lighting → inconsistent corrections), as shown in ***Figure 1***.

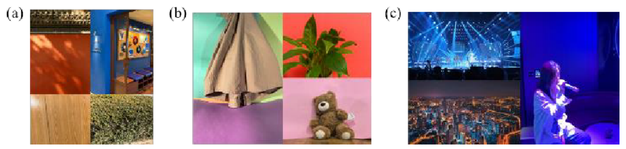

Figure 1. *Challenging AWB scenarios: (a) Monochrome, (b) Misleading colors, (c) Mixed illuminants.*

Quantitative AWB Metrics

AWB aims to equalize RGB responses for white objects under any illuminant. Reference gains (***Rgain, Bgain***) are derived from:

$$Rgain = G_{input} / R_{input}, \; Bgain = G_{input} / B_{input}$$

Ground truth is obtained via gray/white cards or spectral integration of light source spectrum with pre-calibrated RGB sensor response curves.

Key metrics:

1. Angular Error ($\Delta\theta$) [10]: Angle between estimated and true illuminant chromaticity vectors:

$$\Delta\theta = \cos^{-1}\left(\frac{e \cdot g}{\|e\| \cdot \|g\|}\right) \tag{1}$$

Where e is the algorithm-estimated illuminant chromaticity vector, g is the ground-truth illuminant chromaticity vector, "·" denotes the vector dot product, and $\|e\|$ represents the L2-norm (Euclidean norm) of vector e. Notably, $\Delta\theta$ alone may overlook saturation effects (e.g., $\Delta\theta$=5°~10° is tolerable for high-saturation colors but unacceptable for neutrals).

2. ΔE_{00} Color Difference: Perceptual accuracy metric (lower is better). ΔE_{00} provides a numerical score that accurately reflects the human visual experience of a color error. Typically, a ΔE_{00} value of less than 4 is considered acceptable across almost all colors for an average observer.

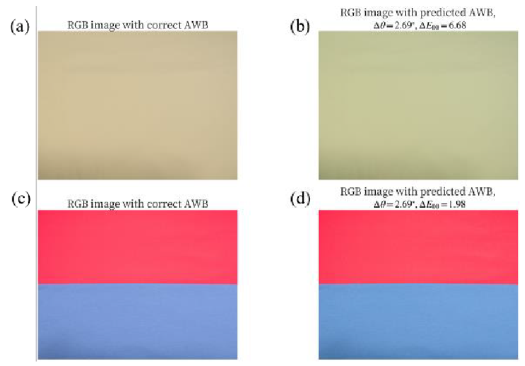

Figure 2. *$\Delta\theta$ vs. ΔE_{00}: Low-saturation yellows show higher ΔE_{00} (6.68) than high-saturation colors (1.98) despite equal $\Delta\theta$.*

Pigment-based Spectral Imaging Sensor

In this work, we propose the study using a pigment-based spectral imaging sensor, which is implemented by integrating large-scale, pixel-aligned integration of spectral filters on a CMOS image sensor (CIS) [11]. The spectral filters are achieved by 9 different types of pigments with mass production on a 12-inch wafer, as shown in ***Figure 3***. The sensor features relatively low production costs, high capturing efficiency comparable to that of ordinary CIS, and relative ease of integration with current ISP pipelines. In light of these advantages, this spectral sensor has been commercialized and adopted by multiple flagship smartphones.

Figure 3. *Pigment-based spectral imaging sensor fabricated by lithography on a 12-inch wafer.*

AWB Solution Based on Pigment-based Spectral Imaging Sensor

We established an end-to-end mapping model from the response values of nine pigments to the illuminant chromaticity vector. This model was integrated with a demosaicing algorithm to realize an AWB solution leveraging pigment-based spectral imaging technology.

Experimental Validation

We conducted tests across 382 real-world scenes, including:

- 159 large-area monochrome scenes
- 64 misleading-color scenes
- 159 typical scenes

Methodology

1. Ground truth for AWB was calculated using the Konica Minolta CL500A spectroradiometer to capture the spectral data of light source.
2. Comparative imaging was performed with:

- The pigment-based spectral sensor (equipped with an IR-cut filter)
- A latest flagship model from mainstream smartphone manufacturers

Key Results

1. Angular Error ($\Delta\theta$):

- Spectral sensor: 3.26° mean error (39.2% lower than the smartphone's 5.36°)
- Challenging scenes:
- Monochrome scenes: 36.7% reduction
- Misleading-color scenes: 64.2% reduction

2. Mean Color Difference (ΔE_{00}):

- Spectral sensor achieved ~40% lower error across all scenes (***Figure 4***).

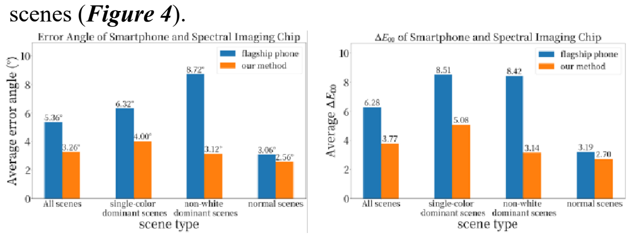

Figure 4. *Performance comparison between Flagship Smartphone Model and the spectral imaging sensor using (a) $\Delta\theta$ metric (b) ΔE_{00} metric*

3. Case Studies (Figure 5)

3.1. Warm Light on Wood (2400K):

- Smartphone: Significant yellow cast (high $\Delta\theta$)
- Spectral sensor: Near-neutral output, aligning with ground truth.

3.2. Yellow-Blue Fabric (7500K):

- Smartphone: Misclassified yellow as neutral, causing blue bias.
- Spectral sensor: Leveraged spectral dimensionality to mitigate interference.

3.3. Outdoor Scene:

- Both systems performed comparably (minor errors).

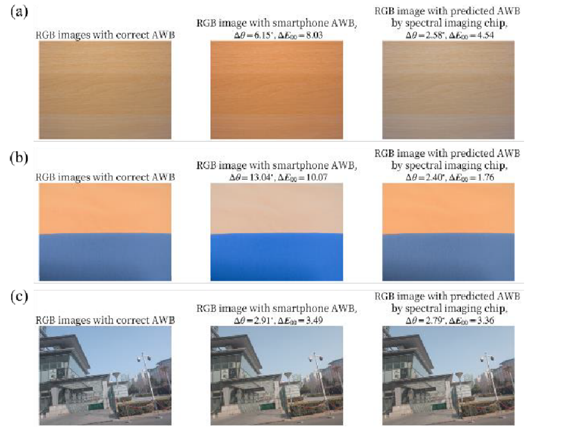

Figure 5. *AWB results comparison: (a) 2400K incandescent light on wood, (b) 7500K D75 light on yellow-blue fabric, (c) Standard outdoor scene*

Summary

We demonstrated the superiority of pigment-based spectral imaging for AWB: mean Δθ of 3.26° (39.2% better than smartphones) in 382 scenes.

The study validates spectral imaging as a viable path for consumer-grade applications, potentially heralding a shift from traditional RGB to spectral-based imaging in the industry.

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HDR Printing, how to produce and display extreme contrast levels

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Abstract

The maximum density that can be achieved with today's printing technologies on reflective material is about 2.4. This results in a contrast range of 250:1. Applying a specialized coating increases the maximum density to around 3, but does not improve the ability to differentiate detail between densities 2.4 and 3.

To achieve larger dynamic ranges, backlit transparencies are essential. However, even with these, the dynamic range of available materials is limited to a maximum density of approximately 3, which equals a displayable contrast range of up to 1000:1 and is classified as SDR.

Higher contrast levels require multi-layer technology in conjunction with a bright, uniform light box. It is necessary to determine how to generate the required tone curve and manage colors to achieve the desired result. ICC color management is referenced to diffuse white and is therefore not defined for real HDR applications. Another challenge is registering multiple layers with each other, especially when they are applied to both sides of the same substrate.

HDR

What is HDR?

Until recently, the term "high dynamic range" (HDR) was not clearly defined. Yes, it must have a dynamic range greater than that of standard dynamic range (SDR), but by how much? And what is SDR?

After much deliberation, ISO TC42 working groups 18 and 23 reached a consensus on the definition of dynamic ranges.

SDR (Standard Dynamic Range)

dynamic range with the contrast ratio up to 1,000:1.

- Note: The dynamic range of 1,000:1 is based on maximum contrast ratio of printed reflective photographs. Similarly, use cases based on IEC 61966-2-1:1999 (sRGB) [1] can achieve dynamic range up to 400:1.

HDR (High Dynamic Range)

dynamic range with the contrast ratio larger than SDR.

- Note: For example, use cases based on ISO 22028-5:2023 [2] can achieve dynamic range much greater than 1000:1.

Why printing HDR?

One might ask why HDR images should be printed at all, given that HDR displays are becoming more affordable.

There are several reasons to print them. Many current displays use SDR mode by default, and whether the whole system can display HDR images depends on the capabilities of the computer and its operating system, the HDR interface and cable, and the monitor's settings and HDR features. Almost no Monitor or TV today can directly read HDR images from a storage device and display them accurately.

Even when the HDR mode is working and HDR images are displayed, the colors are often significantly inaccurate. There are devices from the video world that allow calibration, but they cost several thousand dollars.

Today's HDR displays provide 1,000 or 2,000 nits, which works okay for visualizing HDR images in a relatively dark environment, but this will not be sufficient for visualizing HDR images in a bright room, which may even have sunlight. Printed versions with a backlight that provides up to 30,000 nits have these capabilities.

Digital image files needed for presentation on HDR displays can always be copied. For this reason, photographers are reluctant to give these files to customers, especially when they view their images as pieces of art. A print usually cannot be copied without quality degradation, and a high-quality copy requires time and the right equipment. For this reason, a "fine art HDR print" is more likely to be used for HDR image exhibitions than a digital display.

Printing background and challenges

According to the definition of HDR printing, printing HDR images on reflective material is not possible. Regardless of the printing method used—e.g., inkjet, photochemical paper, offset, screen, or dye sublimation—the colorants are embedded in or applied to a substrate, which scatters and reflects a certain amount of light. This limits the maximum density of a reflective print to about 2.4, meaning at least 1/250 of the incident light is always reflected, and contrast ranges above 250:1 cannot be reproduced using reflective printing processes.

$$r = I_r/I_0 = 10^{-D} \qquad (1)$$

r = reflection

I_r = Intensity of the reflected light

I_0 = Intensity of the incident light

D = optical density

When transmissive material is used the scattering also takes place in the direction of the incident light and in combination with absorption by the colorants in the transmissive material it is possible to get to densities above 2.4.

$$\tau = I_\tau/I_0 = 10^{-D} \qquad (2)$$

Looking at the materials currently available, the theoretical maximum density that can be found in photographic color films, for example, is approximately 4. However, when measuring the densities of prints, the limit is between 3 and 3.5, resulting in a maximum reproducible contrast range of 1,000:1 to 3,000:1.

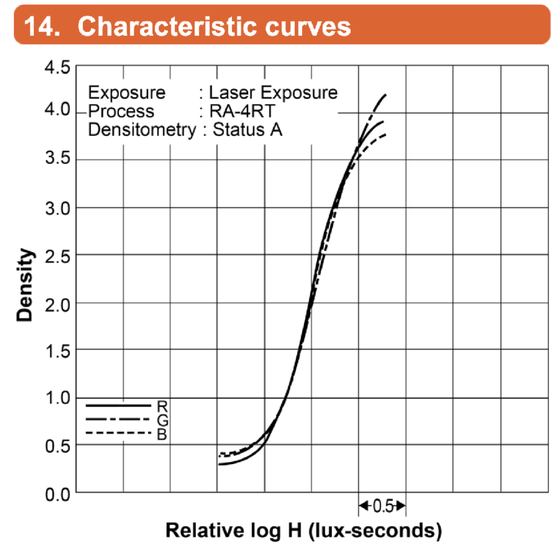

Figure 1: *Fujitrans characteristic curve (source Fujifilm material data sheet)*

This range is insufficient for reproducing many HDR images captured with today's cameras. Higher densities are required for HDR, which can be achieved with multilayer technology. This technology can be used for printing, allowing colorants to be applied to both sides of the substrate. Alternatively, two separate prints can be combined using precise alignment and registration technology, similar to that used in analog printing.

Using two layers with maximum densities of 3 each results in a sum of 6 densities, or, when discussing transmittance, the densities are multiplied, leading to a maximum contrast range of 1,000,000:1.

There are multiple ways to create the layers. One option is to print the SDR image as one layer and print the gain map as specified in ISO 21496 [3]. Another method is to calculate the HDR image and separate it into an image and a mask layer. However, separating the HDR image into two layers often leads to an oversaturated image, which can be compensated for by making adjustments as necessary.

Illumination of the prints

To illuminate prints with details in density levels around 5 — the level used to view total eclipses of the sun — a bright light box is required. Most light boxes on the market use LEDs around the border or a diffusor plate. However, this does not provide enough light, so a new box was developed with a grid of LEDs behind the print, combined with a diffuser between the LEDs and the print. This box needs to be dimmable because, in a relatively dark room, the highlights might be too bright for the human eye, which has adapted to the darkness. However, in a bright room, a very bright light is necessary to visualize an HDR image.

References

[1] IEC 61966-2-1:1999 Multimedia systems and equipment - Colour measurement and management - Part 2-1: Colour management - Default RGB colour space - sRGB

[2] ISO 22028-5 Photography and graphic technology — Extended colour encodings for digital image storage, manipulation and interchange Part 5: High dynamic range and wide colour gamut encoding for still images (HDR/WCG)

[3] ISO 21496 Digital photography — Gain map metadata for image conversionPart 1: Dynamic range conversion

AUTHOR INDEX

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NOTES

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