CIC27

Twenty-seventh Color and Imaging Conference

Color Science and Engineering Systems, Technologies, and Applications

October 21–25, 2019
Paris, France
#CIC27

MCS 2019: 20th International Symposium on Multispectral Colour Science

Sponsored by the
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FINAL PROGRAM AND PROCEEDINGS

The papers in this volume represent the program of the Twenty-seventh Color and Imaging Conference (CIC27)
held October 21-25, 2019, in Paris, France.

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Bienvenue à CIC27!

Thank you for joining us in Paris at the Twenty-seventh Color and Imaging Conference (CIC27), returning this year to Europe for an exciting week of courses, workshops, keynotes, and oral and poster presentations from all sides of the lively color and imaging community.

I've attended every CIC since CIC13 in 2005, first coming to the conference as a young PhD student and monitoring nearly every course CIC had to offer. I have learned so much throughout the years and am now truly humbled to serve as the general chair and excited to welcome you to my hometown!

The conference begins with an intensive one-day introduction to color science course, along with a full-day material appearance workshop organized by GDR APPAMAT, focusing on the different disciplinary fields around the appearance of materials, surfaces, and objects and how to measure, model, and reproduce them.

On Tuesday we offer a great variety of established or novel and basic or advanced short courses followed by four participant-generated workshops designed to allow a deeper dive into specific color arenas: image quality, lighting and chromatic adaptation, high-end digital color print-making, and cultural heritage digitalization.

For the technical sessions held Wednesday to Friday, the conference committee has put together a very strong technical program with 31 oral papers, and 38 interactive (poster) papers, providing a great opportunity to learn, discuss, and share knowledge.

In addition, we are thrilled to host outstanding invited speakers:

- Dr. Marina Zannoli, vision scientist in the Display Systems Research group at Facebook Reality Labs, delivers the opening keynote, focusing on the perception-centered development of near-eye displays, making the case that building mixed reality technology that seamlessly interfaces with our sensorimotor system allows for immersive and comfortable experiences.
- Dr. Beau Watson, chief vision scientist at Apple Inc., reveals the chromatic pyramid of visibility in his keynote, a simplified model of the spatio-temporal luminance contrast sensitivity function.
- Dr. Clotilde Boust, head of the imaging group at the Centre de recherche et de restauration des musées de France, talks about her work shining invisible light on archeological artefacts and famous paintings to expose their well kept secrets and guide restoration scientists.
- Dr. Panagiotis-Alexandros Bokaris, augmented reality research engineer at L'Oréal, delivers the closing keynote, enlightening us with an AR immersive experience in which he shares the challenges in developing a video-projected AR system and its applications in the beauty industry.

Long coffee breaks and lunches, plus the Welcome and Conference Receptions, provide the perfect time to meet new associates, reconnect with friends, and delve into the many exciting topics related to color and imaging.

In closing, I would like to acknowledge the contributions of the hard-working people responsible for creating this outstanding event. These include the Technical Program, Short Course, Interactive Paper, and Workshop Chairs, the reviewers, Steering Committee, and the tireless staff of IS&T.

Please enjoy your time at CIC27, and make the most of the many technical and social programs offered by the conference. The committee and I are confident the conference will inspire you and your research.

I hope you enjoy your week in the city of light and I look forward to cruising on the Seine by night with each and every one of you.

—Nicolas Bonnier, General Chair, CIC27

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- German Society for Color Science and Application (DfwG)
- GI Fachbereich Graphische Datenverarbeitung
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- IOP Printing and Graphics Science Group
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- Swedish Colour Centre Foundation
- The Colour Group (Great Britain)
- The Royal Photographic Society of Great Britain/Imaging Science Group
- Society of Motion Picture and Television Engineers (SMPTE)

CIC27 TECHNICAL PAPERS PROGRAM: SCHEDULE AND CONTENTS

Monday 21 October 2019

8:00 – 17:45
SHORT COURSE PROGRAM

SC01: Color and Imaging
Instructor: Gaurav Sharma, University of Rochester

SC02: Solving Color Problems Using Vector Space Arithmetic
Instructor: Michael Vrhel, Artifex Software, Inc.

SC03: The Art of Making Better Pixels: High Dynamic Range Display Concepts and Technologies
Instructor: Timo Kunkel, Dolby Laboratories, Inc.

SC04: The Human Imaging Pipeline: Color Vision and Visual Processing from Optics to Perception
Instructor: Andrew Stockman, UCL Institute of Ophthalmology

MATERIAL APPEARANCE WORKSHOP
Organized by GDR APPAMAT

Tuesday 22 October 2019

8:00 – 15:30
SHORT COURSE PROGRAM

SC05: Color and Appearance in 3D Printing
Instructor: Philipp Urban, Fraunhofer Institute for Computer Graphics Research IGD

SC06: Fundamentals of Psychophysics
Instructor: James A. Ferwerda, Rochester Institute of Technology

SC07: Digital Cinema Environment and Image Quality Evaluation
Instructors: Miloslav Novák, Silesian University, and Antonín Charvát, EIZO Group

SC08: Camera Color Characterization: Theory and Practice
Instructors: Dietmar Wueller, Image Engineering GmbH & Co. Kg, and Eric Walowit, consultant

SC09: Characterizing Surface Appearance
Instructor: James A. Ferwerda, Rochester Institute of Technology

SC10: Spatial Color Perception and Image Processing
Instructor: Edoardo Provenzi, Université de Bordeaux

SC11: Color Optimization for Displays
Instructor: Michael Murdoch, Rochester Institute of Technology

SC12: Advanced Colorimetry and Color Appearance
Instructor: Gaurav Sharma, University of Rochester

SC13: Color Fundamentals in LED Lighting
Instructor: Michael Murdoch, Rochester Institute of Technology

SC14: Using the New Colour Management Technology, iccMAX: Architecture and Practical Applications
Instructor: Philip Green, Norwegian University of Science and Technology

SC15: Color Imaging Challenges with Compact Camera Optics
Instructor: Kevin J. Matherson, Microsoft Corporation

15:45 – 18:15
CIC27 WORKSHOPS

W1: Future Directions in Image Quality
Conveners: Marius Pedersen and Seyed Ali Amirshahi, NTNU (Norway)
Confirmed speakers/topics:

- Azeddine Beghdadi (Galilee Institute): image enhancement and issues on quality assessment
- Aladine Chetouani (Université d'Orléans – Polytech'Orléans): recent trends in machine learning for image quality
- Christophe Charrier (Université de Caen Normandie): image quality in biometrics
- Chaker Larabi (University of Poitiers): quality assessment of xr applications
- Claudio Greco (DXOMARK): color image quality assessment in smartphones
- Razvan Lordache (GE Healthcare France): challenges in medical image quality
- Frédéric Dufaux (University Paris-Sud): the future of video quality metrics

Future Directions in Image Quality, *Seyed Ali Amirshahi[1,2] and Marius Pedersen[1]; [1]Norwegian University of Science and Technology (Norway) and [2]Universite Paris 13 (France)* . . **see appendix on USB for full paper**
With the advancements made in the field of image processing and computer vision, the last few decades have seen an increase in studies focused on image quality assessment. While this has resulted in the introduction of different new metrics which some show high correlation with the perceptual judgement of the human observers there still exists a huge room for improvement.

W2: Lighting and Chromatic Adaptation
Convener: Michael J. Murdoch, RIT (US)
Confirmed speakers/topics:

- Marcel Lucassen (Signify): chromatic discrimination under different spectral lighting conditions
- Michael Murdoch (RIT): chromatic adaptation to temporally-dynamic lighting
- Kevin Smet (Katholieke Universiteit Leuven): chromatic adaptation, effects of background field size, mixed illumination, and chromatic lighting

W3: The Art and Science of High-End Digital Color Print-Making
Conveners: Peter Morovic, HP Inc. (Spain) and Ján Morovic, HP Inc. (UK)
Confirmed speakers/Talk titles (see conference website for abstracts of talks):

- Clotilde Boust (Louvre): Digital Photography for Art Conservation
- Ján Morovic and Peter Morovic (HP Inc.): High-end Printing Pipelines and Workflows in the (Truly) Digital Age
- Stefan Neumann (Hahnemühle): Paper-making Effect on Longevity of Fine-art Prints
- Joseph Padfield (National Gallery London): Imaging and Printing Old Master Paintings at the National Gallery, London
- Marianna Santoni (photographer) and Cyril Bertolone (Canson Infinity): The Challenge of Red!

W4: Cultural Heritage Digitalization
Convener: Sony George, NTNU (Norway)
Confirmed speakers/topics (see conference website for abstracts of talks):

- Christian Degrigny (Haute Eclose Arc Conservation-Restoration): Restoration: technical study and conservation condition of Château de Germolles's wall paintings using imaging techniques combined with non-invasive analytical techniques
- Lindsay MacDonald (University College London): Visual Realism in Digital Heritage
- Robert Sitnik (Warsaw University): 3D documentation process of cultural heritage objects
- Vitaliy V. Yurchenko (Norsk Elektro Optikk A/S): Key quality indicators of hyperspectral cameras: current status and case study from pigment analysis

18:15 – 19:45
WELCOME RECEPTION
Details provided onsite.

facebook

Reality Labs

WEDNESDAY, OCTOBER 23, 2019

WELCOME AND OPENING KEYNOTE

Session Chair: Nicolas Bonnier, Apple Inc. (US)

9:00 – 10:00

Perception-Centered Development of Near-Eye Displays, *Marina Zannoli, Facebook Reality Labs (US)* . . . . *

To create compelling mixed reality experiences, we need to better understand what it means to be an active observer in a complex environment. In this talk, I will make the case that building mixed reality technology that seamlessly interfaces with our sensorimotor system allows for immersive and comfortable experiences. First, I will present a theoretical framework that describes how mixed-reality technologies interface with our sensorimotor system. Then, I will show how we can use knowledge about the human visual system to develop novel image quality metrics for near-eye displays. Finally, I will describe how the Display Systems Research group at Facebook Reality Labs develops image quality metrics, testbeds, and prototypes to define requirements for future AR/VR displays. More specifically, I will present a series of head-mounted prototypes, rendering techniques, and benchtop testbeds that explore various paths to support focus cues in near-eye displays.

LIGHTING

Session Chair: Raimondo Schetini, Università Degli Studi di Milano-Bicocca (Italy)

10:00 – 10:40

10:00 **CIC27 Best Paper Award Color Temperature Tuning: Allowing Accurate Post-capture White-balance Editing,** *Mahmoud Afifi[1], Abhijith Punnappurath[1], Abdelrahman Abdelhamed[1], Hakki Can Karaimer[1,2], Abdullah Abuolaim[1], and Michael S. Brown[1,3]; [1]York University (Canada), [2]Ecole Polytechnique Federale de Lausanne (Switzerland), and [3]Samsung Research (Canada)* **1**

The in-camera imaging pipeline consists of several routines that render the sensor's scene-referred raw-RGB image to the final display-referred standard RGB (sRGB) image. One of the crucial routines applied in the pipeline is white balance (WB). WB is performed to normalize the color cast caused by the scene's illumination, which is often described using correlated color temperature. WB is applied early in the in-camera pipeline and is followed by a number of nonlinear color manipulations. Because of these nonlinear steps, it is challenging to modify an image's WB with a different color temperature in the sRGB image. As a result, if an sRGB image is processed with the wrong color temperature, the image will have a strong color cast that cannot be easily corrected. To address this problem, we propose an imaging framework that renders a small number of "tiny versions" of the original image (e.g., 0.1% of the full-size image), each with different WB color temperatures. Rendering these tiny images requires minimal overhead from the camera pipeline. These tiny images are sufficient to allow color mapping functions to be computed that can map the full-sized sRGB image to appear as if it was rendered with any of the tiny images' color temperature. Moreover, by blending the color mapping functions, we can map the output sRGB image to appear as if it was rendered through the camera pipeline with any color temperature. These mapping functions can be stored as a JPEG comment with less than 6 KB overhead. We demonstrate that this capture framework can significantly outperform existing solutions targeting post-capture WB editing.

10:20 **Coupled Retinex,** *Javier Vazquez-Corral[1,2] and Graham D. Finlayson[1]; [1]University of East Anglia (UK) and [2]Universitat Pomeu Fabra (Spain)* **7**

Retinex is a colour vision model introduced by Land more than 40 years ago. Since then, it has also been widely and successfully used for image enhancement. However, Retinex often introduces colour and halo artefacts. Artefacts are a necessary consequence of the per channel color processing and the lack of any strong control for controlling the locality of the processing (halos are very local errors).

In this paper we relate an input to the corresponding output processed retinex image by using a single shading term which is both spatially varying and smooth and a global colour shift. This coupling dramatically reduces common Retinex artefacts. Coupled Retinex is strongly preferred in preference tests.

10:40 – 11:20 COFFEE BREAK

CHROMATIC ADAPTATION

Session Chair: Patrick Callet, MINES Paristech (France)

11:20 – 12:50

11:20 **Time Course of Chromatic Adaptation under Dynamic Lighting,** *Rik M. Spieringhs[1], Michael J. Murdoch[2], and Ingrid M. L. C. Vogels[1]; [1]Eindhoven University of Technology (the Netherlands) and [2]Rochester Institute of Technology (US)* **13**

Chromatic adaptation is an extensively studied concept. However, less is known about the time course of chromatic adaptation under gradually-changing lighting. Two experiments were carried out to quantify the time course of chromatic adaptation under dynamic lighting. In the first experiment, a step change in lighting chromaticity was used. The time course of adaptation was well described by the Rinner and Gegenfurtner slow adaptation exponential model, and the adaptation state after saturation differed between observers. In the second experiment, chromatic adaptation was measured in response to two different speeds of lighting chromaticity transitions. An adjusted exponential model was able to fit the observed time course of adaptation for both lighting transition speeds.

11:40 **Degree of Chromatic Adaptation under Adapting Conditions with Different Luminance and Chromaticities,** *Siyuan Chen and Minchen Wei, Hong Kong Polytechnic University (Hong Kong)* **19**

Adapting chromaticities are not considered in characterizing the degree of chromatic adaptation in various chromatic adaptation transforms (CATs). Though several recent studies have clearly suggested that the effect of adapting chromaticities on degree of chromatic adaptation should not be ignored, these studies were only carried out under a single adapting luminance level. This study was carefully designed to systematically vary the adapting luminance and chromaticities to investigate whether the adapting luminance and chromaticities jointly affect the degree of chromatic adaptation. Human observers adjusted the color of a stimulus produced by a self-luminous display to make it appear the whitest under each of the 17 different adapting conditions. It was found the adapting chromaticities and luminance jointly affected the degree of chromatic adaptation. At a same adapting luminance level, the degree of chromatic adaptation was found lower under a lower adapting CCT (i.e., 2700 and 3500 K). A higher adapting luminance can significantly increase the degree of chromatic adaptation, especially when the adapting CCT was low (i.e., 2700 and 3500 K).

*No proceedings paper associated with talk.

12:00 **Evaluation and Modification of von Kries Chromatic Adaptation Transform,** *Shining Ma[1], Peter Hanselaer[1], Kees Teunissen[2], and Kevin Smet[1]; [1]KU Leuven (Belgium) and [2]Signify (the Netherlands)* **23**

Over the years, various chromatic adaptation transforms have been derived to fit the visual perception. However, some research demonstrated that CAT02, the most widely used chromatic adaptation transform, overestimates the degree of adaptation, especially for colored illumination. In this study, a memory color matching experiment was conducted in a real scene with the background adapting field varying in field of view, luminance, and chromaticity. It showed that a larger field of view results in more complete adaptation. The results were used to test several existing chromatic adaptation models and to develop three new types of models. All of them improved the performance to some extent, especially for the illuminations with low CCT.

12:20 **Colors and Emotions (Invited),** *Christine Fernandez-Maloigne (University of Poitiers) (France)* . . . . *

Emotions play an important role for the human being in the way of apprehending and reacting to their physical and social environment: they play a fundamental role in decision-making, learning processes, or even in communication. Over the past thirty years, many studies in the cognitive sciences have shown that emotions are an integral part of the ability to process information and respond appropriately, impacting cognitive processes such as attention and memory. Today, artificial intelligence (AI) has made it possible to imitate the capabilities of human intelligence, including reasoning, language comprehension, and vision. Thus, some cameras are now able to trigger as soon as the subject smiles. However, this AI is often restricted because it fails to grasp the complexity of human reasoning by optimally integrating the emotional dimension. In this context, a sub-field of artificial intelligence—very related to psychology and cognitive science—called affective computing or emotional artificial intelligence (EAI) aims to detect and model human emotions. One can then use the detected emotions to improve, in loop, the performances of software/machines and to adapt progressively their answers to the detected emotion. Emotions used in the decision process may be emotions detected on the face (facial expressions) with computer vision and AI techniques. But color analysis has also been the subject of numerous works by psychologists as well as computer scientists. This talk presents recent works of literature on emotions and colors, and shows by some tests how colors can impact the emotions felt and behaviors, including regarding food! Some examples are given of the application of affective computing in e-education, serious game, and for humanoid robots.

12:40 – 14:00 LUNCH ON OWN

*No proceedings paper associated with talk.

MATERIAL APPEARANCE

Session Chair: Chloe LeGendre, Google, Inc. (USA)

14:00 – 15:00

14:00 **JIST-First Detecting Wetness on Skin using RGB Camera,** *Mihiro Uchida and Norimichi Tsumura, Chiba University (Japan)* **28**

In this study, we propose a method to detect wetness on the surface of human skin and skin phantoms using an RGB camera. Recent research on affect analysis has addressed the non-contact multi-modal analysis of affect aimed at such applications as automated questionnaires. New modalities are needed to develop a more accurate system for analyzing affects than the current system. Thus we focus on emotional sweating, which is among the most reliable modalities in contact methods for affect analysis. However, sweat detection on the human skin has not been achieved by other researchers, and thus it is unclear whether their feature values are useful. The proposed method is based on feature values of color and glossiness obtained from images. In tests of this method, the error rate was approximately 6.5% on a skin phantom and at least approximately 12.7% on human skin. This research will help to develop non-contact affect analysis.

14:20 **Perceived Glossiness: Beyond Surface Properties,** *Davit Gigilashvili, Jean-Baptiste Thomas, Marius Pedersen, and Jon Yngve Hardeberg, Norwegian University of Science and Technology (Norway)* **37**

Gloss is widely accepted as a surface- and illumination-based property, both by definition and by means of metrology. However, mechanisms of gloss perception are yet to be fully understood. Potential cues generating gloss perception can be a product of phenomena other than surface reflection and can vary from person to person. While human observers are less likely to be capable of inverting optics, they might also fail predicting the origin of the cues. Therefore, we hypothesize that color and translucency could also impact perceived glossiness. In order to validate our hypothesis, we conducted series of psychophysical experiments asking observers to rank objects by their glossiness. The objects had the identical surface geometry and shape but different color and translucency. The experiments have demonstrated that people do not perceive objects with identical surface equally glossy. Human subjects are usually able to rank objects of identical surface by their glossiness. However, the strategy used for ranking varies across the groups of people.

14:40 **Appearance Perception of Textiles: A Tactile and Visual Texture Study,** *Fereshteh Mirjalili and Jon Yngve Hardeberg, Norwegian University of Science and Technology (Norway)* **43**

Texture analysis and characterization based on human perception has been continuously sought after by psychology and computer vision researchers. However, the fundamental question of how humans truly perceive texture still remains. In the present study, using a series of textile samples, the most important perceptual attributes people use to interpret and evaluate the texture properties of textiles were accumulated through the verbal description of texture by a group of participants. Smooth, soft, homogeneous, geometric variation, random, repeating, regular, color variation, strong, and complicated were ten of the most frequently used words by participants to describe texture. Since the participants were allowed to freely interact with the textiles, the accumulated texture properties are most likely a combination of visual and tactile information. Each individual texture attribute was rated by another group of participants via rank ordering. Analyzing the correlations between various texture attributes showed strong positive and negative correlations between some of the attributes. Principal component analysis on the rank ordering data indicated that there is a clear separation of perceptual texture attributes in terms of homogeneity and regularity on one hand, and non-homogeneity and randomness on the other hand.

TWO-MINUTE INTERACTIVE PAPER PREVIEWS I

Session Chair: David Alleysson, LPNC: Laboratoire de Psychologie et Neurocognition (France)

15:00 – 15:40

In order for a smartphone-based colorimetry system to be generalizable, it must be possible to account for results from multiple phones. A move from device-specific space to a device independent space such as XYZ space allows results to be compared, and means that the link between XYZ values and the physical parameter of interest needs only be determined once. We compare mapping approaches based on calibration data provided in image metadata, including the widely used open-source software dcraw, to a separate calibration carried out using a colorcard. The current version of dcraw is found to behave suboptimally with smartphones and should be used with care for mapping to XYZ. Other metadata approaches perform better, however the colorcard approach provides the best results. Several phones of the same model are compared and using an xy distance metric it is found that a device-specific calibration is required to maintain the desired precision.

Color Halftoning is a technique for generating a halftone image by using a limited number of colorants to simulate a continuous-tone image as perceived by a human viewer. This paper describes an algorithm to jointly design three screens for Cyan, Magenta and Yellow colorants using the Direct Binary Search algorithm. The results show that high-quality color halftone images can be obtained using the screens sets, and the computational complexity will be greatly reduced.

Ghostscript has a long history in the open source community and was developed at the same time that page description languages were evolving to the complex specification of PDF today. Color is a key component in this specification and its description and proper implementation is as complex as any other part of the specification. In this document, the color processing and management that takes place in Ghostscript is reviewed with a focus on how its design achieves computational efficiency while providing flexibility for the developer and user.

In the paper "Colour-to-Greyscale Image Conversion by Linear Anisotropic Diffusion of Perceptual Colour Metrics", Farup et al. presented an algorithm to convert colour images to greyscale. The algorithm produces greyscale reproductions that preserve detail derived from local colour differences in the original colour image. Such detail is extracted by using linear anisotropic diffusion to build a greyscale reproduction from a gradient of the original image that is in turn calculated using Riemannised colour metrics. The purpose of the current paper is to re-evaluate one of the psychometric experiments for these two methods (CIELAB L* and anisotropic ΔE_{99}) by using a flipping method to compare their resulting images instead of the side by side method used in the original evaluation. In addition to testing the two selected algorithms, a third greyscale reproduction was manually created (colour graded) using a colour correction software commonly used to process motion pictures. Results of the psychometric experiment found that when comparing images using the flipping method, there was a statistically significant difference between the anisotropic ΔE_{99} and CIELAB L* conversions that favored the anisotropic method. The comparison between ΔE_{99} conversion and the manually colour graded image also showed a statistically significant difference between them, in this case favoring the colour graded version.

The goal is to develop a display characterization model to include the personal vision characteristics. A two-step model for visually characterizing displays was developed. It was based on the concept of half-toning technique for obtaining gamma factor for each colour channel, and unique hue concept for achieving 3x3 matrix coefficients, respectively. The variation can be presented by the optimized RGB primaries for each observer. The typical difference between the individual and the measured ground truth is 2.2 in terms of CIEDE2000 units.

To reproduce colors in one system which differs from another system in terms of the color gamut, it is necessary to use a color gamut mapping process. This color gamut mapping is a method to translate a specific color from a medium (screen, digital camera, scanner, digital file, etc.) into another system having a difference in gamut volume. There are different rendering intent options defined by the International Color Consortium to use the different reproduction goals of the user.

Any rendering intent used to reproduce colors, includes profile engine decisions to do it, i.e. looking for color accuracy, vivid colors, or pleasing reproduction of images. Using the same decisions on different profile engines, the final visual output can look different (more than one Just Noticeable Difference) depending on the profile engine used and the color algorithms that they implement.

Profile performance substantially depends on the profiler engine used to create them. Different profilers provide the user with varying levels of liberty to design a profile for their color management needs and preference. The motivation of this study is to rank the performance of various market leading profiler engines on the basis of different metrics designed specifically to report the performance of particular aspects of these profiles. The study helped us take valuable decisions regarding profile performance without any visual assessment to decide on the best profiler engine.

Most modern cameras allow captured images to be saved in two color spaces: (1) raw-RGB and (2) standard RGB (sRGB). The raw-RGB image represents a scene-referred sensor image whose RGB values are specific to the color sensitivities of the sensor's color filter array. The sRGB image represents a display-referred image that has been rendered through the camera's image signal processor (ISP). The rendering process involves several camera-specific photo-finishing manipulations intended to make the sRGB image visually pleasing. For applications that want to use a camera for purposes beyond photography, both the raw-RGB and sRGB color spaces are undesirable. For example, because the raw-RGB color space is dependent on the camera's sensor, it is challenging to develop applications that work across multiple cameras. Similarly, the camera-specific photo-finishing operations used to render sRGB images also hinder applications intended to run on different cameras. Interestingly, the

Technology with a heart.

Rady Children's Hospital utilizes HP 3D printers to create intricate models of pediatric hearts to help reduce surgery time and improve patient outcomes.

keep reinventing

ISP camera pipeline includes a colorimetric conversion stage where the raw-RGB images are converted to a device-independent color space. However, this image state is not accessible. In this paper, we advocate for the ability to access the colorimetric image state and recommend that cameras output a third image format that is based on this device-independent colorimetric space. To this end, we perform experiments to demonstrate that image pixel values in a colorimetric space are more similar across different makes and models than sRGB and raw-RGB.

Because our sensitivity to human skin color leads to a precise chromatic adjustment, skin color has been considered a calibration target to enhance the quality of images that contain human faces. In this paper, we investigated the perceived quality of portrait images depending on how the target skin color is defined: measured, memory, digital, or CCT skin color variations. A user study was conducted; 24 participants assessed the quality of white-balanced portraits on five criteria: reality, naturalness, appropriateness, preference, and emotional enhancement. The results showed that the calibration using measured skin color best served the aspects of reality and naturalness. With regard to appropriateness and preference, digital skin color obtained the highest score. Also, the memory skin color was appropriate to calibrate portraits with emotional enhancement. In addition, the other two CCT target colors enhanced the affective quality of portrait images, but the effect was quite marginal. In the foregoing, labelled Skin Balance, this study proposes a set of alternative targets for skin color, a simple but efficient way of reproducing portrait images with affective enhancement.

In this paper we give a new method to find a grayscale image from a color image. The idea is that the structure tensors of the grayscale image and the color image should be as equal as possible. This is measured by the energy of the tensor differences. We deduce an Euler-Lagrange equation and a second variational inequality. The second variational inequality is remarkably simple in its form. Our equation does not involve several steps, such as finding a gradient first and then integrating it. We show that if a color image is at least two times continuous differentiable, the resulting grayscale image is not necessarily two times continuous differentiable.

Quality lighting is characterized by four major factors, one of them being the color temperature. When designed for elderly, this quality lighting can allow them to evolve within their environment safely, independently and above all comfort without having to focus on the effects of aging. This article aims to show the benefits of designing color temperature scenarios, made possible for example by dynamic LED lighting, thus contributing to the production of comfortable lighting and thus quality.

The image quality is affected by the black luminance level of the image. This research aimed to investigate how low luminance levels are required to maintain image quality. The psychophysical experiment was carried out in a dark room using OLED display. Total of 6 different black luminance levels (0.003, 0.05, 0.1, 0.2, 0.3, and 1 cd/m^2) were used in the experiment. Total of 20 participants was invited to evaluate the image quality. For the experiment, twelve test images are used and these test images categorized into three groups as dark, medium bright, and bright image group by image histogram distribution. Each image is rendered by adjusting six different black luminance levels. Result found that the black level is higher than 0.1 cd/m^2, the preference for the image is decreased. The best performance is achieved when the black level is 0.003 cd/m^2, but there is no big difference from 0.1 cd/m^2. The final result shows that a change in black level between about 0.003 cd/m^2 and 0.1 cd/m^2 does not significantly affect image quality.

A new image test set of synthetically generated, full-spectrum images with pixelwise ground truth has been developed to aid in the evaluation of illumination estimation methods for colour constancy. The performance of 9 illumination methods is reported for this dataset along and compared to the optimal single-illuminant estimate. None of the methods specifically designed to handle multi-illuminant scenes is found to perform any better than the optimal single-illuminant case based on completely uniform illumination.

This study investigates an optimal chromaticity and placement of refrigerator lighting to meet users' preference. In the experiment, eighteen lighting stimuli were provided by combining six chromaticities and three placements. A total of 177 women aged 20 to 69 participated and assessed the lighting stimuli using ten affective scales. Based on the assessments, we derived four aspects to describe the characteristics of lighting styles: performance, aesthetics, visual comfort, and overall satisfaction. Specifically, cool white lighting placed in front appealed the well-functioning, performance support aspect. Further, when the shelves were lit in magenta-white, the refrigerator interior was evaluated to be the most attractive. When visual comfort matters more, shelf lighting in cyan-white would be optimal. An age effect was also discovered. Younger participants in their 20s and 30s preferred cool white when lit indirectly. Participants over 40, however, found magenta-white more attractive, especially when they viewed it directly. By expanding this study to diverse product categories, it could produce additional empirical findings for designers, so that they may choose and place lighting properties more efficiently and successfully.

In this paper, we perform multi-resolution analysis by using Wavelet transform for the components of surface reflection on faces in order to acquire features of wrinkles and fine asperities on the face. Also, by applying principal component analysis to the acquired trend of the wrinkles and the fine asperities, we analyze the relationship between the distribution of wrinkles and asperities, and actual age statistically. In the previous researches, components of facial surface reflection were directly used for multiresolution analysis, and it is considered that the acquired relationship was dependent on the luminance unevenness of lighting on the face. In this research, therefore, we propose to remove the luminance unevenness of the lighting on the face is transformed into uniform distribution by signal processing, and it contributes to the appropriate analysis to the component of surface reflection on the face.

Opacity is an important appearance attribute in the textile industry. Obscuring power and the way textile samples block light can define product quality and customer satisfaction in the lingerie, shirting, and curtain industries. While the question whether opacity implies the complete absence of light transmission remains open, various factors can impact cues used for opacity assessment. We propose that perceived opacity has poor consistency across various conditions and it can be dramatically impacted by the presence of a high-illuminance light source. We have conducted psychophysical experiments asking human subjects to classify textile samples into opaque and non-opaque categories under different illumination conditions. We have observed interesting behavioral patterns and cues used for opacity assessment. Finally, we found obvious indications that the high-illuminance light source has a significant impact on opacity perception of some textile samples, and to model the impact based on material properties remains a promising direction for future work.

Translucency is one of the major appearance attributes. Apparent translucency is impacted by various factors including object, shape, and geometry. Despite general proposals that object shape and geometry have a significant effect on apparent translucency, no quantification has been made so far. Quantifying and modeling the impact of geometry, as well as comprehensive understanding of the translucency perception process, are a point of not only academic, but also industrial interest with 3D printing as an example among many. We hypothesize that a presence of thin areas in the object facilitates material translucency estimation and changes in material properties have larger impact on apparent translucency of the objects with thin areas. Computer-generated images of objects with various geometry and thickness have been used for a psychophysical experiment in order to quantify apparent translucency difference between objects while varying material absorption and scattering properties. Finally, absorption and scattering difference thresholds where the human visual system starts perceiving translucency difference need to be identified and its consistency needs to be analyzed across different shapes and geometries.

In this paper, we examined the physical meaning of the widely used gloss evaluation. Gloss is one of the important qualities for materials. A visual test of the sharpness of a specular reflection image, i.e. gloss, on the surface of materials is often performed to estimate the gloss of materials. If the specular reflection image is sharp, we estimate that it has high gloss. This means that gloss can be estimated by measuring the sharpness of the specular reflection image. In this case, a line light source such as a fluorescent lamp is often used. Here we call it the line light source observation method. We developed a measurement apparatus based on the line light source observation method. As a result of experimental verification, it is confirmed that the Line Spread Function of Specular Reflection (SR-LSF) can be derived from the line light source observation images. However, the reflected image of line light source observation method is considered to be strictly different from SR-LSF. On the other hand, it is clarified that the line source observation method is an approximate SR-LSF measurement method. We also introduce the reconstruct method of gloss unevenness image by following visual observation conditions and image processing in human brain.

3D reconstruction is used for inspection of industrial products. The demand for measuring 3D shapes is increased. There are many methods for 3D reconstruction using RGB images. However, it is difficult to reconstruct 3D shape using RGB images with gloss. In this paper, we use the deep neural network to remove the gloss from the image group captured by the RGB camera, and reconstruct the 3D shape with high accuracy than conventional method. In order to do the evaluation experiment, we use CG of simple shape and create images which changed geometry such as illumination direction. We removed gloss on these images and corrected defect parts after gloss removal for accurately estimating 3D shape. Finally, we compared 3D estimation using proposed method and conventional method by photo metric stereo. As a result, we show that the proposed method can estimate 3D shape more accurately than the conventional method.

In this paper, we propose a method to estimate the concentration of pigments mixed in a painting, using the encoder-decoder model of neural networks. Encoder-decoder model is trained to output value which is same as input and its middle output extracts a certain feature as compressed information of the input. In this instance, the input and the output are spectral data of a painting. We trained the model to have pigments concentration as compressed information as a middle output. We used the dataset which was obtained from 19 pigments. The dataset has scattering coefficient and absorption coefficient of each pigment. We applied Kubelka-Munk theory to the coefficients to obtain many patterns of spectral data. It's shown that the accuracy of estimation is very high, and the speed of execution is very fast compared with a conventional method using simple for-loop optimization. We concluded our method is more effective and practical.

We investigated how well a multilayer neural network could implement the mapping between two trichromatic color spaces, specifically from camera R,G,B to tristimulus X,Y,Z. For training the network, a set of 800,000 synthetic reflectance spectra was generated. For testing the network, a set of 8,714 real reflectance spectra was collated from instrumental measurements on textiles, paints, and natural materials. Various network architectures were tested, with both linear and sigmoidal activations. Results show that over 85% of all test samples had color errors of less than 1.0 ΔE_{2000} units, much more accurate than could be achieved by regression.

15:40 – 16:20 COFFEE BREAK

PRINTING

Session Chair: Shoji Yamamoto, Tokyo Metropolitan College of Industrial Technology (Japan)

16:20 – 17:40

16:20 **JIST-first Angular Color Prediction Model for Anisotropic Halftone Prints on a Metallic Substrate,** *Petar Pjanic[1], Li Yang[2], Anita Teleman[2], and Roger D. Hersch[1]; [1]Ecole Polytechnique Federale de Lausanne (Switzerland) and [2]RISE (Sweden)* . . . **159**

Under specular reflection, non-isotropic halftones such as line halftones printed on an ink-receiving plastic layer superposed with a metallic layer change their colors upon in-plane rotation of the print. This color change is due to the orientation-dependent optical dot gain of the halftone. A strong dot gain occurs when the incident light is perpendicular to the halftone line structure. A color prediction model is proposed which predicts under specular reflection the color of cyan, magenta, and yellow line halftones as a function of the azimuthal rotation angle, the incident angle, and the line frequency. The model is calibrated by measuring 17 reflectances at the (25° : 25°) measurement geometry, with the incident light parallel to the halftone lines. The model has been tested for several azimuthal rotation and incident viewing angles, each time for 125 different cyan, magenta, and yellow ink surface coverages. The obtained prediction accuracies are between $\Delta E_{94} = 3.5$ and $\Delta E_{94} = 7$.

16:40 **Printing with Light: Daylight-fluorescent Inks for Large-gamut Multi-color Printing,** *Peter Morovic[1], Ján Morovic[2], Peter Klammer[3], Javier Maestro[1], Garry Hinch[3], and James Stasiak[3]; [1]HP Inc. (Spain), [2]HP Inc. (UK), and [3]HP Inc. (US)* **170**

With printing technologies continuously reaching ever higher degrees of performance and quality, the need for novelty and impact also keeps increasing. Specialty inks have always played an important role here, albeit not without challenges. Often the use of such materials involved dedicated solutions that deal with these inks outside of the constraints of normal pipelines and workflows, which constrains their application and results in limited use. This is so since specialty inks, such as fluorescents, behave differently to traditional dye or pigment-based ones. So much so that most applications use specialty inks as spot colors, explicitly determining (by means of a separate layer in the input) where they are to be used for given content. For example, for materials such as fluorescents or quantum dots, the possibility of presenting more light at a given wavelength than is incident at that wavelength, breaks some of the basic assumptions of current processes, from how they are measured to how they can be used in building color separations all the way to how color management deals with them. In this paper we describe first experiments of using fluorescent inks that are activated by visible—instead of the more customary UV—radiation, showing performance of spectrophotometer measurement with a dedicated model to handle the specific properties of these inks, as well as results of the impact such inks can have on extending color gamuts that go significantly beyond current printing gamuts and therefore also pose new challenges.

17:00 **Estimation of Layered Ink Layout from Arbitrary Skin Color and Translucency in Inkjet 3D Printer,** *Junki Yoshii[1], Shoji Yamamoto[2], Kazuki Nagasawa[1], Wataru Arai[3], Satoshi Kaneko[3], Keita Hirai[1], and Norimichi Tsumura[1]; [1]Chiba University, [2]Tokyo Metropolitan College of Industrial Technology, and [3]Mimaki Engineering Corporation (Japan)* **177**

In this paper, we propose a layout estimation method for multi-layered ink by using PSF measurement and machine learning. This estimation can bring various capabilities of color reproduction for the newfangled 3D printer that can apply multi-layered inkjet color. Especially, the control of translucency is useful for the reproduction of skin color that is overpainted flesh color on bloody-red layer. Conventional method of this layer design and color selection depended on the experience of professional designer. However, it is difficult to optimize the color selection and layer design for reproducing complex colors with many layers. Therefore, in this research, we developed an efficiency estimation of color layout for human skin with arbitrary translucency by using machine learning. Our proposed method employs PSF measurement for quantifying the color translucency of overlapped layers. The machine learning was performed by using the correspondence between these measured PSFs and multi-layered printings with 5-layer neural network. The result was evaluated in the CG simulation with the combination of 14 colors and 10 layers. The result shows that our proposed method can derive an appropriate combination which reproduce the appearance close to the target color and translucency.

17:20 **A Psychovisual Study of Print Smoothness via Metameric Samples,** *Sergio Etchebehere and Peter Morovic, HP Inc. (Spain), and Ján Morovic, HP Inc. (UK)* **183**

The smoothness of a print is one of its main image quality attributes. Here smoothness can refer to the level of unexpected changes or discontinuities in color transitions (at a macro scale) or the level of local variation (at a micro scale), sometimes also described as grain. This paper starts with presenting an approach to building a first-ever set of metameric printed samples that match in color but vary in grain, followed by a psychovisual study of smoothness perception based on a large number of evaluations by both experts and non-experts. This data shows high levels of intra- and inter-observer correlation and can therefore serve as a robust ground truth for understanding and modelling the print smoothness phenomenon. Then, a previously published predictive smoothness model is revisited, that estimates smoothness from a digital halftone before it is printed, and it is shown to result in high degrees of correlation between observer assigned smoothness judgments and computationally predicted scores. The paper also reports the results of tuning the smoothness metrics parameters to further enhance is alignment with the psychovisual ground truth.

THURSDAY, OCTOBER 24, 2019

THURSDAY KEYNOTE

Session Chair: Peter Morovic, HP Inc. (Spain)

9:00 – 10:00

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The Chromatic Pyramid of Visibility, *Andrew B. Watson, Apple Inc. (US)* *

The Pyramid of Visibility is a simplified model of the spatio-temporal luminance contrast sensitivity function (Watson and Ahumada 2016). It posits that log sensitivity is a linear function of spatial frequency, temporal frequency, and log luminance. It is valid only away from the spatiotemporal frequency origin. Though very useful in a range of applications, the pyramid would benefit from an extension to the chromatic domain. In this talk I will describe our efforts to develop this extension. Among the issues we address are the choice of color space, the definition of color contrast, and how to combine sensitivities among multiple pyramids.

*No proceedings paper associated with talk.

COLOR PERCEPTION

Session Chair: Sophie Wuerger, University of Liverpool (UK)

10:00 – 12:00

Experiments were carried out to investigate the simultaneous colour contrast effect on a self-luminous display using colour matching method. The goals of this study were to accumulate a new visual dataset and to extend CAM16 to predict the simultaneous colour contrast effect. Five coloured targets together with a neutral grey were studied. A total of 132 test/background combinations were displayed on a calibrated display. Twenty normal colour vision observers performed colour matching in the experiment. In total, 2,640 matches were accumulated. The data were used to accurately model the lightness and hue contrast results. The model was also successfully tested using two independent datasets.

Diffuse white is an important concept in all color appearance models. However, there is a lack of research directly about the perceived diffuse white in HDR images. Three experiments were conducted to explore the perceptual estimation of diffuse white in real HDR images when presented on displays. The first experiment showed that the perceptual estimation of diffuse white relied more on the image content than the clipped peak luminance levels. Experiment II used images with different neutral density filters rather than clipping. The normalized luminance levels of the perceptual estimation were similar, depending on image content but not on image absolute luminance levels. Moreover, in both experiments, no significant difference can be found between expert and naive observers. The variance across images agreed with each other between experiment I and II. However, both results demonstrated that the absolute luminance level of observers' estimation is higher than the calibrated diffuse white level. Experiment III focused on exploring the impact of measurement methodologies on the absolute luminance level of the estimated diffuse white. Results of experiment III verified that the absolute luminance level of the perceptual estimation can be manipulated by the measurement methodology but the variance across image content is stable.

10:40-11:20 COFFEE BREAK

This pilot study made a wide variety of visual measurements before, during, and after bilateral cataract surgery. This article describes the changes in color discrimination and color appearance resulting from cataract implants. It used the F-M 100 Hue Test, color matching of real scenes, and color-balance titration measurements. The pre-surgery data indicated that the previously normal color observers had severe tritanopic anomalies. Lens replacement restored normal color vision.

In September 2017, the first author suffered a rhegmatogenous retinal detachment. This experience included a series of remarkable, sometimes unsettling visual phenomena, which included visible differences in the color vision between her two eyes during the recovery from retinal detachment, as a cataract developed, and following cataract surgery. Her right eye is now equipped with a new lens, replacing one that had yellowed from years of exposure to ultraviolet radiation, which provides a cooler view of the world than before retinal detachment, with slight distortions, and occasionally with sparkles early in the morning. In this review, the color vision changes that were experienced are quantified and detailed. While this does not represent a typical study with a hypothesis and testing of various participants, we hope that it inspires others to ask interesting questions that lead to increased consideration of the relationships between perception and visual health and that it raises awareness of the warning signs of retinal detachment.

TWO-MINUTE INTERACTIVE PAPER PREVIEWS II

Session Chair: David Alleysson. LPNC: Laboratoire de Psychologie et Neurocognition (France)

12:00 – 12:40

We construct redness-greenness (r,g) coordinates to fit the spectral locus into a triangle in the normalised CIE 2006 LMS plane. The reflection spectra for the Munsell patches for blackbody illuminants from 5000 to 6500 K appear as near circles in this space, suggesting that equal steps in (r,g) space may correspond to equal perceived colour contrasts within the gamut of reflective colours. We fit a matrix to convert from XYZ to LMS for reflective colours.

Over time, much work has been carried out to ascertain the accuracy of the CIE standard color-matching functions, but no definitive answer has been given. Recent work indicates an undeniable discrepancy between visual and computed metamers calculated using the existing CIE (the International Commission on Illumination) standard observer CMFs, especially when matching with narrowband sources. With a spectrally tunable solid-state light source, a series of pilot matching experiments have been done using primaries with different peak wavelengths. The results indicate which regions in wavelength space are most sensitive to generating matching inaccuracies for a given CMF set and which primary combinations have the most stable matching performance.

While for many years achromatic contrast sensitivity has been widely studied by different research groups from various fields of work, the same attention has not been paid to chromatic contrast sensitivity. Due to the challenging nature of contrast sensitivity tests even the limited number of studies in the field do not agree on different issues. In this work, through a subjective test, we aim to further investigate the relationship between the chromatic contrast sensitivity for the red-green channels in the vertical (0°) and oblique (45°) orientations. The results show that the contrast sensitivity between the two different orientations is similar.

The purposes of this study was to investigate the chromatic adaptation and adaptive whites on a display under various ambient lighting conditions with different chromaticity and illuminance. An image including black text and white background was rendered by means of the CAT02 chromatic adaptation transform, into 42 different white stimuli varying at 6 CCTs and 7 Duv levels. Twenty observers assessed the neutral white evaluations of each color stimulus via psychophysical experiments. The optimization based on the neutral white stimulus under each ambient lighting condition suggested a lower degree of chromatic adaptation under the conditions with a lower CCT and a lower illuminance level. The results were used to model the adaptive display white and the incomplete adaptation factor (D) for CAT02 under different ambient illumiantions.

Color appearance models have been extensively studied for characterizing and predicting the perceived color appearance of physical color stimuli under different viewing conditions. These stimuli are either surface colors reflecting illumination or self-luminous emitting radiations. With the rapid development of augmented reality (AR) and mixed reality (MR), it is critically important to understand how the color appearance of the objects that are produced by AR and MR are perceived, especially when these objects are overlaid on the real world. In this study, nine lighting conditions, with different correlated color temperature (CCT) levels and light levels, were created in a real-world environment. Under each lighting condition, human observers adjusted the color appearance of a virtual stimulus, which was overlaid on a real-world luminous environment, until it appeared the whitest. It was found that the CCT and light level of the real-world environment significantly affected the color appearance of the white stimulus, especially when the light level was high. Moreover, a lower degree of chromatic adaptation was found for viewing the virtual stimulus that was overlaid on the real world.

A perceptual study was conducted to enhance colour image quality in terms of naturalness and preference using perceptual scales of saturation and vividness. Saturation scale has been extensively used for this purpose while vividness has been little used. We used perceptual scales of a recently developed colour appearance model based on $J_z a_z b_z$ uniform colour space. A two-fold aim of the study was (i) to test performance of recently developed perceptual scales of saturation and vividness compared with previously used hypothetical models and (ii) to compare performance and chose one of saturation and vividness scales for colour image enhancement in future. Test images were first transformed to $J_z a_z b_z$ colour space and their saturation and vividness were then decreased or increased to obtain 6 different variants of the image. Categorical judgment method was used to judge preference and naturalness of different variants of the test images and results are reported.

A magnitude estimation experiment was carried out to scale the extent of whiteness from a set of near white textile samples including fluorescent white agent. Each was assessed under 4 different CCTs, each having a high and a low level of UV energy. The results were used to test various existing whiteness formulae. Finally, by fitting to the present data, two new metrics were developed. One is based on CIECAM02, and the other is based on the present CIE whiteness formula by transforming the data to D65 chromaticity from the other white sources via CAT02 chromatic adaption transform with a proper incomplete adaptation factor (D). It was also tested using an independent set of data. Both formulae gave accurate prediction to the data. The former metric is proposed because it is based on a colour appearance model.

Tone-mapping operators transform high dynamic range (HDR) images into displayable low dynamic range (LDR) images. Image quality evaluation of these LDR images is not possible by comparison with their corresponding high dynamic range images. Hence, a no-reference image quality metric for tone-mapped LDR images is proposed based on the fitting to the present psychophysical results including different visual image quality attributes. Ten images, including HDR natural scenes, were tone-mapped using six TMOs. They were used in the assessment and visual attributes were determined to predict the quality of these images. The visual attributes (brightness and Naturalness) were modeled using parameters derived from CAM16-UCS. Results showed that the quality prediction of the model had a reasonable degree of accuracy.

Contrast Limited Histogram Equalisation moves the input image histogram gently towards one which has a more uniform distribution. Viewed as a tone mapping operation, CLHE generates a tone curve with bounded max and min slopes. It is this boundedness which ensures that the processed images have more detail but few artefacts. Outside of limiting contrast, recent improvements to histogram equalisation include constraining the tone curve to make good whites and blacks and constraining the tone curve to be smooth. This paper makes three contributions. First, we show that the CLHE formalism is not least-squares optimal but optimality can be achieved by reformulating the problem in a quadratic programming framework. Second, we incorporate the additional constraints of tone curve smoothness and good whites and blacks in our quadratic programming CLHE framework. Third, experiments demonstrate the utility of our method.

Omnidirectional or 360-degree images are becoming very popular in many applications and several challenges are raised because of both the nature and the representation of the data. Quality assessment is one of them from two different points of view: objectively or subjectively. In this paper, we propose to study the performance of different metrics belonging to various categories including simple mathematical metrics, human perception-based metrics, and spherically optimized metrics. The performance of these metrics is measured using different tools such as PLCC, SROCC, KROCC, and RMSE based on the only publically available database from Nanjing University. The results show that the metric that are considered as optimized for 360 degrees images are not providing the best correlation with the human judgement of the quality.

High Dynamic Range (HDR) imaging applications have been commonly placed recently. Several tone mapping operators (TMOs) have been developed which project the HDR radiance range to that of a display. Currently, there is no agreement on a technique for evaluation of tone mapping operators. The goal of this study is to establish a method based on reference images to evaluate the TMOs. Two psychophysical experiments were carried out for the evaluation of tone mapping operators. In the first experiment, a set of high quality images were generated to possess right extents of image features including contrast, colourfulness and sharpness. These images were further used in the second experiment as reference images to evaluate different TMOs. It was found Reinhard's photographic reproduction based on local TMO gave an overall better performance. CIELAB(2:1) and S- CIELAB metrics were also used to judge colour image quality of the same TMOs. It was found that both metrics agreed well with the visual results.

In this paper, we investigated the correlation between blood pressure (BP) and image-based pulse transit time (iPTT) acquired from only face using RGB camera. In general, the value of iPTT can be calculated from a transition time at peaks of hemoglobin amount which is extracted from RGB values of the camera. The transition time of peaks is obtained by time of the peak at the face and the palm. In the previous research, it is known that there is a correlation between BP and iPTT. Therefore, blood pressure can be estimated by acquiring iPTT from video taken using RGB camera. However, it is necessary to take video of face and palm simultaneously in this conventional iPTT measurement method. It is difficult to take the video of face and palm simultaneously. In order to solve this problem, we investigated whether iPTT can be acquired from a single part of body. At first, we took a video of face and palm using a high-speed camera and investigated whether the pulse wave flow can be observed. As a result, we were able to observe the propagation of the pulse wave in the regions of face and palm. Hence, iPTT acquisition from the single part of body is expected to be possible in these two parts. Next, we set a region of interest (ROI) on the chin and the forehead for the face, and the center of the palm and thenar for the palm. Then, pulse waves were extracted from each region, and iPTT was calculated from each part. We found that iPTT acquired from face is long and stable, but iPTT acquired from palm is short and unstable. Moreover, we examined the correlation between blood pressure and iPTT acquired from face. Consequently, a correlation was found between blood pressure and iPTT acquired from only face.

Measuring, Modeling, and Reproducing Material Appearance from Specular Profile, *Shoji Tominaga[1,2] and Giuseppe Claudio Guarnera[1]; [1]Norwegian University of Science and Technology (Norway) and [2]Nagano University (Japan)* **279**

A method is proposed for measuring, modeling, and reproducing material appearance from the specular profile representing reflectance distribution around a specular highlight. Our method is aimed at opaque materials with a highly glossy surface like plastic, ceramic, and metals. Hence, the material surface is assumed to be not a perfect mirror, but a surface with some roughness. We do not use a goniospectrophometer nor an image-based measurement setup. Instead, we make use of a gloss meter with a function to measure the specular profile, containing for glossy materials appearance such as roughness, sharpness, and intensity. The surface reflection is represented as a linear sum of diffuse and specular reflection components, the latter described by the Cook-Torrance model. The specular function represents the glossy surface appearance by a small number of control parameters. Mitsuba rendering system is utilized to perform the rendering algorithms. Finally, the feasibility of the proposed method is examined using different materials.

MCS 2019 Exposure Invariance in Spectral Reconstruction from RGB Images, *Yi-Tun Lin and Graham D. Finlayson, University of East Anglia (UK)* **284**

In the spectral reconstruction (SR) problem, reflectance and/or radiance spectra are recovered from RGB images. Most of the prior art only attempts to solve this problem for fixed exposure conditions, and this limits the usefulness of these approaches (they can work inside the lab but not in the real world). In this paper, we seek methods that work well even when exposure is unknown or varies across an image, namely 'exposure invariance'. We begin by re-examining three main approaches—regression, sparse coding, and Deep Neural Networks (DNN)—from a varying exposure viewpoint. All three of these approaches are predominantly implemented assuming a fixed capturing condition. However, the leading sparse coding approach (which is almost the best approach overall) is shown to be exposure-invariant, and this teaches that exposure invariance need not come at the cost of poorer overall performance. This result in turn encouraged us to revisit the regression approach. Remarkably, we show that a very simple root-polynomial regression model—which by construction is exposure-invariant—provides competitive performance without any of the complexity inherent in sparse coding or DNNs.

MCS 2019 Estimation of Blood Concentrations in Skin Layers with Different Depths, *Kaito Iuchi[1], Rina Akaho[1], Takanori Igarashi[2], Nobutoshi Ojima[2], and Norimichi Tsumura[1]; [1]Chiba University and [2]Kao Corporation (Japan)* **290**

In this research, we proposed a method to estimate the concentrations of melanin and blood in different layers of skin tissue. Furthermore, we stimulated skin with a warm bath and a carbon dioxide bath and obtained spectral data by a multispectral camera six times during 18 minutes. Based on the captured image, we estimated the blood concentrations in each blood layers by the proposed method. The result showed that the blood concentration of the deep layer is increased only with the stimulation by carbon dioxide bath, and the blood concentration in the shallow layer is increased in both stimuli cases, but the rate of increase in the carbon dioxide bath was higher and the increase time was longer. Our result is consistent with the result of the previous research.

MCS 2019 Deep Learning for Dental Hyperspectral Image Analysis, *Oleksandr Boiko, Joni Hyttinen, Pauli Fält, Heli Jäsberg, Arash Mirhashemi, Arja Kullaa, and Markku Hauta-Kasari, University of Eastern Finland (Finland)*. **295**

The aim of this work is automatic and efficient detection of medically-relevant features from oral and dental hyperspectral images by applying up-to-date deep learning convolutional neural network techniques. This will help dentists to identify and classify unhealthy areas automatically and to prevent the progression of diseases. Hyperspectral imaging approach allows one to do so without exposing the patient to ionizing X-ray radiation. Spectral imaging provides information in the visible and near-infrared wavelength ranges. The dataset used in this paper contains 116 hyperspectral images from 18 patients taken from different viewing angles. Image annotation (ground truth) includes 38 classes in six different sub-groups assessed by dental experts. Mask region-based convolutional neural network (Mask R-CNN) is used as a deep learning model, for instance segmentation of areas. Preliminary results show high potential and accuracy for classification and segmentation of different classes.

MCS 2019 Spectral Image Recovery from Spectral Filter Array Cameras using LMMSE, *Prakhar Amba and David Alleysson, Universite Grenoble Alpes (France)*. **300**

A hyperspectral camera can record a cube of data with both spatial 2D and spectral 1D dimensions. Spectral Filter Arrays (SFAs) overlaid on a single sensor allows a snapshot version of a hyperspectral camera. But acquired image is subsampled both spatially and spectrally, and a recovery method should be applied. In this paper we present a linear model of spectral and spatial recovery based on Linear Minimum Mean Square Error (LMMSE) approach. The method learns a stable linear solution for which redundancy is controlled using spatial neighborhood. We evaluate results in simulation using gaussian shaped filter's sensitivities on SFA mosaics of up to 9 filters with sensitivities both in visible and Near-Infrared (NIR) wavelength. We show by experiment that by using big neighborhood sizes in our model we can accurately recover the spectra from the RAW images taken by such a camera. We also present results on recovered spectra of Macbeth color chart from a Bayer SFA having 3 filters.

MCS 2019 Development of the Stool Color Card for Early Detection of Biliary Atresia using Multispectral Image, *Masaru Tsuchida[1], Hideaki Gunji[2], Hideki Nakajima[3], Takahito Kawanishi[1], Kunio Kashino[1], and Akira Matsui[3]; [1]NTT Communication Science Laboratories, [2]Japan Association of Graphics Arts Technology, and [3]National Center for Child Health and Development (Japan)* **304**

The stool color card for early detection of biliary atresia have been developed using multispectral images of stools of newborns. Color and its spectra were measured and analyzed spectrally first in the world and used to design the stool color card. Representative texture was selected by medical specialists from captured multispectral images and spectral information of the images was replaced and edited according to the result of spectral and chromaticity analysis. The stool color card was placed within the Maternal and Child Health Handbook that was distributed to all pregnant women by their respective local government according to the Maternal and Child Health Law in Japan.

12:40 – 14:00 LUNCH BREAK

COLOR APPEARANCE

Session Chair: Jonathan Phillips, Google Inc. (US)

14:00 – 15:20

It is desirable to communicate colour with intuitive terms which are understood not only by experts. Studies have showed that chroma, saturation, and colourfulness are more difficult to understand for "ordinary people" than other colour terms. Vividness has recently been proposed as a formal colour scale, and it is believed to be more intuitive than other colour science terms. In this work we investigate how people interpret vividness of colour samples and test current models by collecting visual data in a psychophysical experiment. 31 people were asked to judge the vividness of 53 NCS patches and 53 colour matches on display on a scale from 0 to 100. The majority of the variations in the vividness data is predicted by chroma, while the results indicate that lightness does not contribute in prediction of the observers' interpretation of vividness. Current models did not outperform chroma as a single predictor for the vividness data obtained in this experiment.

If an image, for example a company logo, is shown on different devices the degree of colour consistency amongst this set of stimuli can be defined as common or consistent colour appearance (CCA). In this work, a procedure which is able to evaluate CCA is developed for the first time. A psychophysical experiment is presented with which the existence of CCA is proofed. For the evaluation of CCA, the colour naming approach from is consistently continued and a measuring tool is developed. In addition, the correctness of the measuring tool is tested on the basis of the experiment. This work is based on two psychophysical experiments, the first to proof CCA, the second to create the colour naming database. This setup is very general and can therefore also be applied to other cultures in order to develop a measuring tool for CCA.

Great efforts have been made to develop color appearance models to predict color appearance of stimuli under various viewing conditions. CIECAM02, the most widely used color appearance model, and many other color appearance models were all developed based on corresponding color datasets, including LUTCHI data. Though the effect of adapting light level on color appearance, which is known as "Hunt Effect", is well known, most of the corresponding color datasets were collected within a limited range of light levels (i.e., below 700 cd/m^2), which was much lower than that under daylight. A recent study investigating color preference of an artwork under various light levels from 20 to 15000 lx suggested that the existing color appearance models may not accurately characterize the color appearance of stimuli under extremely high light levels, based on the assumption that the same preference judgements were due to the same color appearance. This article reports a psychophysical study, which was designed to directly collect corresponding colors under two light levels—100 and 3000 cd/m^2 (i.e., ≈ 314 and 9420 lx). Human observers completed haploscopic color matching for four color stimuli (i.e., red, green, blue, and yellow) under the two light levels at 2700 or 6500 K. Though the Hunt Effect was supported by the results, CIECAM02 was found to have large errors under the extremely high light levels, especially when the CCT was low.

This paper presents data on CIELAB chromatic contrast sensitivity collected in a psychophysical experiment. To complement previously published data in the low-frequency range, we selected five spatial frequencies in the range from 2.4 to 19.1 cycles per degree (cpd). A Gabor stimulus was modulated along six chromatic directions in the a*-b* plane. We also investigated the impact on contrast sensitivity from spatial orientations – both vertically and diagonally oriented stimuli were used. The analysis of the collected data showed lowest contrast sensitivity in the chromatic direction of around 120° from the positive a*-axis. The contrast sensitivity in the diagonal spatial orientation is slightly lower when compared to the vertical orientation.

INTERACTIVE POSTER, EXHIBIT, AND DEMONSTRATION SESSION

15:20 – 17:00

Discuss the interactive (poster) papers with their authors over a glass of wine.

IMAGING AND CULTURAL HERITAGE APPLICATIONS

Session Chair: Gael Obein, CNAM—Conservatoire National des Arts et Métiers (France)

17:00 – 17:30

Scientific imaging is an important part of conservation sciences developed in museum laboratories, mainly because it is noninvasive process, a decisive advantage to studying unique artworks. Various 2D and 3D optical techniques using several radiations (visible, UV, IR, X-rays) lead to a precise report of the state of the artwork, for color, shape, and surface on first examination. Depending on what conservators are trying to learn, more investigation can be undertaken to detect original or previous restoration materials and/or fabrication techniques. Several examples of using imaging for art conservation are presented, with a focus on color collections and multimodal images.

CONFERENCE RECEPTION

18:00 – 20:00

Enjoy the city of lights with a cruise along the Seine with colleagues.

*No proceedings paper associated with talk.

FRIDAY, OCTOBER 25, 2019

FRIDAY KEYNOTE AND AWARDS

Session Chair: Maria Vanrell, CVC – Universitat Autònoma de Barcelona (Spain)
9:00 – 10:10

Video-projected augmented reality offers unique immersive experiences while it changes the way we perceive and interact with the world. By projecting on real-world objects we can change their appearance and create numerous effects. Due to physical limitations and the complexity of such AR systems, color calibration and processing for desired appearance changes require to be specifically addressed.

This talk will focus on the challenging aspects of video-projected AR systems composed of video projectors and cameras: geometric calibration, latency, color calibration and characterization of desired effects. Such an AR solution developed at L'Oréal will be presented to demonstrate applications in beauty industry.

DISPLAYS

Session Chair: Minchen (Tommy) Wei, The Hong Kong Polytechnic University (Hong Kong)
10:10 – 12:40

In this paper we discuss a model to estimate the power consumption and lifetime (LT) of an OLED display based on its pixel value and the brightness setting of the screen (scbr). This model is used to illustrate the effect of OLED aging on display color characteristics. Model parameters are based on power consumption measurement of a given display for a number of pixel and scbr combinations. OLED LT is often given for the most stressful display operating situation, i.e. white image at maximum scbr, but having the ability to predict the LT for other configurations can be meaningful to estimate the impact and quality of new image processing algorithms. After explaining our model we present a use case to illustrate how we use it to evaluate the impact of an image processing algorithm for brightness adaptation.

This study proposes an illuminant estimation method that reproduces the original illuminant of a scene using a mobile display as a target. The original lighting environment of an auto white-balancing (AWB) photograph is obtained through reverse calibration, using the white point of a display in the photograph. This reproduces the photograph before AWB processed, and we can obtain the illuminant information using Gray World computation. The study consists of two sessions. In Session 1, we measured the display's white points under varying illuminants to prove that display colors show limited changes under any light conditions. Then, in Session 2, we generated the estimations and assessed the performance of display-based illuminant estimation by comparing the result with the optically measured values in the real situation. Overall, the proposed method is a satisfactory way to estimate the less chromatic illuminants under 6300 K that we experience as indoor light in our daily lives.

*No proceedings paper associated with talk.

10:50 – 11:20 COFFEE BREAK

Recently, the CIE published a new standard in which the so called 'melanopic daylight efficacy ratio' (abbreviated to melanopic DER) is introduced. This number is helpful in estimating the impact that a light source may have on our circadian rhythm. Although the melanopic DER can be directly calculated from the spectral power distribution, in case the latter is unknown a spectrophotometer or similar instrument is required, which is usually unavailable to the general public. Here we demonstrate how the melanopic DER can be accurately estimated from a smartphone image of two selected color samples. In addition, using the smartphone's camera parameters we provide a method to estimate the illuminance. Combined these measurements allow an evaluation of the absolute melanopic stimulation.

The goal of this study is to develop quantitative metrics for evaluating color tracking and gray tracking in a color medical display. Color tracking is the chromaticity consistency of the red, green, or blue shades. Gray tracking is the chromaticity consistency of the gray shades. Color tracking and gray tracking are the most important colorimetric responses of a color medical display because they directly indicate the color calibration quality and can therefore be used to compare color performance between displays. Two metrics, primary purity and gray purity, are defined to measure the color shift of the primary shades and gray shades of a color display, respectively. The area under the curves of primary purity and gray purity can then represent the quality of color tracking (C_AUC) and gray tracking (G_AUC), respectively. Fifteen displays including medical, professional-grade, consumer-grade, mobile, and special displays were tested to compare their C_AUC and G_AUC. The OLED displays have the greatest C_AUC values. The medical and professional-grade displays have the greatest combinations of C_AUC and G_AUC values. Most consumer-grade displays have lower C_AUC and G_AUC values, but some show better gray tracking than color tracking. The special displays exhibit particularly poor color and gray tracking. Using C_AUC and G_AUC together can quantitatively predict and compare color performance of different displays.

Two experimental data sets were accumulated for evaluating colour differences under a wide range of luminance levels using the printed colours in a spectrum tuneable viewing cabinet and selfluminous colours on a display respectively. For the surface mode experiment, pairs of samples were assessed at 9 phases ranged from 0.25 to 1128 cd/m^2. For the luminous mode experiment, it was conducted in 6 phases ranged from 0.25 to 279 cd/m^2. There were 140 and 42 pairs of samples judged by 20 observers using a six-category scales for each phase. The results were used to establish the just noticeable difference (JND) at each luminance level and showed a great agreement between two modes of colours. These were used to test the performance of 5 uniform colour spaces and colour difference equations. Also, the spaces or equations were extended to improve the fit to the present data sets.

12:20 **2019 Land Medal Winner Talk on Camera Optics: The CAOS Camera—Empowering Full Spectrum Extreme Linear Dynamic Range Imaging,** *Nabeel A. Riza, University College Cork (Ireland)* *

Multi-pixel imaging devices such as CCD, CMOS, and FPA photo-sensors dominate the imaging world. These Photo-Detector Array (PDA) devices certainly have their merits including increasingly high pixel counts and shrinking pixel sizes, nevertheless, they are also being hampered by limitations in robustness and reliability of acquired image data, instantaneous high linear dynamic range, inter-pixel crosstalk, quantum full well capacity, signal-to-noise ratio, sensitivity, spectral flexibility, and in some cases, imager response time. Recently invented is the Coded Access Optical Sensor (CAOS) Smart Camera that works in unison with current PDA technology to counter fundamental limitations of PDA-based imagers while providing extreme linear dynamic range, full spectrum coverage (e.g., 350 nm to 2700 nm), extreme image security, extreme inter-pixel isolation, and high enough imaging spatial resolution and pixel counts to match application needs. This talk describes the CAOS smart camera imaging invention using the Texas Instruments (TI) Digital Micromirror Device (DMD). Highlighted are some experimental demonstrations including CAOS-mode imaging over a 177 dB linear dynamic range and high reliability true image data acquisition. The CAOS smart camera can benefit imaging applications in sectors such as automotive, surveillance, security, bright light photography, HDR still photography, calibration/test instrumentation, medical/biological analysis, and industrial sensing. Details on the CAOS camera can be found at www.nabeelriza.com.

12:40 – 14:00 LUNCH BREAK

APPLICATIONS & ANALYSIS

Session Chair: Rafael Huertas, Universidad de Granada (Spain)
14:00 – 15:00

14:00 **JIST-first Deep Learning Approaches for Whiteboard Image Quality Enhancement,** *Mekides Assefa Abebe and Jon Yngve Hardeberg, Norwegian University of Science and Technology (Norway)* **360**

Different whiteboard image degradations highly reduce the legibility of pen-stroke content as well as the overall quality of the images. Consequently, different researchers addressed the problem through different image enhancement techniques. Most of the state-of-the-art approaches applied common image processing techniques such as background foreground segmentation, text extraction, contrast, and color enhancements, and white balancing. However, such types of conventional enhancement methods are incapable of recovering severely degraded pen-stroke contents and produce artifacts in the presence of complex pen-stroke illustrations. In order to surmount such problems, the authors have proposed a deep learning based solution. They have contributed a new whiteboard image data set and adopted two deep convolutional neural network architectures for whiteboard image quality enhancement applications. Their different evaluations of the trained models demonstrated their superior performances over the conventional methods.

*No proceedings paper associated with talk.

14:20 **Analyzing Color Harmony of Food Images,** *Gianluigi Ciocca, Paolo Napoletano, and Raimondo Schettini, University of Milano-Bicocca, and Isabella Gagliardi and Maria Teresa Artese, National Research Council of Italy (Italy)* **369**

Color of food images play a key role in human perception of food quality and calories, as well as in food choice. In this paper we investigate the use of computational methods for color harmony analysis of food images. To this end we propose a computational pipeline that includes color segmentation, color palette extraction, and color harmony prediction. Such a pipeline makes it possible to analyze the emotions elicited by pairs and multiple combinations of food dishes.

14:40 **Physical Noise Propagation in Color Image Construction: A Geometrical Interpretation,** *Axel Clouet, Jérôme Vaillant, and David Alleysson, Université Grenoble Alpes (France)* **375**

To avoid false colors, classical color sensors cut infrared wavelengths for which silicon is sensitive (with the use of an infrared cutoff filter called IR-cut). However, in low light situation, noise can alter images. To increase the amount of photons received by the sensor, in other words, the sensor's sensitivity, it has been proposed to remove the IR-cut for low light applications. In this paper, we analyze if this methodology is beneficial from a signal to noise ratio point of view when the wanted result is a color image. For this aim we recall the formalism behind physical raw image acquisition and color reconstruction. A comparative study is carried out between one classical color sensor and one specific color sensor designed for low light conditions. Simulated results have been computed for both sensors under same exposure settings and show that raw signal to noise ratio is better for the low light sensor. However, its reconstructed color image appears more noisy. Our formalism illustrates geometrically the reasons of this degradation in the case of the low light sensor. It is due on one hand to the higher correlation between spectral channels and on the other hand to the near infrared part of the signal in the raw data which is not intrinsically useful for color.

15:00 – 15:30 COFFEE BREAK

21ST INTERNATIONAL SYMPOSIUM ON MULTISPECTRAL COLOUR SCIENCE (MCS)

Session Chair: Markku Hauta-Kasari, University of Eastern Finland (Finland)
15:30 – 17:00

15:30 **Polarized Multispectral Imaging for the Diagnosis of Skin Cancer,** *Laura Rey-Barroso[1], Francisco Javier Burgos-Fernández[1], Santiago Royo[1], Susana Puig[2], Josep Malvehy[2], Giovanni Pellacani[3], Xana Delpueyo[1], Sara Peña[1], Fernando Díaz-Doutón[1], and Meritxell Vilaseca[1]; [1]Universidad Politécnica de Cataluña (Spain), [2]Clinic Hospital of Barcelona (Spain), and [3]Università di Modena e Reggio Emilia (Italy)* **381**

The effective and non-invasive diagnosis of skin cancer is a hot topic in biophotonics since the current gold standard, a biopsy, is slow and costly. Non-invasive optical techniques such as polarization and multispectral imaging have arisen as powerful tools to overcome these constraints. The combination of these techniques provides a comprehensive characterization of skin chromophores including polarization, color, and spectral features. Hence, in this work we propose a polarized multispectral imaging device that works from 414 nm to 995 nm and at 0°, 45°, and 90° polarization configurations. Preliminary results performed over 20 nevi and 20 melanoma found statistically significant descriptors ($p<0.05$) that discriminated between these two lesion etiologies. A further analysis of more lesions is expected to contribute in reducing the false positives during the diagnosis process and, as a consequence, the number of necessary biopsies.

15:50 **Relative Spectral Difference Occurrence Matrix: A Metrological Spectral-spatial Feature for Hyperspectral Texture Analysis,** *Rui Jian Chu, Noël Richard, and Christine Fernandez-Maloigne, Universite de Poitiers (France), and Jon Yngve Hardeberg, Norwegian University of Science and Technology (Norway)* . **386**

We develop a spectral-spatial feature, Relative Spectral Difference Occurrence Matrix (RSDOM) for hyperspectral texture recognition. Inspired by Julesz's conjecture, the proposed feature is based on spectral difference approach and respects the metrological constraints. It simultaneously considers the distribution of spectra and their spatial arrangement in the hyperspectral image. The feature is generic and adapted for any number of spectral bands and range. We validate our proposition by applying a classification scheme on the HyTexiLa database. An accuracy comparable to local binary pattern approach is obtained, but at a much reduced cost due to the extremely small feature size.

16:10 **Appearance Reconstruction of Fluorescent Objects based on Reference Geometric Factors,** *Shoji Tominaga, Norwegian University of Science and Technology (Norway) and Nagano University (Japan), and Keita Hirai and Takahiko Horiuchi, Chiba University (Japan)* **393**

An approach is proposed for the reliable appearance reconstruction of fluorescent objects under arbitrary conditions of material and illuminant based on reference geometric factors. First, a large set of spectral images is acquired from a variety of scenes of fluorescent objects paired with a mutual illumination effect under different conditions. The target fluorescent object is constructed using a cube and a flat plate supporting it, and is subsequently illuminated using a directional light source. We produce many target objects of the same size with different fluorescent materials and observe them under different illumination conditions. The observed spectral images are subsequently decomposed into five components, combining the spectral functions and geometric factors. The reference geometric factors are independent of the material, illuminant, and illumination direction change; instead, they are only dependent on object geometries. A reliable estimation method of reference geometric factors is presented using the whole spectral images observed under various conditions. Further, we propose an algorithm for reconstructing a realistic appearance including mutual illumination effect under arbitrary conditions of material, illuminant, and illumination direction. Finally, the reliability of the proposed approach is examined experimentally.

16:30 **Hyperspectral Imaging for Cultural Heritage,** *Anne Michelin, Muséum National d'Histoire Naturelle (France)* . . . . *

Hyperspectral reflectance imaging is a non-invasive, in situ, optical analysis technique that involves the acquisition of hundreds of wavelength-resolved images from the visible to the near infrared range. It can also be considered as a chemical imaging technique since this equipment makes the collection of reflectance spectra in each pixel of the field of view. These spectra may have specific signature of materials that could be mapped to highlight their spatial distribution. Initially developed for remote sensing, these techniques are now applied in various fields: industrial, biomedical, and more recently for the study and conservation of works of art. Hyperspectral Imaging provides spatially resolved information on the nature of chemical species that can be interesting, for example, to locate damages (moisture, chemical transformations…), restorations, pentimenti, or underdrawings in artworks. The data processing is challenging as cubes of several million spectra are collected in a few minutes involving computerized processing protocols. Different approaches may be considered, according to the scientific problem, from simple combination of images to statistical analysis or extraction and mapping of specific spectral features. In this presentation, several cases of application on heritage objects will be presented to illustrate these different points.

CLOSING REMARKS AND BEST STUDENT PAPER AWARD

Nicolas Bonnier, Apple Inc. (US); Maria Vanrell, CVC – Universitat Autònoma de Barcelona (Spain); and Peter Morovic, HP Inc. (Spain)

16:50 – 17:00

*No proceedings paper associated with talk.

AUTHOR INDEX

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A testing paradigm for quantifying ICC profilers

Pooshpanjan Roy Biswas, Alessandro Beltrami, Joan Saez Gomez, HP Inc., Barcelona, Spain

Abstract

To reproduce colors in one system which differs from another system in terms of the color gamut, it is necessary to use a color gamut mapping process. This color gamut mapping is a method to translate a specific color from a medium (screen, digital camera, scanner, digital file, etc) into another system having a difference in gamut volume. There are different rendering intent options defined by the International Color Consortium [5] to use the different reproduction goals of the user [19].

Any rendering intent used to reproduce colors, includes profile engine decisions to do it, i.e. looking for color accuracy, vivid colors or pleasing reproduction of images. Using the same decisions on different profile engines, the final visual output can look different (more than one Just Noticeable Difference[16]) depending on the profile engine used and the color algorithms that they implement.

Profile performance substantially depends on the profiler engine used to create them. Different profilers provide the user with varying levels of liberty to design a profile for their color management needs and preference. The motivation of this study is to rank the performance of various market leading profiler engines on the basis of different metrics designed specifically to report the performance of particular aspects of these profiles. The study helped us take valuable decisions regarding profile performance without any visual assessment to decide on the best profiler engine.

Keywords: ICC, metrics, invertibility, round trip, gray balance, gamut mapping, Fogra, gamut volume etc

Introduction

Color management can be achieved using a variety of workflows [17]. ICC profiles form an integral part of cross device color communication. HP Latex printers [12] use ICC color management to convert colors from one device space to another. This is done by translating color information from a device dependent color space (printer CMYK, printer RGB etc) to a device independent color space (ex CIELAB. CIEXYZ etc). There are ways to characterize the device in this particular direction [11], referred to as the forward transform[10] which is done by printing a particular sampling of the device color space and then measuring the samples with a spectrophotometer or colorimeter, to establish the relation between the device color space and the independent color space.

Printing happens using the reverse part of the transform [10]. The image to be printed can be in any RGB or CMYK color space, but the final printing to be done on a particular device's CMYK space needs to undergo the ICC color management workflow. This happens by first converting to the device independent space using a forward transform, and finally for the printing to happen, it needs to use the reverse transform to translate to the device CMYK (dCMYK). The reverse transform needs the computation involved as the mapping now becomes from three to four dimensions (a point has the opportunity to be mapped to any point on a line). The process of inversion from CIELAB to dCMYK also involves decision regarding the black generation, which is an important factor for printing to control the grain and ink efficiency. This mapping might lead to an imbalance in the gray neutrality of mapped colors which can deeply influence color casts. Finally, from a gamut volume point of view, all these factors decide how many colors can be accessed by the printer in the device independent space and can be finally reproduced.

As most of these aspects are related to the colorimetric tag of the ICC profiles, these can be quantified using various metrics as have been done in the past with some studies [8] [7] and as suggested by the ICC itself [4]. In this study we modify and improve the existing metrics and create some new ones to quantify missing aspects. Hence, scores are reported according to our evaluation metrics. The intention of this study was to use only quantitative metrics instead of psychometric evaluation to avoid subjective and preferential aspects. This research is concentrated to have a single green-button approach for an ICC profile's performance without the requirement of printing any physical samples or visual assessment of the profile applied images/reproductions.

Profilers

Four ICC profilers were part of this study. These profilers have completely different color engines having different algorithms inside them. We name the profiles from these profilers as Profile 1,2,3 and 4 respectively. Accessible gamut has been calculated treating profile 1 as the reference profile to see relative increase/decrease, but the same methodology can be used to get absolute numbers. Profiles 2,3 and 4 were generated using the best settings provided by the profiler softwares in terms of black generation, GCR etc [20], All the profiles except profile 2 (which required a custom target characterization chart) were created using the same target chart (ECI 2002[13]) and printed using the same state of the printer to avoid any changes in the printer behaviour. The printer in discussion is an HP inkjet printer using Latex inks [12].

Metrics

In the subsequent sections all the metrics are defined for this study later followed by their results.

Forward Transform Accuracy of the Colorimetric Tag (A2B1)

This is an initial flag test to identify if the A2B1 tag of the ICC profile is a close match to the actual measurements of the target chart used in terms of their color difference (CIEDE2000 [14]). This is a requirement implicitly defined in the ICC conformations [19]. The A2B1 tag is encoded in relative colorimetry which is first converted to absolute colorimetry for this test. Sometimes, if the measurements are not respected in the A2B1 tag, this can result into unnecessary profile inversion problems, unless these changes are intentionally done. Since all the profiles used embed all the color transformations in the LUT, and the A2B1 tag contains the relative colorimetric values, the absolute colormetric values were extracted using the guidelines in ICC.1:2004-10 (section 6.3.2) [19]. These 16-bit values were then converted to the respective ranges of L*, a* and b* and compared to the original CIELAB using CIEDE2000 [14] color difference formula for the node points of the CMYK quadruples of the actual target chart.

Profile Inversion

ICC specification ICC. 1:2004-10 [19] define that the A2B1 transform should be based on the measurements used for creating the profile. Ideally, to achieve proper preview and proofing goals, the BtoA1 transform should also be an exact inverse of the A2B1 tag but this does not happen usually due to various reasons like interpolation due to different in sizes of the forward and reverse transform LUTs, black generation and ink limiting preferences etc[10]. The inversion accuracy of a profile can be done by doing a round-trip of the all the in-gamut colors[10]. Out of gamut/boundary colors contribute to gamut mapping decisions and are bound to have a non-invertible response when round tripped. For in-gamut color, the inversion should hold true. This is done by following the algorithm below.

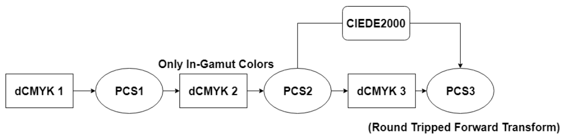

Figure 1. *Round trip error calculation algorithm.*

By passing the original dCMYK sampling through the extra step of PCS 1 and then to PCS 2 ensures that in PCS2 only in-gamut colors have been converted to CIELAB as PCS1 already had only the reproducible (in-gamut) CIELABs[10][Fig 1]. The CMYK values were incremented in each channel in steps of 2 as steps of 1 made the iteration computationally very expensive. Comparing the PCS2 to PCS3 CIELABs using the CIEDE2000 gave us the round-trip accuracy. The mean and the max round trip errors were reported. Top 2 percentile of the errors were reported in terms of CIELAB coordinates to identify which are the worst colors for round tripping, and if they follow a trend in terms of the primary colors being moved intentionally.

Accessible Gamut

Accessible gamut is defined by the total gamut that can be reproduced by an output device taking into account the physical limits of the device, for ex, the ink coverage, ink behavior etc [1] of the printer. As it is not possible to have a perfect dense modelling of the relationship between the total ink space sampling and their colorimetry, the gamut of a device is created by applying different gamut boundary descriptors' algorithms[1] to a sampling of the device space's colorimetric measurements. For this test, we evaluated the accessible printer gamut for the absolute and perceptual cases. A 33 node uniform sampling of the CIELAB color space is converted to dCMYK using the absolute and perceptual tag. The algorithm that a profiler applies to calculate the reverse transform, B2A, defines how the original CIELAB sampling would be converted to the dCMYK in this case. These constitute the final CMYK combinations that can be printed on the device using the B2A reverse transform incorporating the black generation and gamut mapping algorithms[1][17]. These dCMYKs are converted to CIELAB again using the A2B in absolute colorimetry to predict how they finally appear for the absolute and perceptual cases. As the B2A tables for the first step are different for each profiler for this test, this translates to different CIELABs in the final step and this impacts the gamut boundary of a particular device[1]. The CIELABs are then triangulated[6] to create the gamut boundary of the points using the convex hull algorithm[2][Fig 2]. This gave us the accessible gamut volume of the of all the profiles in CIELAB units.

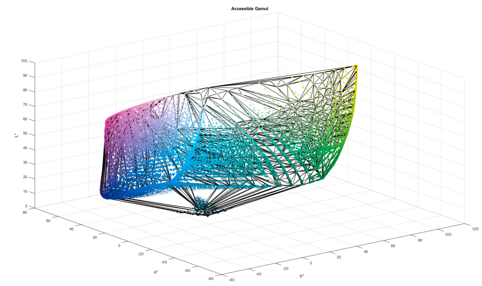

Figure 2. *MATLAB tool to visualize the accessible gamut using convex hull[2], CIELAB color space.*

Spot Color Library Coverage

For spot colors, it is imperative to have a close match to their colorimetry. If a Spot color lies inside the reproducible gamut of the profile, it can be printed with good accuracy. Spot colors can be emulated using an ICC profile by using the absolute colorimetric tag (B2A1) of the ICC profile. For this test, we used the Fogra53[9][Fig 3] characterization data as a pseudo spot color dataset but the same methodology can be applied to any standard spot color libraries to replicate the intended results.

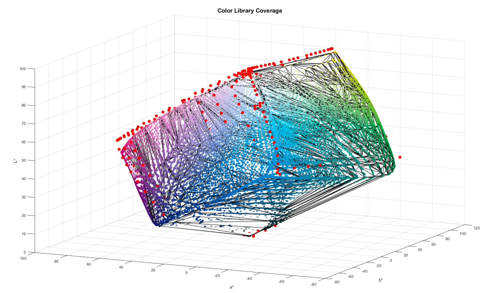

Figure 3. *Fogra53[9] dataset (red circles) plotted with the accessible gamut of Profile 4, CIELAB color space.*

The original CIELABs from the dataset are converted to dCMYK which are again converted to CIELAB in absolute colorimetry respectively. These CIELABs are searched inside the convex hull of the accessible printer gamut using a simplex search[6][18] to find out how many colors from the dataset can be reproduced using the printer profiles.

Skintones

Skintones are an important part of a profile's pleasantness especially in the perceptual tag. Primary adjustments implicitly done in profiles' perceptual tag often incorporate an unwanted color cast on skintones, thus making some profiles undesirable, for ex, colors might be too saturated in reds, which might result in reddish skintones etc. For this test a 16bit CIELAB image of the Roman16©[3] CIELAB skintones dataset was created [Fig 5]. It was also checked that all the 37 points of the Roman16 skintones lie inside the actual device gamut [Fig 4].

This image was converted to the dCMYK using the perceptual and relative colorimetric tag respectively. How these values would finally appear after printing were calculated by changing

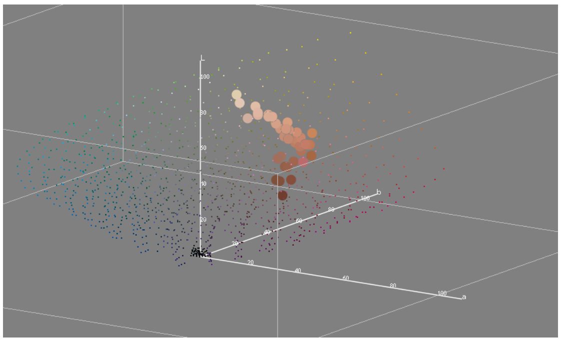

Figure 4. Visualization of the Roman16 skintones (skin colored spheres) with the actual printer gamut on the CIELAB space to show that the Roman16 skintones LAB lie inside the device gamut and can be reproduced.

these dCMYK to LABs using the absolute colorimetry. Finally, the CIEDE2000 between the original Roman16 dataset and the converted LABs were reported.

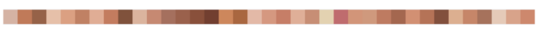

Figure 5. The Roman16 dataset converted to 16bits CIELAB image.

Gray Neutrality Index (GI)

Reproduction of gray colors is one the most sensible performance of a profiler. Usually the loss of gray neutrality comes from the printer device variability, but sometimes the ICC profile itself can introduce small deviations to the calculated gray axis that can be amplified by those printing variabilities. There are two different gray neutrality deviance (one in chroma and the other in hue angle) that we can observe and, to simplify the evaluation process, we created a single index that can combine together those deviations. Gray neutrality is expressed as the ability to reproduce the L* axis (a*=b*=0). Even if every device or every printing standard can have a different definition of gray reproduction, all will lie in that region.

$$GI = \overline{\Delta C^*} \cdot \left[\frac{\sigma(\Delta h)}{2\pi} + 1 \right]$$

The formula used for the GI link together the average difference of chroma (ΔC* in LCh color space), that express the possible deviation from the neutrality, with the standard deviation of the hue (Δh in LCh color space) that express the presence of opposite hues around the neutral axis. This is because if the gray axis is not perfectly neutral, to have different hues at different L* levels (so called "rainbow effect")[Fig 6] is worse than a constant deviation with a small hue range.

The GI will raise up if the average of chroma is high or if the standard deviation of hue differences are high, or both. This index does not represent a new color space or perceptually uniform metric but is just a metric to be used comparing an attribute (gray-neutrality) that can present two types of deviations (chroma deviation and hue variations) as a root cause. This test was implemented by converting a pure L* image in steps of 1 with (a*=0,b*=0) and converting it using the colorimetric tag to predict how much chroma and hue is added to the pure neutral image in terms of the GI.

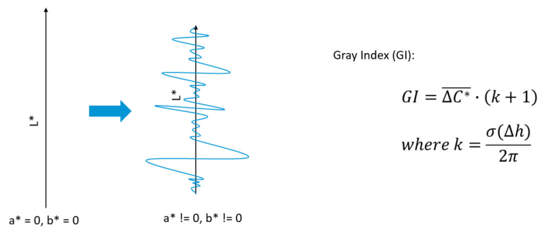

Figure 6. The Gray Neutrality Index (GI)

Out of Gamut to In-Gamut Transition

When out of gamut colors are converted to in-gamut using a profile, due to different gamut mapping techniques, there can be loss in the transition trend that was present originally between the original colors and the gamut mapped colors[17]. For a perceptual match to screen or the original, the out of gamut colors, once mapped inside the gamut should follow a similar transition trend. For this test 6 PRMG [19] primaries and secondaries were used (RGBCMY). PRMG lightness, chroma and hue angles were acquired by the ICC specification for the v4 profiles[19]. The profile's gamut boundary colors in the perceptual accessible gamut were extracted (B2A0 then A2B1 in absolute colorimetry). These points were first scanned in the L* range [-5 to +5 L* units of the PRMG primaries and secondaries] on the printer's accessible perceptual gamut boundary colors to find the closest L* match, and then the least match with respect to the hue angle was found. This defined the vector for the chroma search. Now the chroma was reduced in steps of 1 Chroma unit till the CIELAB of the gamut boundary color of the respective profiles were reached. For each of these points on the gamut boundary, the chroma was found out [Fig 7,8]. As the original vector had a constant chroma difference of 1 unit, thus resulting in original standard deviation of 0 unit for the consecutive Chroma differences, the gamut mapped Chroma differences also should have similar standard deviation.

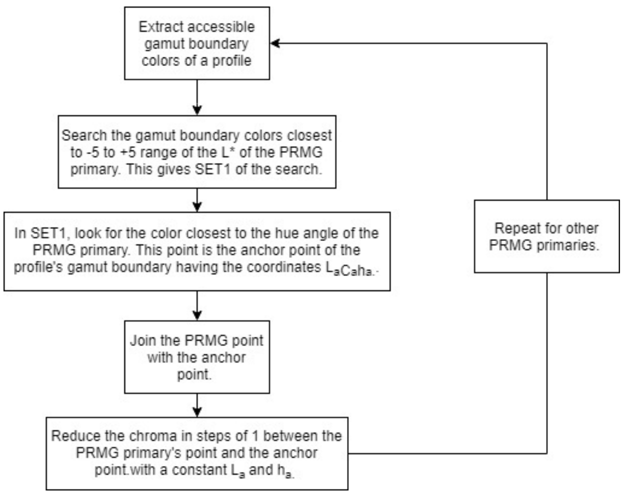

Figure 7. Algorithm describing the method of quantifying change in chroma after perceptual gamut mapping

Tools Used

The printer in discussion is an HP inkjet printer using Latex inks and Avery Dennison MPI3001 self-adhesive media printed with an 8 passes high quality printmode. Different target charts

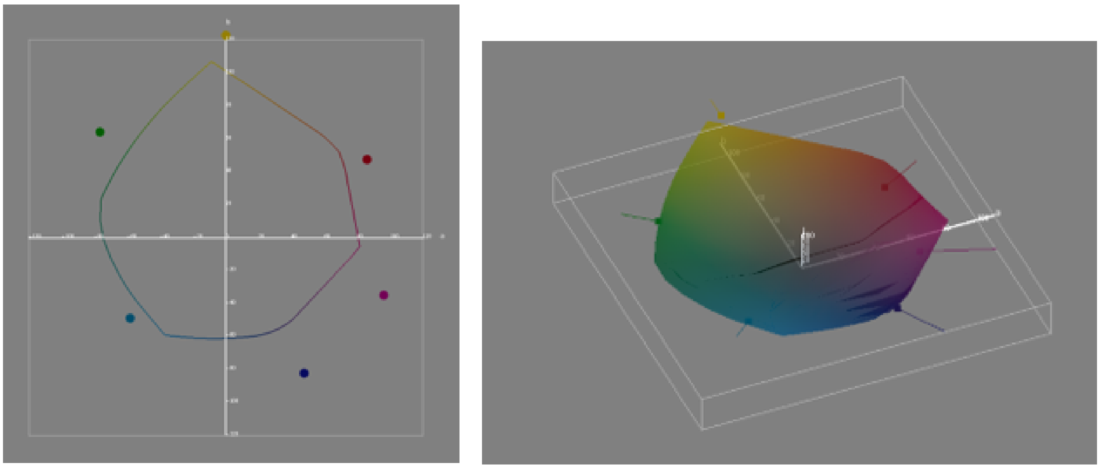

Figure 8. (Left) The PRMG primaries projected into the CIEab plane with a profile's perceptual accessible gamut. (Right) An example of the anchor points on the accessible gamut boundary and the search vector joining the PRMG primaries to them. This defines the search direction by reducing the chroma, keeping the L and hue angle constant. CIELAB space.*

were printed matching the requirements and demands of the profiler softwares respectively. The printed charts were measured using a Konica Minolta FD7 spectrophotometer. All the testing was done using the littleCMS [15] open source color management engine's C++ library and the data was processed using python's numpy library and Matlab 2017b.

Results

Overall results for all the tests are summarized in Table 1. The A2B1 colorimetric accuracy is very good for all the profilers except profiler 3. This implies that this profiler does some modifications to the actual measurements of the target chart used to create the profile and this reflects in the colorimetric tag of this profile. Profile 3 has the best round-trip average as well as the least round-trip maximum. During this test, the color coordinates having the highest two percentiles for the CIEDE2000 errors were identified. This helped us identify if there are certain colors that have worse invertibility. In Figure 9, the top 2 percentile errors of profile 4 for the round-trip can be seen.

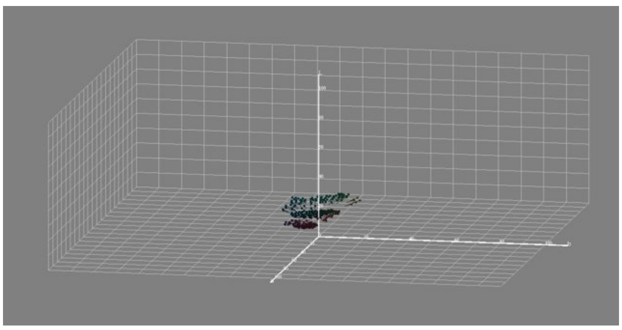

Figure 9. Top 2 percentile of Round Trip Errors for profile 4 were concentrated in the shadow regions.

For profile 4, there is worse invertibility for dark colors [Fig 9]. The length of the arrows signify the magnitude of the CIEDE2000 between the original CIELABs (PCS2) and the round tripped CIELABs (PCS3). The accessible perceptual gamut was compared to the reference Profile 1. Profiler 4 has the highest accessible gamut ratio among all the profilers as well as the highest Fogra53 coverage. All the profiles performed quite bad in terms of preserving the Roman16 skintones as can be seen by the high CIEDE2000 values using the perceptual or the relative colorimetric workflow. Profile 4 has the best gray neutrality among the four profiles as can be seen by the low GI value. This means that a pure neutral CIELAB after the ICC application emerges out having the least chroma or hue added to the gray axis. This has a big impact on how the profile deals with pure neutral colors as there won't be any color cast on the neutral colors.

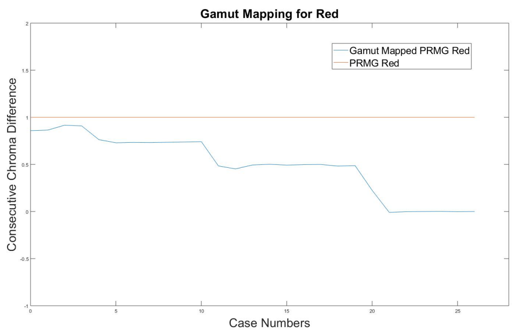

Figure 10. An example of the anchor points on the accessible gamut boundary and the search vector joining the PRMG primaries to them. This defines the search direction by reducing the chroma, keeping the L and hue angle constant in CIELAB space.*

An example of the change in chroma after gamut mapping can be seen in Fig 10. Out of gamut to in-gamut mapping is reported in terms of the standard deviation for the gamut mapped chroma [Table 2]. Profile 2 has better performance than the other profilers in mapping out of gamut colors except the yellow. It successfully conserves the chroma difference between the original colors which would lead to a reproduction with better transitions in terms of chroma for out of gamut colors.

In general, profile 2 and 4 have better performance than the rest with profile 4 performing better in gamut coverage and gray

Table 1: Metric results for all the tests. The last column defines the metric reported.

	Profiler 1	Profiler 2	Profiler 3	Profiler 4	Metric
Accuracy A2B1	0,27	0,12	0,61	0,25	CIEDE2000
Profile Inversion (RoundTrip Average)	1,26	0,31	0,19	0,39	CIEDE2000
Profile Inversion (RountTrip Maximum)	2,41	2,33	2,32	2.51	CIEDE2000
Accessible Printer Gamut (Abs)	(ref)	102%	99.9%	107.38%	% Coverage
Accessible Printer Gamut (Perc)	(ref)	102.05%	100.63%	108.34%	% Coverage
Gray Neutrality	0,28	0,31	0,30	0,19	GI
Spot Color Library Coverage	79,41%	80,09%	79,41%	81,82%	% Coverage
Skintones Perceptual	2.82	2.92	3.46	3.36	Max CIEDE2000
Skintones RelativeCol	3.24	3.65	3.38	3.45	Max CIEDE2000

Table 2: Standard deviation of the vector connecting PRMG primaries and secondaries and the anchor point found on the gamut boundary of all the profiles using the algorithm described in Figure 7.

PRMG	Red	Yellow	Green	Cyan	Blue	Magenta
Profiler 1	0.32	0.01	0.13	0.05	0.16	0.3
Profiler 2	0.06	0.39	0.09	0.09	0.19	0.08
Profiler 3	0.22	0.36	0.09	0.05	0.21	0.02
Profiler 4	0.28	0.5	0.19	0.05	0.06	0.01

neutrality. Profile 1 has the worst performance in terms of invertibility, gamut coverage and skin tone reproduction. The higher CIEDE2000 for skin-tones can be due to the primary adjustments affecting the color gamut region around skin-tones. All the profiles except profile 4 have worse performance in gray neutrality, which could lead to a color cast on the final printing.

Conclusions

Four different profiler engines were compared in this study quantitatively with a motive of having a completely digital workflow for evaluating profiles. Different weak points of the profilers' performance were identified. This enabled us to take valuable decisions regarding their utility. Some aspects have been left for future investigations, for example, quantifying gamut mapping in terms of lightness and hue preservation, quantifying GCR[20] performance, graininess etc.

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