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TECHNICAL PROGRAM: SCHEDULE AND ABSTRACTS

DAY 1
MONDAY 1 NOVEMBER / TUESDAY 2 NOVEMBER

WELCOME AND OPENING KEYNOTE

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

1 NOV: 10:00 – 11:10 NY / 15:00 – 16:10 PARIS / 23:00 – 00:10 TOKYO

Welcome Remarks

Sessions Host: Peter Morovic, HP Inc. (Spain)

Some of the Interesting Challenges of Developing the HoloLens Sensor Array, and Some Fun and Hard Imaging Problems Ahead, *Andy Goris, formerly Microsoft HoloLens, HP Camera Division, and HP Computer Graphics Lab (US)* [abstract only; no proceedings paper]

The HoloLens augmented reality computer has nine cameras of five types, including monochrome visible light, infrared, and color. These cameras sample the user's motion, gaze, and hands, as well as the world the user works in. The color camera sends video to remote people working in real time with the HoloLens wearer. The first part of this talk describes a few of the interesting problems developing these cameras. The second part cover some new and hard problems ahead for cameras and image processing that will require machine learning, a deeper understanding of information theory, and an understanding of the human visual experience below the conscious level.

ONLINE ICEBREAKER/WELCOME RECEPTION

1 NOV: 11:10 – 11:50 NY / 16:10 – 16:50 PARIS
2 NOV: 00:10 – 00:50 TOKYO

Meet other attendees in the CIC29 Gather.town for a fun event designed to help you meet new colleagues. After brief introductions, attendees answer the following questions as they wish and see where the conversation leads. What's the most fun color-related experience you've had? What color-related paper or book you've read has impressed or inspired you most? What is your pet peeve about commonly-stated color "facts"? Everyone is highly encouraged to attend!

CAMERA COLOR

Session Chair: Michael Brown, York University (Canada)

1 NOV: 11:50 – 12:50 NY / 16:50 – 17:50 PARIS
2 NOV: 00:50 – 01:50 TOKYO

11:50 (New York) / 16:50 (Paris)
00:50 (Tokyo)

Designing a Color Filter with High Overall Transmittance for Improving the Color Accuracy of Digital Cameras, *Yuteng Zhu and Graham D. Finlayson, University of East Anglia (UK)* **1**

Previously improved color accuracy of a given digital camera was achieved by carefully designing the spectral transmittance of a color filter to be placed in front of the camera. Specifically, the filter is designed in a way that the spectral sensitivities of the camera after filtering are approximately linearly related to the color matching functions (or tristimulus values) of the human visual system. To avoid filters that absorbed too much light, the optimization could incorporate a minimum per wavelength transmittance constraint.

In this paper, we change the optimization so that the overall filter transmittance is bounded, i.e. we solve for the filter that (for a uniform white light) transmits (say) 50% of the light. Experiments demonstrate that these filters continue to solve the color correction problem (they make cameras much more colorimetric). Significantly, the optimal filters by restraining the average transmittance can deliver a further 10% improvement in terms of color accuracy compared to the prior art of bounding the low transmittance.

12:10 (New York) / 17:10 (Paris)
01:10 (Tokyo)

GamutNet: Restoring Wide-gamut Colors for Camera-captured Images, *Hoang Le[1], Taehong Jeong[2], Abdelrahman Abdelhamed[3], Hyun Joon Shin[4], and Michael Brown[1]; [1]York University (Canada), [2]MAXST (Republic of Korea), [3]Samsung AI Center (Canada), and [4]Ajou University (Republic of Korea)* **7**

Most cameras still encode images in the small-gamut sRGB color space. The reliance on sRGB is disappointing as modern display hardware and image-editing software are capable of using wider-gamut color spaces. Converting a small-gamut image to a wider-gamut is a challenging problem. Many devices and software use colorimetric strategies that map colors from the small gamut to their equivalent colors in the wider gamut. This colorimetric approach avoids visual changes in the image but leaves much of the target wide-gamut space unused. Noncolorimetric approaches stretch or expand the small-gamut colors to enhance image colors while risking color distortions. We take a unique approach to gamut expansion by treating it as a restoration problem. A key insight used in our approach is that cameras internally encode images in a wide-gamut color space (i.e., ProPhoto) before compressing and clipping the colors to sRGB's smaller gamut. Based on this insight, we use a softwarebased camera ISP to generate a dataset of 5,000 image pairs of images encoded in both sRGB and ProPhoto. This dataset enables us to train a neural network to perform wide-gamut color restoration. Our deep-learning strategy achieves significant improvements over existing solutions and produces color-rich images with few to no visual artifacts.

12:30 (New York) / 17:30 (Paris)
01:30 (Tokyo)

The Discrete Cosine Maximum Ignorance Assumption, *Graham D. Finlayson[1], Javier Vazquez-Corral[2], and Fufu Fang[1]; [1]University of East Anglia (UK) and [2]Universitat Autònoma de Barcelona (Spain)* **13**

The performance of colour correction algorithms are dependent on the reflectance sets used. Sometimes, when the testing reflectance set is changed the ranking of colour correction algorithms also changes. To remove dependence on dataset we can make assumptions about the set of all possible reflectances. In the Maximum Ignorance with Positivity (MIP) assumption we assume that all reflectances with per wavelength values between 0 and 1 are equally likely. A weakness in the MIP is that it fails to take into account the correlation of reflectance functions between wavelengths (many of the assumed reflectances are, in reality, not possible).

In this paper, we take the view that the maximum ignorance assumption has merit but, hitherto it has been calculated with respect to the wrong coordinate basis. Here, we propose the Discrete Cosine Maximum

Ignorance assumption (DCMI), where all reflectances that have coordinates between max and min bounds in the Discrete Cosine Basis coordinate system are equally likely. Here, the correlation between wavelengths is encoded and this results in the set of all plausible reflectances 'looking like' typical reflectances that occur in nature. This said the DCMI model is also a superset of all measured reflectance sets.

Experiments show that, in colour correction, adopting the DCMI results in similar colour correction performance as using a particular reflectance set.

1 Nov: 12:50 – 13:20 (New York) / 17:50 – 18:20 (Paris)
2 Nov: 01:50 – 02:20 (Tokyo)
SESSION BREAK / POSTERS AVAILABLE FOR VIEWING
Join speakers and other attendees in the CIC29 Gather.town.

SPECTRA

Session Chair: Michael Brown, York University (Canada)
1 NOV: 13:20 – 14:20 NY / 18:20 – 19:20 PARIS
2 NOV: 02:20 – 03:20 TOKYO

13:20 (New York) / 18:20 (Paris)
02:20 (Tokyo)
Investigating the Upper-bound Performance of Sparse-coding-based Spectral Reconstruction from RGB Images, *Yi-Tun Lin and Graham D. Finlayson, University of East Anglia (UK)* **19**
In Spectral Reconstruction (SR), we recover hyperspectral images from their RGB counterparts. Most of the recent approaches are based on Deep Neural Networks (DNN), where millions of parameters are trained mainly to extract and utilize the contextual features in large image patches as part of the SR process. On the other hand, the leading Sparse Coding method 'A+'—which is among the strongest point-based baselines against the DNNs—seeks to divide the RGB space into neighborhoods, where locally a simple linear regression (comprised by roughly 102 parameters) suffices for SR.

In this paper, we explore how the performance of Sparse Coding can be further advanced. We point out that in the original A+, the sparse dictionary used for neighborhood separations are optimized for the spectral data but used in the projected RGB space. In turn, we demonstrate that if the local linear mapping is trained for each spectral neighborhood instead of RGB neighborhood (and theoretically if we could recover each spectrum based on where it locates in the spectral space), the Sparse Coding algorithm can actually perform much better than the leading DNN method. In effect, our result defines one potential (and very appealing) upper-bound performance of point-based SR.

13:40 (New York) / 18:40 (Paris)
02:40 (Tokyo)
Spectral-reflectance Estimation under Multiple Light Sources, *Shoji Tominaga, Norwegian University of Science and Technology (Norway) / Nagano University (Japan)* **25**
We describe a comprehensive method for estimating the surface-spectral reflectance from the image data of objects acquired under multiple light sources. This study uses the objects made of an inhomogeneous dielectric material with specular highlights. A spectral camera is used as an imaging system. The overall appearance of objects in a scene results from the chromatic factors such as reflectance and illuminant and the shading terms such as surface geometry and position. We first describe the method of estimating the illuminant spectra of multiple light sources based on detecting highlights appearing on object surfaces. The highlight candidates are detected first, and then some appropriate highlight areas are interactively selected among the candidates. Next, we estimate the spectral reflectance from a wide area selected from an object's surface. The color signals observed from the selected area are described using the estimated illuminant spectra, the surface-spectral reflectance, and the shading terms. This estimation utilizes the fact that the definition domains of reflectance and shading terms are different in each other. We develop an iterative algorithm for estimating the reflectance and the shading terms in two steps repeatedly. Finally, the feasibility of the proposed method is confirmed in an experiment using everyday objects under the illumination environment with multiple light sources.

14:00 (New York) / 19:00 (Paris)
03:00 (Tokyo)
Investigating the Kokhanovsky Snow Reflectance Model in Close-range Spectral Imaging, *Mathieu Nguyen, Jean-Baptiste Thomas, and Ivar Farup, Norwegian University of Science and Technology (Norway)* **31**
The internal structure of the snow and its reflectance function play a major contribution in its appearance. We investigate the snow reflectance model introduced by Kokhanovsky and Zege in a close-range imaging scale. By monitoring the evolution of melting snow through time using hyperspectral cameras in a laboratory, we estimate snow grain sizes from 0.24 to 8.49 mm depending on the grain shape assumption chosen. Using our experimental results, we observe differences in the reconstructed reflectance spectra with the model regarding the spectra's shape or magnitude. Those variations may be due to our data or to the grain shape assumption of the model. We introduce an effective parameter describing both the snow grain size and the snow grain shape, to give us the opportunity to select the adapted assumption. The computational technique is ready, but more ground truths are required to validate the model.

Break in program to accommodate time zones

IMPROVING DISPLAYS

Session Chair: Tommy Wei, The Hong Kong Polytechnic University (Hong Kong)
1 NOV: 19:00 – 20:10 NY
2 NOV: 00:00 – 01:10 PARIS / 08:00 – 09:10 TOKYO

19:00 (New York)
00:00 (Paris) / 08:00 (Tokyo)
Welcome Remarks
Sessions Host: Michael Murdoch, RIT (US)

Methods to Improve Colour Mismatch between Displays, *Keyu Shi[1] and Ming Ronnier Luo[1,2]; [1]Zhejiang University (China) and [2]Leeds University (UK)* **37**
With the rapid development of display technology, the colour mismatch of the colours having same tristimulus values between devices is an urgent problem to be solved. This is related to the well-known problem of observer metamerism, caused by the spectral power distribution (SPD) of primaries and the difference between individual observers' and the standard CIE colour matching functions. An experiment was carried out for 20 observers to perform colour matching of colour stimuli with a field-of-view of 4° between 5 displays, including two LCD and two OLED, against a reference LCD display. The results were used to derive a matrix-based colour correction

method. The method was derived from colorimetric visually matched colorimetric data. Furthermore, different colour matching functions were evaluated to predict the degree of observer metamerism. The results showed that the correction method gave satisfactory results. Finally, it was found that the use of 2006 2° colour matching function outperformed 1931 2° CMFs with a large margin, most marked between an OLED and an LCD display.

19:30 (New York)
00:30 (Paris) / 08:30 (Tokyo)
Effects of Display and Ambient Illuminance on Visual Comfort for Reading on a Mobile Device, *Yu Liu and Ming Ronnier Luo, Zhejiang University (China)* **42**
A psychophysical experiment was carried out to investigate visual comfort when reading on three OPPO Find X3s displays at three luminance levels (100, 250 and 500 cd/m^2) at five illuminance levels (0, 10, 100, 500 and 1000 lx). Twenty young observers evaluated visual comfort using a 6-category points method. The results showed that observers felt most comfortable at the illuminance of 500 lx or display luminance of 500 cd/m^2. There was an interaction between ambient illuminance and display luminance. High ambient light and display brightness levels provide a more pleasant visual experience. In low ambient light, however, the lower the brightness level, the more comfortable it is to see. Regarding the influence of background colour on visual comfort, the observers felt more comfortable having a grey background than white or black colour. When at dim illuminance, the background colour would have a great influence on visual comfort for negative contrast conditions, but when at higher illuminance, different background lightness levels had a great impact on visual comfort for positive contrast conditions. The above findings are very similar to the display luminance levels of 100 and 250 cd/m^2.

19:50 (New York)
00:50 (Paris) / 08:50 (Tokyo)
JIST-first Preliminary Result on the Direct Assessment of Perceptible Simultaneous Luminance Dynamic Range, *Fu Jiang and Mark D. Fairchild, Rochester Institute of Technology (US)* **47**
The human visual system is capable of adapting across a very wide dynamic range of luminance levels; values up to 14 log units have been reported. However, when the bright and dark areas of a scene are presented simultaneously to an observer, the bright stimulus produces significant glare in the visual system and prevents full adaptation to the dark areas, impairing the visual capability to discriminate details in the dark areas and limiting simultaneous dynamic range. Therefore, this simultaneous dynamic range will be much smaller, due to such impairment, than the successive dynamic range measurement across various levels of steady-state adaptation. Previous indirect derivations of simultaneous dynamic range have suggested between 2 and 3.5 log units. Most recently, Kunkel and Reinhard reported a value of 3.7 log units as an estimation of simultaneous dynamic range, but it was not measured directly. In this study, simultaneous dynamic range was measured directly through a psychophysical experiment. It was found that the simultaneous dynamic range is a bright-stimulus-luminance dependent value. A maximum simultaneous dynamic range was found to be approximately 3.3 log units. Based on the experimental data, a descriptive log-linear model and a nonlinear model were proposed to predict the simultaneous dynamic range as a function of stimulus size with bright-stimulus luminance-level dependent parameters. Furthermore, the effect of spatial frequency in the adapting pattern on the simultaneous dynamic range was explored. A log parabola function, representing a traditional Contrast Sensitivity Function (CSF), fitted the simultaneous dynamic range data well.

1 Nov: 20:10 – 20:30 (New York)
2 Nov: 01:10 – 01:30 (Paris) / 09:10 – 09:30 (Tokyo)
SESSION BREAK / POSTERS AVAILABLE FOR VIEWING
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INTERPRETATIONS

Session Chair: Tommy Wei, The Hong Kong Polytechnic University (Hong Kong)
1 NOV: 20:30 – 21:10 NY
2 NOV: 01:30 – 02:10 PARIS / 09:30 – 10:10 TOKYO

20:30 (New York)
01:30 (Paris) / 09:30 (Tokyo)
Color Layer Scissioning in See-through Augmented Reality, *Tucker Downs and Michael Murdoch, Rochester Institute of Technology (US)* **60**
Color appearance of transparent objects is not adequately described by colorimetry or color appearance models. Despite the fact that the retinal projection of a transparent object is a combination of its color and the background, measurements of this physical combination fail to predict the saliency with which we perceive the object's color. When the perceive color forms in the mind, awareness of their physical relationship separates the physical combination into two unique perceptions. This is known as color scissioning.

In this paper a psychophysical experiment utilizing a seethrough augmented reality display to compare virtual transparent color samples to real color samples is described and confirms the scissioning effect for lightness and chroma attributes. A previous model of color scissioning for AR viewing conditions is tested against this new data and does not satisfactorily predict the observers' perceptions. However, the model is still found to be a useful tool for analyzing the color scissioning and provides valuable insight on future research directions.

20:50 (New York)
01:50 (Paris) / 09:50 (Tokyo)
Visual Perception of Surface Properties through Manipulation, *James Ferwerda and Snehal Padhye, Rochester Institute of Technology (US)* . . . **66**
Vision is a component of a perceptual system whose function is to support purposeful behavior. In this project we studied the perceptual system that supports the visual perception of surface properties through manipulation. Observers were tasked with finding dents in simulated flat glossy surfaces. The surfaces were presented on a tangible display system implemented on an Apple iPad, that rendered the surfaces in real time and allowed observers to directly interact with them by tilting and rotating the device. On each trial we recorded the angular deviations indicated by the device's accelerometer and the images seen by the observer. The data reveal purposeful patterns of manipulation that serve the task by producing images that highlight the dent features. These investigations suggest the presence of an active visuo-motor perceptual system involved in the perception of surface properties, and provide a novel method for its study using tangible display systems.

DAY 2
TUESDAY 2 NOVEMBER / WEDNESDAY 3 NOVEMBER

IMAGE QUALITY

Session Chair: Marius Pedersen, Norwegian University of Science and Technology (Norway)
2 NOV: 08:30 – 09:40 NY / 13:30 – 14:40 PARIS / 21:30 – 22:40 TOKYO

08:30 (New York) / 13:30 (Paris) / 21:30 (Tokyo)
Welcome Remarks
Sessions Host: Peter Morovic, HP Inc. (Spain)

08:40 (New York) / 13:40 (Paris) / 21:40 (Tokyo)
Image Enhancement for Colour Deficiency via Gamut Mapping, *Lihao Xu, Hangzhou Dianzi University, and Qiang Xu and Ming Ronnier Luo, Zhejiang University (China)* **71**
This paper describes a colour image enhancement method for those having colour-vision deficiencies. The proposed method can be divided into 3 stages. Firstly, a conversion relation between the wavelength shift (measured in nanometers) of a colour deficient observer (CDO) and the severity of colour deficiency was established. Secondly, the perceived colour gamut was built by applying the conversion relation. Finally, the original images were re-coloured by adopting a gamut mapping algorithm to map colours from the gamut of colour normal observer (CNO) to that of a CDO. Psychophysical experiments were then conducted to show the effectiveness of the method.

09:00 (New York) / 14:00 (Paris) / 22:00 (Tokyo)
The Development of Three Image Quality Evaluation Metrics based on a Comprehensive Dataset, *Dalin Tian, Muhammad Usman Khan, and Ming Ronnier Luo, Zhejiang University (China)*. **77**
In this study, a large scale experiment was carried out to assess the image quality of 2266 images using categorical judgement method by 20 observers. These images were rendered in color contrast, chroma, colorfulness, lightness, and vividness directions. The results were used to derive three No-Reference (NR) Image Quality Estimation Models (IQEMs). The first model was based on color science, (different scales in CIELAB). The second model was a Neural Network model while the third model was a statistics model based on color appearance attributes. Their performances were evaluated using two databases, those developed at Zhejiang University and those available from the public databases in terms of correlation coefficients between the objective and predicted image quality scores.

09:20 (New York) / 14:20 (Paris) / 22:20 (Tokyo)
How Good is Too Good? A Subjective Study on Over Enhancement of Images, *Sahar Azimian and Farah Torkamani Azar, Shahid Beheshti University (Iran); and Seyed Ali Amirshahi, Norwegian University of Science and Technology (Norway)* **83**
For a long time different studies have focused on introducing new image enhancement techniques. While these techniques show a good performance and are able to increase the quality of images, little attention has been paid to how and when over-enhancement occurs in the image. This could possibly be linked to the fact that current image quality metrics are not able to accurately evaluate the quality of enhanced images. In this study we introduce the Subjective Enhanced Image Dataset (SEID) in which 15 observers are asked to enhance the quality of 30 reference images which are shown to them once at a low and another time at a high contrast. Observers were instructed to enhance the quality of the images to the point that any more enhancement will result in a drop in the image quality. Results show that there is an agreement between observers on when over-enhancement occurs and this point is closely similar no matter if the high contrast or the low contrast image is enhanced.

2 Nov: 9:40 – 10:00 (New York) / 14:40 – 15:00 (Paris) / 22:40 – 23:00 (Tokyo)
SESSION BREAK / POSTERS AVAILABLE FOR VIEWING
Join speakers and other attendees in the CIC29 Gather.town.

TUESDAY KEYNOTE AND IS&T AWARDS

Session Chair: Jeremie Gerhardt, Faurecia IRYStec Inc. (Canada)
2 NOV: 10:00 – 11:00 NY / 15:00 – 16:00 PARIS / 23:00 – 00:00 TOKYO

Scene-referred Gamut Compression in ACES, *Carol Payne, Netflix (US); Matthias Scharfenberg, Industrial Light & Magic (Canada); and Nick Shaw, Antler post (UK)* [abstract only; no proceedings paper]
The Academy Color Encoding System (ACES) is an open-source color management framework used in film and TV production. One barrier to wider adoption of ACES has been its handling of values outside the working gamut.

Gamut mapping is a reasonably well-defined problem space in the context of known display and viewing conditions. However, when the image state is scene-referred, "traditional" gamut mapping approaches may not apply. This presentation walks through the research, development, testing, and implementation of the Academy Color Encoding System (ACES) Gamut Compression algorithm—the solution developed to fix out-of-gamut pixel values in a scene-referred spaces.

IS&T Award Presentations
Presenter: Susan Farnand, IS&T President

Gaurav Sharma, *2021 Raymond C. Bowman Award for educating, mentoring, and increasing knowledge of color imaging and science through university classes, conference short courses, and academic journals.*

Brian Funt and Hoda Aghaei, *Charles E. Ives Journal Award for "A Flying Gray Ball Multi-illuminant Image Dataset for Color Research," which appeared in JIST 64 #5.*

2 Nov: 11:00 – 11:30 (New York) / 16:00 – 16:30 (Paris)
3 Nov: 00:00 – 00:30 (Tokyo)
SESSION BREAK / POSTERS AVAILABLE FOR VIEWING
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COLOR CONTRAST

Session Chair: Jennifer Gille, independent (US)
2 NOV: 11:30 – 12:10 NY / 16:30 – 17:10 PARIS
3 NOV: 00:30 – 01:10 TOKYO

11:30 (New York) / 16:30 (Paris)
00:30 (Tokyo)
JPI-first Colour Conversion in Deep Autoencoders, *Arash Akbarinia and Raquel Gil-Rodriguez, Justus-Liebig University (Germany)* **89**
While RGB is the status quo in machine vision, other colour spaces offer higher utility in distinct visual tasks. Here, we investigated the impact of colour spaces on the encoding capacity of a visual system that is subject

to information compression, specifically variational autoencoders (VAEs) with a bottleneck constraint. To this end, we propose a framework—colour conversion—that allows a fair comparison of colour spaces. We systematically investigated several ColourConvNets, i.e. VAEs with different input-output colour spaces, e.g. from RGB to CIE L*a*b* (in total five colour spaces were examined). Our evaluations demonstrate that, in comparison to the baseline network (whose input and output are RGB), ColourConvNets with a colour-opponent output space produce higher quality images. This is also evident quantitatively: (i) in pixel-wise low-level metrics such as colour difference (DE), peak signal-to-noise ratio (PSNR) and structural similarity index measure (SSIM); and (ii) in high-level visual tasks such as image classification (on ImageNet dataset) and scene segmentation (on COCO dataset) where the global content of reconstruction matters. These findings offer a promising line of investigation for other applications of VAEs. Furthermore, they provide empirical evidence on the benefits of colour opponent representation in a complex visual system and why it might have emerged in the human brain.

11:50 (New York) / 16:50 (Paris)
00:50 (Tokyo)
Modeling Chromatic Contrast Sensitivity across Different Background Colors and Luminance, *Marcel Lucassen, Dragan Sekulovski, and Marc Lambooij, Signify Research (the Netherlands); and Qiang Xu and Ming Ronnier Luo, Zhejiang University (China)* **99**
In this research we compare chromatic contrast sensitivity models for two separate datasets and for the pooled dataset. They were obtained from two studies employing a very similar experimental paradigm. The data represent threshold visibilities of chromatic Gabor patterns varying in spatial frequency, background chromaticity, direction of color modulation and luminance, at constant stimulus size. Using the extended data set, we reconfirm our previously reported finding that a model based on color-opponent contrast signals is an improvement over a cone contrast model. However, when linear background scaling in classic cone contrast is replaced by nonlinear background scaling, an improvement of almost similar size is obtained. The results of this study can be of interest for the development of vision models employing the processing of spatio-chromatic information.

NOISE

Session Chair: Jennifer Gille, independent (US)
2 NOV: 12:10 – 12:50 NY / 17:10 – 17:50 PARIS
3 NOV: 01:10 – 01:50 TOKYO

12:10 (New York) / 17:10 (Paris)
01:10 (Tokyo)
Influence of Procedural Noise on the Glossiness of 2.5D Printed Patches, *Abigail Trujillo Vazquez[1], Donatela Šaric[2], Susanne Klein[1], and Carinna Parraman[1]; [1]University of the West of England (UK) and [2]Fogra Research Institute for Media Technology (Germany)* **105**
Perlin noise, a type of procedural noise, was used for the design of elevation files for 2.5D printing. This printing method uses elevation data from a height map to create physical relief by superimposing layers of ink. In this experiment, the grayscale values of noise functions were used as elevation values to build different surface structures in UV curable ink by 2.5D printing. Printed samples with varying levels of Perlin noise were created and their reflectance properties were studied by measuring the values of specular gloss. The roughness and specular gloss of the printed surfaces were effectively influenced when varying the persistence and octaves of the noise functions. The aim of implementing the procedural approach to a high-resolution printing method has been to explore the reflectance properties of custom noise functions when transferred to the physical realm. This might contribute to better understand the effect of surface structure on the appearance of materials. Potentially, this approach will enable the use of relief printing to produce structures with a more natural appearance and a desired gloss value by using a low-cost computing process.

12:30 (New York) / 17:30 (Paris)
01:30 (Tokyo)
Real World Metamer Sets: Or How We Came to Love Noise, *Peter Morovic, HP Inc. (Spain) and Jan Morovic, HP Inc. (UK)* **111**
It is well known that color formation acts as a noise-reducing lossy compression mechanism that results in ambiguity, known as metamerism. Surfaces that match under one set of conditions—an illuminant and observer or capture device—can mismatch under others. The phenomenon has been studied extensively in the past, leading to important results like metamer mismatch volumes, color correction, reflectance estimation and the computation of metamer sets—sets of all possible reflectances that could result in a given sensor response. However, most of these approaches have three limitations: first, they simplify the problem and make assumptions about what reflectances can look like (i.e., being smooth, natural, residing in a subspace based on some measured data), second, they deal with strict mathematical metamerism and overlook noise or precision, and third, only isolated responses are considered without taking the context of a response into account. In this paper we address these limitations by outlining an approach that allows for the robust computation of approximate unconstrained metamer sets and exact unconstrained paramer sets. The notion of spatial or relational paramer sets that take neighboring responses into account, and applications to illuminant estimation and color constancy are also briefly discussed.

2 Nov: 12:50 – 13:20 (New York) / 17:50 – 18:20 (Paris)
3 Nov: 01:50 – 02:20 (Tokyo)
SESSION BREAK / POSTERS AVAILABLE FOR VIEWING
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IMPROVING PRINTS

Session Chair: Andreas Kraushaar, Fogra (Germany)
2 NOV: 13:20 – 14:20 NY / 18:20 – 19:20 PARIS
3 NOV: 02:20 – 03:20 TOKYO

13:20 (New York) / 18:20 (Paris)
02:20 (Tokyo)
Color Printing on Pre-colored Textiles, *Peter Morovic[1], Jan Morovic[2], and Sergio Etchebehere[1]; [1]HP Inc. (Spain) and [2]HP Inc. (UK)* **118**
Managing color on a particular imaging system is a well-understood challenge with a wealth of existing models, methods and techniques. In the case of printing systems, these tend to operate in the context of a single substrate, where managing color on every additional substrate is approach as a separate, detached problem. While such a mind-set works reasonably well in general, it breaks down when it comes to printing onto pre-colored textiles, such as pre-dyed fabrics. The present paper therefore introduces a family of approaches that support the use of multiple pre-colored textiles on a given printing system that also allow for a balance between characterization effort and color match accuracy. This, in turn provides solutions that can fit a variety of practical working patterns to maximize overall efficiency and performance.

13:40 (New York) / 18:40 (Paris)
02:40 (Tokyo)
Estimation of BRDF Measurements for Printed Colour Samples, *Tanzima Habib, Phil Green, and Peter Nussbaum, Norwegian University of Science and Technology (Norway)* **123**
In this paper, we describe a method to estimate BRDF measurements for different printed colours, using just the BRDF measurements of the substrate and the primary inks. A model is trained using the BRDF measurements of the unprinted substrate and the cyan, magenta, and yellow inks, where four different diffuse and specular measurements of each are used as predictors to find the reflectance factor at a different lighting and viewing angle. In this approach only four spectral measurements of each test colour are required to estimate BRDF. This reduces the number of measurements required to estimate BRDF of a printed surface and to estimate the spectral reflectances that describe its material surface characteristics.

14:00 (New York) / 19:00 (Paris)
03:00 (Tokyo)
JIST-first Numerical Pathology in Selected Kubelka-Munk Formulas, and Strategies for Mitigation, *J. A. Stephen Viggiano, Rochester Institute of Technology (US)*. **129**
Causes of numerical pathology in formulas for reflectance factor (R), transmittance factor (T), and reflectance factor over a perfectly black background (R_0) under the Kubelka–Munk model are posited, and alternate formulas believed less prone to these pathologies are introduced. Suggestions are offered not only for R, T, and R_0, but also for intermediate or adjunct quantities used in the main formulas. Computational experiments were performed to verify that the new models produce the same results as the existing ones under non-pathological conditions, exhibit acceptable levels of precision in a customary floating-point environment, and are more robust with respect to edge cases where an input quantity is zero. The new formulas performed well, with some evidence that the new hyperbolic forms provide better accuracy than their exponential counterparts.

COLOR CONUNDRUMS I

2 NOV: 14:20 – 15:10 NY / 19:20 – 20:10 PARIS
3 NOV: 03:20 – 04:10 TOKYO

Join colleagues for an informal discussion about one of the color-related topics listed below. While each conundrum is led by a facilitator, the goal is for everyone to share their opinions and experiences. Choices during Color Conundrums I are:

Conundrum A:
What is HDR?
Facilitator: *Timo Kunkel, Dolby Laboratories, Inc.*
HDR is widely talked about in a multitude of contexts. On the surface, it often seems straight forward to define what HDR is. However, when starting to dig deeper, it is not that simple anymore: Is HDR a special effect? a type of image processing or encoding? a graphics technique? a series of images at different exposures? a special camera? a special display? Let's discuss what HDR means to you!

Conundrum B:
Communication of Color
Facilitator: *Philipp Urban, Fraunhofer Institute for Computer Graphics Research IGD*
Is color a separable property of objects? The physiological evidence of color channels in early vision would seem to support this view, however many color phenomena contradict this simple idea. What does this mean for how we measure, characterize, and ultimately communicate color?

Conundrum C:
Color and Vision: Beyond the Rainbow
Facilitator: *James Ferwerda, Rochester Institute of Technology*
How do processes other than those based on the spectral properties of light contribute to the perception of color? How do color illusions arise? How do simultaneous contrast, assimilation, induction colors, etc. work? What is the role of expectation? What can these phenomena tell us about color processing at all levels of the visual system?

Break in program to accommodate time zones

TWO-MINUTE INTERACTIVE PAPER PREVIEWS FOLLOWED BY INTERACTIVE PAPER POSTER SESSION A

Session Chair: Minjung Kim, Facebook Reality Labs (US)
2 NOV: 19:00 – 20:20 NY
3 NOV: 00:00 – 01:20 PARIS / 08:00 – 09:20 TOKYO

Interactive (Poster) Paper authors provide a brief overview of their work, followed by talks with authors in the CIC29 Gather.town.

Welcome Remarks
Session Host: Jeremie Gerhardt, Faurecia IRYStec Inc. (Canada)

Development of a Three-dimensional Color Rendition Space for Tunable Solid-state Light Sources, *Dorukalp Durmus, Pennsylvania State University (US)* **136**
The quality of building electric lighting systems can be assessed using color rendition metrics. However, color rendition metrics are limited in quantifying tunable solid-state light sources, since tunable lighting systems can generate a vast number of different white light spectra, providing flexibility in terms of color quality and energy efficiency. Previous research suggests that color rendition is multi-dimensional in nature, and it cannot be simplified to a single number. Color shifts under a test light source in comparison to a reference illuminant, changes in color gamut, and color discrimination are important dimensions of the quality of electric light sources, which are not captured by a single-numbered metric. To address the challenges in color rendition characterization of modern solid-state light sources, the development of a multi-dimensional color rendition space is proposed. The proposed continuous measure can quantify the change in color rendition ability of tunable solid-state light devices with caveats. Future work, discretization of the continuous color rendition space, will be carried out to address the shortcomings of a continuous three-dimensional space.

Selection of Optimal External Filter for Colorimetric Camera, *Michael Vrhel, Artifex Software, and H. Joel Trussell, North Carolina State University (US)* **141**
A database of realizable filters is created and searched to obtain the best filter that, when placed in front of an existing camera, results in improved colorimetric capabilities for the system. The image data with the external filter is combined with image data without the filter to provide a six-band system. The colorimetric accuracy of the system is quantified using simulations that include a realistic signal-dependent noise model. Using a training data set, we selected the optimal filter based on four criteria: Vora Value, Figure of Merit, training average ΔE, and training maximum ΔE. Each selected filter was used on testing data. The filters chosen using the training ΔE criteria consistently outperformed the theoretical criteria

Effect of Digitally Generated Colored Filters on Farnsworth-Munsell 100 Hue Test by Red-green Color Vision-deficient Observers, *Shunnma Saito and Keiko Sato, Kagawa University (Japan)* **148**

In this study, the effects of four different digitally generated colored filters on the Farnsworth-Munsell 100 hue test (100-hue test) are analyzed by red-green color-vision deficient (CVD) observers. We digitally simulate the colored filters based on the spectral transmittance of four colored filters, which have been used previously. Five red-green CVD observers are subjected to the 100-hue test on a monitor under nine filter conditions, which comprise one condition without filter and eight conditions with filters. The results suggest that a colored filter that transmits long wavelengths and absorbs medium wavelengths may improve the color discrimination performance of protans and deutans.

Highlighted Document Image Classification, *Yafei Mao[1], Yufang Sun[1], Peter Bauer[2], Todd Harris[2], Mark Shaw[2], Lixia Li[2], and Jan Allebach[1]; [1]Purdue University and [2]HP Inc. (US)* **154**

There are many existing document image classification researches, but most of them are not designed for use in constrained computer resources, like printers, or focused on documents with highlighter pen marks. To enable printers to better discriminate highlighted documents, we designed a set of features in CIE Lch(a*b*) space to use along with the support vector machine. The features include two gamut-based features and six low-level color features. By first identifying the highlight pixels, and then computing the distance from the highlight pixels to the boundary of the printer gamut, the gamut-based features can be obtained. The low-level color features are built upon the color distribution information of the image blocks. The best feature subset of the existing and new features is constructed by sequential forward floating selection (SFFS) feature selection. Leave-one-out cross-validation is performed on a dataset with 400 document images to evaluate the effectiveness of the classification model. The cross-validation results indicate significant improvements over the baseline highlighted document classification model.

A Digital Test Chart for Visual Assessment of Color Appearance Scales, *Mark Fairchild, Rochester Institute of Technology (US)* **160**

A digital color appearance test chart, akin to a ColorChecker® Chart for human perception, was developed and evaluated both perceptually and computationally. The chart allows an observer to adjust the appearance of a limited number of color patches to allow a quick evaluation of perceived brightness, colorfulness, lightness, saturation, and hue on a display. The resulting data can then be used to compared observed results with the predictions of various color appearance models. Analyses in this paper highlight some known shortcomings of CIELAB, CIECAM02, and CAM16. Differences between CIECAM02 and CAM16 are also highlighted. This paper does not provide new psychophysical data for model testing, it simply describes a technique to generate such data and a computational comparison of models.

Time Course Chromatic Adaptation under Highly Saturated Illuminants, *Hui Fan, Ming Ronnier Luo, and Yuechen Zhu, Zhejiang University (China)* **166**

The goal of this study was to investigate the time course characteristics of chromatic adaptation under highly saturated illuminants. A psychophysical experiment with neutral matching method was conducted on a mobile display at different luminance levels. Models of chromatic adaptation degree against duration of time were fitted using a proportional rate growth function. The upper limit and growth rate of adaptation degree were studied. It was found that higher adapting luminance and lower display luminance led to higher degree and faster speed of chromatic adaptation. This study also proposed the time to achieve stable chromatic adaptation.

Models to Predict Naturalness and Image Quality for Images Containing Three Memory Colors: Sky, Grass, and Skin, *Jason Ji, Dalin Tian, and Ming Ronnier Luo, Zhejiang University (China)* **171**

When evaluating the image quality, people mostly would like to concentrate on the color appearance of memory objects, representing the naturalness and reality of the image scene. Generally, an image with objects which have perfect memory colors reproduction will give natural and harmonious feelings. Many previous studies had proved the critical role of naturalness in image quality assessment, but it was still tough to scale the image naturalness precisely. In this study, natural images with blue sky, green grass, and skin colors were selected and partially rendered to develop the model of preference and naturalness of typical memory colors. A psychophysical experiment was conducted to collect the visual data of these images. Afterward, the psychophysical data were used to build the preference models and naturalness models, respectively. The models were then compared with previous studies. Results showed that the new models could accurately predict the preference and naturalness of target memory colors.

New Colour Appearance Scales under High Dynamic Range Conditions, *Xi Lv[1] and Ming Ronnier Luo[1,2]; [1]Zhejiang University (China) and [2]Leeds University (UK)* **175**

New colour appearance scales close to daily experience and image quality enhancement are highly desired including whiteness, blackness, vividness and depth. This article describes a new experiment to accumulate the data under HDR (high dynamic range) conditions. The data were then used to test the performance of different colour appearance scales such as CIELAB and CAM16-UCS plus the recent extension by Berns' Vab*, Dab*. The results showed those Berns' scales gave a reasonable performance. However, it was found no scale is capable of predicting colour appearance data covering a wide dynamic range. New scales were developed based on the absolute scales of brightness and colourfulness of CAM16-UCS and gave accurate predictions to the data.

Dye Amount Estimation in a Papanicolaou-stained Specimen using Multispectral Imaging, *Saori Takeyama, Tomoaki Watanabe, and Masahiro Yamaguchi, Tokyo Institute of Technology; Takumi Urata and Fumikazu Kimura, Shinshu University; and Keiko Ishii, Okaya City Hospital (Japan)* **179**

Papanicolaou stain is mainly used in cytological diagnosis such as gynecological diseases. In the image analysis of stained histopathology specimens, color unmixing technique, which estimates the dye abundance map, is useful. In this paper, we apply the dye amount estimation method based on color unmixing to Papanicolaou-stained specimen. In the proposed method, we capture the Papanicolaou-stained samples using a multispectral microscope, and then we estimate the amount of dyes from the observation and practically measured the spectral characteristics of the stain. Besides, we construct an application depicting the amount of stain and the bar-graph plot. In the experiments, we verify the feasibility of the proposed method and analyze a precancerous lesion of the uterine cervix using the proposed method.

A New Corresponding Color Dataset Covering a Wide Luminance Range under High Dynamic Range Viewing Condition, *Xinye Shi, Yuechen Zhu, and Ming Ronnier Luo, Zhejiang University (China)* **184**

An experiment was carried out to investigate the change of color appearance for 13 surface stimuli viewed under a wide range of illuminance levels (15-32000 lux) using asymmetrical matching method. Addition to the above, in the visual field, observers viewed colours in a dark (10 lux) and a bright (200000 lux) illuminance level at the same time to simulate HDR viewing condition. The results were used to understand the relationship

between the color changes under HDR conditions, to generate a corresponding color dataset and to verify color appearance model, such as CIECAM16.

White Appearance for Optimal Text-background Lightness Combination Document Layout on a Tablet Display under Normal Light Levels, *Hsin-Pou Huang[1], Hung-Chung Li[2], Minchen Wei[3], and Yu-Cheng Huang[1]; [1]Chihlee University of Technology (Taiwan), [2]Chang Gung University of Science and Technology (Taiwan), and [3]The Hong Kong Polytechnic University (Hong Kong)* **188**
In the study, two psychophysical experiments are carried out to understand the visual comfort and white appearance of a tablet display. Twenty-four observers assess the visual comfort of document layouts, and eleven observers rate the whiteness percentage of the stimulus under normal light levels with a CCT of 6500 K. The result of the experiment for visual comfort indicates that a combination of black text with a light grey background presents the better visual comfort. On the other hand, the finding of the white appearance experiment shows that the observers rate the stimulus with CCT of 6515 K and a Duv of 0 as the whitest.

White Balance Preference under Multiple Light Sources, *Anku and Susan P. Farnand, Rochester Institute of Technology (US)* **193**
White balance is one of the key processes in a camera pipeline. Accuracy can be challenging when a scene is illuminated by multiple color light sources. We designed and built a studio which consisted of a controllable multiple LED light sources that produced a range of correlated color temperatures (CCTs) with high color fidelity that were used to illuminate test scenes. A two Alternative Forced Choice (2AFC) experiment was performed to evaluate the white balance appearance preference for images containing a model in the foreground and target objects in the background indoor scene. The foreground and background were lit by different combinations of cool to warm sources. The observers were asked to pick the one that was most aesthetically appealing to them. The results show that when the background is warm, the skin tones dominated observers' decisions and when the background is cool the preference shifts to scenes with same foreground and background CCT. The familiarity and unfamiliarity of objects in the background scene did not show a significant effect.

JIST-first Emphasis on Material Appearance by a Combination of Dehazing and Local Visual Contrast, *Hiroaki Kotera, Kotera Imaging Laboratory (Japan)* **197**
Material appearance is a perceptual phenomenon that the brain interprets from the retinal image. Though, it is not easy to analyze what features of optical images are effectively related to the stimulus inside the visual cortex. For this reason, an intuitive or heuristic approach has been taken to simulate the material appearance. The simulation results are expected to drive innovation for not only traditional craft or plastic arts industry but also more realistic picture displays on 4K/8K HDTV and Virtual Reality or Computer Graphics. Optical surface property of material is modeled by BRDF (Bidirectional Reflectance Distribution Function). Specular S and Diffusion D components are responsible for the "glossiness" and "texture" and are used to emphasize the material appearance by simply adjusting the mixing ratio. This study introduces the following two key models to emphasize the material appearance of a given image without using such measuring means as BRDF and discusses how they work individually and cooperatively. (1) α-based Dehazing model to emphasize clarity, wetness, gloss. (2) β-based Contrast model to emphasize texture, roughness.

JIST-first New Encoder Learning for Captioning Heavy Rain Images via Semantic Visual Feature Matching, *Chang-Hwan Son and Pung-Hwi Ye, Kunsan National University (Republic of Korea)* **207**
Image captioning generates text that describes scenes from input images. It has been developed for high-quality images taken in clear weather. However, in bad weather conditions, such as heavy rain, snow, and dense fog, poor visibility as a result of rain streaks, rain accumulation, and snowflakes causes a serious degradation of image quality. This hinders the extraction of useful visual features and results in deteriorated image captioning performance. To address practical issues, this study introduces a new encoder for captioning heavy rain images. The central idea is to transform output features extracted from heavy rain input images into semantic visual features associated with words and sentence context. To achieve this, a target encoder is initially trained in an encoder–decoder framework to associate visual features with semantic words. Subsequently, the objects in a heavy rain image are rendered visible by using an initial reconstruction subnetwork (IRS) based on a heavy rain model. The IRS is then combined with another semantic visual feature matching subnetwork (SVFMS) to match the output features of the IRS with the semantic visual features of the pretrained target encoder. The proposed encoder is based on the joint learning of the IRS and SVFMS. It is trained in an end-to-end manner, and then connected to the pretrained decoder for image captioning. It is experimentally demonstrated that the proposed encoder can generate semantic visual features associated with words even from heavy rain images, thereby increasing the accuracy of the generated captions.

JIST-first Development of a System to Measure the Optical Properties of Facial Skin using a 3D Camera and Projector *Kumiko Kikuchi[1], Shoji Tominaga[2,3], and Jon Y. Hardeberg[2]; [1]Shiseido Co., Ltd. (Japan), [2]Norwegian University of Science and Technology (Norway), and [3]Nagano University (Japan)* **219**
We have developed a system to measure both the optical properties of facial skin and the three-dimensional shape of the face. To measure the three-dimensional facial shape, our system uses a light-field camera to provide a focused image and a depth image simultaneously. The light source uses a projector that produces a high-frequency binary illumination pattern to separate the subsurface scattering and surface reflections from the facial skin. Using a dichromatic reflection model, the surface reflection image of the skin can be separated further into a specular reflection component and a diffuse reflection component. Verification using physically controlled objects showed that the separation of the optical properties by the system correlated with the subsurface scattering, specular reflection, or diffuse reflection characteristics of each object. The method presented here opens new possibilities in cosmetology and skin pharmacology for measurement of the skin's gloss and absorption kinetics and the pharmacodynamics of various external agents.

COLOR CONUNDRUMS II

2 NOV: 20:20 – 21:10 NY
3 NOV: 01:20 – 02:10 PARIS / 09:20 – 10:10 TOKYO
Join colleagues for an informal discussion about one of the color-related topics listed below. While each conundrum is led by a facilitator, the goal is for everyone to share their opinions and experiences. Choices during Color Conundrums II are:

Conundrum D:
Color and Color Names Around the World and Through Time
Facilitator: *Minjung Kim, Facebook Reality Labs*
How are colors named across languages or classified in different places? Are there names for particular colors that don't translate well between

languages? Are there color names whose meaning has changed over time, or whose meaning is ambiguous or commonly misunderstood?

Conundrum E:
What does industry need from new color scientists?
Facilitator: *Jerry Jia, Facebook Reality Labs*
What kinds of academic preparation and experience does one need today to succeed in industry as a color and imaging scientist or engineer? What are the most important things academia should be teaching color science/engineering students in order to meet the needs of industry now and for the next 10-20 years?

Conundrum F:
What color problem needs to be solved ASAP?
Facilitator: *Dave Wyble, Avian Rochester, LLC*
What do you think is the most pressing or important color-related problem that needs to be solved now?

DAY 3
WEDNESDAY 3 NOVEMBER / THURSDAY 4 NOVEMBER

WHITE AND COLOR

Session Chair: Kate Edwards, Datacolor (US)
3 NOV: 08:30 – 09:40 NY / 13:30 – 14:40 PARIS / 21:30 – 22:40 TOKYO

08:30 (New York) / 13:30 (Paris) / 21:30 (Tokyo)
Welcome Remarks
Sessions Host: Peter Morovic, HP Inc. (Spain)

08:40 (New York) / 13:40 (Paris) / 21:40 (Tokyo)
JIST-first Perception of White for Stimuli with Luminance beyond the Diffuse White, *Yiqian Li and Minchen Wei, The Hong Kong Polytechnic University (Hong Kong)* **234**
The appearance of color stimuli with luminance levels beyond the diffuse white is gaining importance due to the popularity of high dynamic range (HDR) displays. Past work on color appearance of stimuli, color appearance models, and uniform color spaces mainly focused on the stimuli with luminance levels below the diffuse white, which were produced using surface color samples or conventional standard dynamic range (SDR) displays. In this study, we focused on the perception of white appearance for stimuli with luminance beyond the diffuse white. Human observers adjusted the color appearance of a stimulus to the whitest under different adapting conditions, including a dark condition and 12 illuminated conditions. It was found that the chromaticities for producing the white appearance under the dark condition were generally similar to those under the 6500 K conditions, regardless of the adapting luminance levels. In comparison to a recent study focusing on the stimuli with luminance below the diffuse white, the perception of white under the conditions with the adapting CCT levels of 2700, 3500, and 5000 K was significantly affected by the lightness level of the stimulus, which cannot be accurately characterized by CAM02-UCS. The results can be used for reproducing white appearance for highlights in HDR scenes. Further investigations on uniform color spaces for characterizing stimuli with luminance beyond the diffuse white are urgently needed for processing and displaying HDR images.

09:00 (New York) /14:00 (Paris) / 22:00 (Tokyo)
The Impact of the Helmholtz-Kohlrausch Effect on the Appearance of Near-white Paper Colours, *Gregory High and Phil Green, Norwegian University of Science and Technology (Norway)*. **241**
This paper investigates the impact of the Helmholtz-Kohlrausch effect on near-white substrate colours. As the luminance of the test colour (or its simulated reflectance in a soft-proof setup) approaches that of the adapting white point the viewing mode changes from 'surface mode' to 'aperture mode', and the appearance of the test colour becomes self-luminous. However, some substrates with optical brighteners fall close to this threshold between viewing modes, since the OBAs not only increase the perceived reflectance but also increase the H-K effect, where it is very prominent in bluish colours. For graphic arts content shown on a display system, this essentially breaks the soft-proofing paradigm. The practical application of this work relates to cross-media colour reproduction, where the light- ness appearance of some substrates is not adequately described by their colorimetric values, and this may impact on choice of proofing strategies.

09:20 (New York) / 14:20 (Paris) / 22:20 (Tokyo)
CIC29 BEST PAPER: G_0 Revisited as Equally Bright Reference Boundary, *Hao Xie and Mark Fairchild, Rochester Institute of Technology (US)* . . . **247**
Brilliance and zero grayness (denoted as G_0) and are two terms coined by Ralph Evans. Nayatani, Heckaman and Fairchild have done series of work to incorporate them into comprehensive color appearance models. In this work, those concepts were reexamined to scale lightness/brightness across the chromaticity diagram. Specifically, observers, mostly with a color science background, were asked to adjust the luminance of a color patch to appear with no grayness, or equivalently just about/cease to glow. The hypothesis was that lightness can be equalized across those chromaticities and the Helmholtz-Kohlrausch effect is automatically incorporated. This hypothesis was verified in a follow-up experiment where another group of observers completed paired comparisons of the brightness between the collected G_0 results. The G_0 task was also repeated under another two levels of adaption backgrounds, based on which different absolute brightness results for a given chromaticity might be derived. In addition, high correlations between the G_0 results (as a perceptual boundary between appearance modes) and different physical gamut boundaries including MacAdam's optimal colors were found for possible computational proxies and ecologically meaningful implications.

3 Nov: 09:40 – 10:00 (New York) / 14:40 – 15:00 (Paris) / 22:40 – 23:00 (Tokyo)
SESSION BREAK / POSTERS AVAILABLE FOR VIEWING
Join speakers and other attendees in the CIC29 Gather.town.

CLOSING KEYNOTE

Session Chair: Michael Murdoch, Rochester Institute of Technology (US)
3 NOV: 10:00 – 11:00 NY / 15:00 – 16:00 PARIS / 23:00 – 00:00 TOKYO

Learning to Estimate Lighting from a Single Image, *Jean-François Lalonde, Université Laval (Canada)* [abstract only; no proceedings paper]
Combining virtual and real visual elements into a single, realistic image requires the accurate estimation of the lighting conditions of the real scene. Unfortunately, doing so typically requires specific capture devices or physical access to the scene. This talk presents approaches that alleviate these restrictions and instead automatically estimate lighting from a single image. In particular, recent works that frame lighting estimation as a learning problem for both the indoor and outdoor illumination scenarios are

presented. In both cases, large datasets of omnidirectional HDR images are leveraged for training the models. It will be shown that using our illumination estimates for applications like 3D object insertion can achieve photo-realistic results on a wide variety of challenging scenarios.

IS&T Award Presentations

Presenter: Susan Farnand, IS&T President

Jon Hardeberg, *2020 Fellow, for outstanding contributions to the field of multispectral imaging and digital imaging quality.*

Norimichi Tsumura, *2020 Raymond C. Bowman Award for his many contributions teaching and helping others in imaging science, in particular for color and medical applications.*

3 Nov: 11:00 – 11:30 (New York) / 16:00 – 16:30 (Paris)
4 Nov: 00:00 – 00:30 (Tokyo)
SESSION BREAK / POSTERS AVAILABLE FOR VIEWING
Join speakers and other attendees in the CIC29 Gather.town.

TWO-MINUTE INTERACTIVE PAPER PREVIEWS FOLLOWED BY INTERACTIVE PAPER POSTER SESSION B

Session Chair: Maliha Ashraf, University of Liverpool (UK)
3 NOV: 11:30 – 13:00 NY / 16:30 – 18:00 PARIS
4 NOV: 00:30 – 02:00 TOKYO

Interactive (Poster) Paper authors provide a brief overview of their work, followed by talks with authors in the CIC29 Gather.town.

Use of Spectral Information for Red Scale Pest Control, *Carlos E. García-Guerra[1], Francisco J. Burgos-Fernández[1], Eloi Canals[1], Fernando Díaz-Doutón[1], Abel Zaragoza[2], Albert Virgili[2], and Meritxell Vilaseca[1]; [1]Universitat Politècnica de Catalunya and [2]COMERCIAL QUÍMICA MASSÓ, S.A. (Spain)* **253**
Decreasing the use of pesticides is one of the main goals of current agriculture, which requires fast, precise and continuous assessments of crop pests. Citrus pests cause a lot of damage worldwide and the techniques to evaluate them are mainly based on manual, time-consuming readings of insects stuck on traps spread over the crops. This is the case of red scale insects, whose control is notably challenging due to their small size and high reproduction rate. Hence, in this work, we carry out a spectral characterization of this insect in the visible range through spectrometric devices, microscopy and hyperspectral imaging technology to analyze the feasibility of using this information as a means of automatically identifying specimens belonging to this species in this era of precision agriculture. The results obtained show that spectral reflectance differences between red scales and other insects can be recorded at long (red) wavelengths and that red scales are morphologically different, i.e., smaller and more rounded. A reflectance ratio computed from spectral images taken at 774 nm and 410 nm is proposed as a new approach for automated discrimination of red scales from other insects.

Colourlab Image Database: Geometric Distortions, *Marius Pedersen and Seyed Ali Amirshahi, Norwegian University of Science and Technology (Norway)* **258**
Over the years, a high number of different objective image quality metrics have been proposed. While some image quality metrics show a high correlation with subjective scores provided in different datasets, there still exists room for improvement. Different studies have pointed to evaluating the quality of images affected by geometrical distortions as a challenge for current image quality metrics. In this work, we introduce the Colourlab Image Database: Geometric Distortions (CID:GD) with 49 different reference images made specifically to evaluate image quality metrics. CID:GD is one of the first datasets which include three different types of geometrical distortions; seam carving, lens distortion, and image rotation. 35 state-of-the- art image quality metrics are tested on this dataset, showing that apart from a handful of these objective metrics, most are not able to show a high performance. The dataset is available at www.colourlab.no/cid.

Reflectance Estimation from Snapshot Multispectral Images Captured under Unknown Illumination, *Vlado Kitanovski, Jean-Baptiste Thomas, and Jon Yngve Hardeberg, Norwegian University of Science and Technology (Norway)* **264**
Multispectral images contain more spectral information of the scene objects compared to color images. The captured information of the scene reflectance is affected by several capture conditions, of which the scene illuminant is dominant. In this work, we implemented an imaging pipeline for a spectral filter array camera, where the focus is the estimation of the scene reflectances when the scene illuminant is unknown. We simulate three scenarios for reflectance estimation from multispectral images, and we evaluate the estimation accuracy on real captured data. We evaluate two camera model-based reflectance estimation methods that use a Wiener filter, and two other linear regression models for reflectance estimation that do not require an image formation model of the camera. Regarding the model-based approaches, we propose to use an estimate for the illuminant's spectral power distribution. The results show that our proposed approach stabilizes and marginally improves the estimation accuracy over the method that estimates the illuminant in the sensor space only. The results also provide a comparison of reflectance estimation using common approaches that are suited for different realistic scenarios.

Lippmann Photography: History and Modern Replications of the Elusive Structural Colour, *Elizabete Kozlovska, Susanne Klein, and Frank Menger, University of the West of England (UK)* **270**
In 1908 physicist Gabriel Lippmann won the Nobel Prize for creating a true colour process using standing waves. This paper reviews the historic process of creating Lippmann plates and applies them to recreate the process with modern materials. The optics of the created samples are reviewed, comparing results to Lippmann's own research and modern attempts by other researchers to recreate or improve the process.

Radiometric Spectral Fusion of VNIR and SWIR Hyperspectral Cameras, *Federico Grillini, Jean-Baptiste Thomas, and Sony George, Norwegian University of Science and Technology (Norway)* **276**
When two hyperspectral cameras are sensitive to complementary portions of the electromagnetic spectrum it is fundamental that the calibration processes conducted independently lead to comparable radiance values, especially if the cameras show a shared spectral interval. However, in practice, a perfect matching is hard to obtain, and radiance values that are expected to be similar might differ significantly. In the present study we propose to introduce an ulterior linear correcting factor in the radiometric calibration pipeline of two hyperspectral cameras, operating in the visible near infrared (VNIR) and short wave infrared (SWIR) intervals. The linearity properties of both cameras are preliminarily assessed, conducting acquisitions on five standardized targets, and highlighting noise at the sensors level and different illumination fields as the main causes of radiance mismatch. The correction step that we propose allows the retrieval of accurate and smoothly connected VNIR-SWIR reflectance factor curves.

Optimising a Euclidean Colour Space Transform for Colour Order and Perceptual Uniformity, *Luvin Munish Ragoo and Ivar Farup, Norwegian University of Science and Technology (Norway)* **282**

In this paper, we attempt to optimise a colour space transform for colour order and perceptual uniformity to verify if a trade-off could be achieved between the two. The IPT colour space is used as basis for the optimisation. An optimization model consisting of a modified XYZ-to-LMS matrix, a non-linearity factor, and two geometric transformation matrices is proposed. Two objective functions are constructed based on the optimisation model, where one would improve perceptual uniformity primarily and the other would improve colour order instead. Finally, the two objective functions are combined, in an attempt to optimise both simultaneously and see if a trade-off between the seemingly incompatible features can be achieved. The performance of the optimised IPT transform is then compared to the original IPT transform, in terms of relative improvements in perceptual uniformity and colour order. Finally, the results show that there is indeed an inverse relationship between the two objectives. However, by adjusting the bias of the optimisation, a balance could be achieved between the two, where both colour order and perceptual uniformity was improved with respect to the original IPT transform.

Joint Demosaicing of Colour and Polarisation from Filter Arrays, *Alexandra Spote and Pierre-Jean Lapray, Université de Haute-Alsace (France); and Jean-Baptiste Thomas and Ivar Farup, Norwegian University of Science and Technology (Norway)* **288**

This article considers the joint demosaicing of colour and polarisation image content captured with a Colour and Polarisation Filter Array imaging system. The Linear Minimum Mean Square Error algorithm is applied to this case, and its performance is compared to the state-of-the-art Edge-Aware Residual Interpolation algorithm. Results show that the LMMSE demosaicing method gives statistically higher scores on the largest tested database, in term of peak signal-to-noise ratio relatively to a CPFA-dedicated algorithm.

Image-based Goniometric Appearance Characterisation of Bronze Patinas, *Yoko Arteaga[1,2], Clotilde Boust[1], Angele Dequier[3], and Jon Yngve Hardeberg[2]; [1]Centre of Research and Restoration of the Museums of France (France), [2]Norwegian University of Science and Technology (Norway), and [3]National Institute of Patrimony (France)* **294**

Patinas are a form of metal polychromy used to decorate metallic artworks. Due to the nature of the metallic surface, their colour and gloss is perceived differently when the illumination and viewing directions vary. Sparkle effect on surfaces is a physical phenomenom caused by micro-facets on the surface coating which are also perceived with changing viewing and illumination geometry.

In this paper, a method designed for the measurement of sparkle is applied for the goniometric characterisation of bronze patinas. Using a set of six different patinas, in three colours and two surface finishes, it is found that these surfaces exhibit different appearance when illuminated and viewed at different angles. Moreover, the roughness of the patinas is measured and as expected, as the roughness increases the specular reflection peak decreases. The experiment is repeated at two different institutions with different sets of equipment to test its repeatability and robustness.

The sparkle is presented as a function of the angle of tilting, and it is characterised by its maximum value and full-width half-maximum. It is found that the maximum and the roughness have a negative exponential relationship whereas the full-width half-maximum and the roughness have a linear relationship.

An Analysis of Spectral Similarity Measures, *Mirko Agarla, Simone Bianco, Luigi Celona, and Raimondo Schettini, University of Milano-Bicocca (Italy); and Mikhail Tchobanou, Huawei Technologies Co. Ltd. (Russia)* **300**

In this paper we analyze the most used measures for the assessment of spectral similarity of reflectance and radiance signals. First of all we divide them in five groups on the basis of the type of errors they measure. We proceed analyzing their mathematical definition to identify unintended behaviors and types of errors they are blind to. Then exploiting the Munsell atlas we analyze the correlation between metrics in terms of both Pearson's Linear Correlation Coefficient (PLCC) and Spearman's Rank Order Correlation Coefficient (SROCC). Finally we analyze the behaviour of the selected metrics with respect to two different color properties: the Chroma and the Lightness computed in the CIE L*a*b* color space. The source code of the spectral measures considered is available at the following link: https://celuigi.github.io/spectral-similarity-metrics-comparison/.

Benchmarking Modern Gloss Correlators with Established ISO 2813 Standard and Visual Judgment of Gloss, *Donatela Šaric[1,2], Andreas Kraushaar[1], Marco Mattuschka[3], and Phil Green[2]; [1]Fogra Research Institute for Media Technologies (Germany), [2]Norwegian University of Science and Technology (Norway), and [3]Vizoo 3D (Germany)* **306**

Interaction between the diffuse colour and the gloss of its surface is common. In this work, the influence of different gloss levels is tested on the diffuse colour. Firstly, we investigated how the albedo colour correlates with the reflected specular part. Furthermore, we provided a visual experiment. The visual experiment is conducted in two parts. The results of the visual experiment show that changing the angle of illumination does not affect the final gloss perception. Furthermore, a fitting of the gloss perception is done to find a parameter that correlates with the visual perception of gloss. The results show that there is a quadratic correlation between the Canon scattering indexes and the perceptual gloss.

Extending the Unmixing Methods to Multispectral Images, *Jizhen Cai[1,2,3], Hermine Chatoux[1], Clotilde Boust[2,3], and Alamin Mansouri[1]; [1]University Bourgogne Franche-Comté, [2]Le Centre de Recherche et de Restauration des Musees de France, and [3]Centre National de la Recherche Scientifique (France)* **311**

In the past few decades, there has been intensive research concerning the Unmixing of hyperspectral images. Some methods such as NMF, VCA, and N-FINDR have become standards since they show robustness in dealing with the unmixing of hyperspectral images. However, the research concerning the unmixing of multispectral images is relatively scarce. Thus, we extend some unmixing methods to the multispectral images. In this paper, we have created two simulated multispectral datasets from two hyperspectral datasets whose ground truths are given. Then we apply the unmixing methods (VCA, NMF, N-FINDR) to these two datasets. By comparing and analyzing the results, we have been able to demonstrate some interesting result for the utilization of VCA, NMF, and N-FINDR with multispectral datasets. Besides, this also demonstrates the possibilities in extending these unmixing methods to the field of multispectral imaging.

Estimating Visual Difference between Reproduction Gamuts: Moving Our Pilot Study from the Lab to Online Delivery, *Gregory High, Peter Nussbaum, and Phil Green, Norwegian University of Science and Technology (Norway)* **317**

Images reproduced for different output devices are known to be limited in the range of colours that can be reproduced. It is accepted that reproductions made with different print processes, and on different substrates, will not match, although the overall reproduction appearance can be optimized using an output rendering. However, the question remains: how different

are they visually? This paper reports on a pilot study that tests whether visual difference can be reduced to a single dimensional scale using magnitude estimation. Subject to recent Covid restrictions, the experiment was moved from the lab to an online delivery. We compare the two methods of delivery: in-person under controlled viewing conditions, and online via a web-based interface where viewing conditions are unknown.

Long Range Diffusion with Control of the Directional Differences, *Ali Alsam and Hans Jakob Rivertz, Norwegian University of Science and Technology (Norway)* **323**
A fast, spatially adaptive filter for smoothing colour images while preserving edges is proposed. To preserve the edges, we use a constraint that prohibits the increasing of the gradients in the process of diffusion. This constraint is shown to be very effective in preserving details and flexible in cases where more smoothing is desired. In addition, a filter of exponentially increasing diameter is used to allow averaging non-adjacent pixels, including those separated by strong edges.

Perceptual Navigation in Absorption-scattering Space, *Davit Gigilashvili[1], Philipp Urban[1,2], Jean-Baptiste Thomas[1], Marius Pedersen[1], and Jon Yngve Hardeberg[1]; [1]Norwegian University; of Science and Technology (Norway) and [2]Fraunhofer Institute for Computer Graphics Research IGD (Germany)* **328**
Translucency optically results from subsurface light transport and plays a considerable role in how objects and materials appear. Absorption and scattering coefficients parametrize the distance a photon travels inside the medium before it gets absorbed or scattered, respectively. Stimuli produced by a material for a distinct viewing condition are perceptually non-uniform w.r.t. these coefficients. In this work, we use multi-grid optimization to embed a non-perceptual absorption-scattering space into a perceptually more uniform space for translucency and lightness. In this process, we rely on A (alpha) as a perceptual translucency metric. Small Euclidean distances in the new space are roughly proportional to lightness and apparent translucency differences measured with A. This makes picking A more practical and predictable, and is a first step toward a perceptual translucency space.

Influence of Acquisition Parameters on Pigment Classification using Hyperspectral Imaging, *Dipendra J. Mandal, Sony George, and Marius Pedersen, Norwegian University of Science and Technology (Norway); and Clotilde Boust, Centre de Recherche et de Restauration des Musées de France (France)* **334**
Pigment classification of paintings is considered an important task in the field of cultural heritage. It helps to analyze the object and to know its historical value. This information is also essential for curators and conservators. Hyperspectral imaging technology has been used for pigment characterization for many years and has potential in its scientific analysis. Despite its advantages, there are several challenges linked with hyperspectral image acquisition. The quality of such acquired hyperspectral data can be influenced by different parameters such as focus, signal-to-noise ratio, illumination geometry, etc. Among several, we investigated the effect of four key parameters, namely focus distance, signal-to-noise ratio, integration time, and illumination geometry on pigment classification accuracy for a mockup using hyperspectral imaging in visible and near-infrared regions. The results obtained exemplify that the classification accuracy is influenced by the variation in these parameters. Focus distance and illumination angle have a significant effect on the classification accuracy compared to signal-to-noise ratio and integration time.

The Influence of Wedge Angle, Feedstock Color, and Infill Density on the Color Difference of FDM Objects, *Ali Payami Golhin and Are Strandlie, and Philip John Green, Norwegian University of Science and Technology (Norway)* **347**
The surface appearance in additive manufacturing (AM) has attracted attention in recent years due to its importance in evaluating the quality of 3D printed structures. Fused Deposition Modeling (FDM), also known as Fused Filament Fabrication (FFF), holds an important share of the AM market because of its large economic potential in many industries. Nevertheless, the quality assurance procedure for FDM manufactured parts is usually complicated and expensive. The enhancement of the appearance at different illumination and viewing angles can be exploited in various applications, such as civil engineering, aeronautics, medical fields, and art. There are two steps in improving the microstructure and material appearance of printed objects, including pre-processing and post-processing. This study aims to elucidate the role of the pre-processing phase in the development of FDM parts through the assessment of color differences. For this purpose, a set of polymeric samples with different wedge (slope) angles were 3D printed using an FDM printer. The color difference between the elements is discussed and correlated with the pre-processing parameters. It is revealed that the wedge angle of the elements in the design, slicing process, and infill density could alter the color appearance of the printed parts in a predictable trend. This research suggests that low infill density and wedge angles in polylactide filaments can result in a more stable color appearance.

WORKSHOP I:
ELEVATING THE STORY: BRIDGING ARTS AND SCIENCE

3 NOV: 13:00 – 14:00 NY / 18:00 – 19:00 PARIS
4 NOV: 02:00 – 03:00 TOKYO

Convener and Speaker: Shane Mario Ruggieri, *Dolby Laboratories, Inc. (US)*
Speakers:
Stacey Spears, Spears & Munsil (US)
Joachim Zell, Barco (US)

This workshop explores how color and imaging scientists effectively interact with color creatives to develop technologies and workflows that are ready to elevate image fidelity and creative intent for storytelling.

Shane Mario Ruggieri, CSI, is a world-renown Dolby Vision colorist. Whether creating forward looking HDR content, training other colorists, or consulting on Dolby Vision and HDR workflows, he strives to help define the language of HDR storytelling.

Stacey Spears is the co-creator of the popular Spears & Munsil Benchmark DVD and Blu-ray discs. He has also created content for calibration and test discs for many companies and wrote for many years on home video topics for the audio/video enthusiast site Secrets of Home Theater and High Fidelity.

Joachim Zell is head of HDR content workflow at Barco. Prior to that he was VP of technology and imaging science at EFILM/Deluxe where he designed and monitored production workflows from onset production to movie release. He is ACES project vice chair at the Academy of Motion Picture Arts and Sciences.

Break in program to accommodate time zones

CHANGING APPEARANCE

Session Chair: Javier Vazquez-Corral, Universitat Autònoma de Barcelona (Spain)

3 NOV: 19:00 – 20:10 NY
4 NOV: 00:00 – 01:10 PARIS / 08:00 – 09:10 TOKYO

19:00 (New York)
00:00 (Paris) / 08:00 (Tokyo)
Welcome Remarks
Sessions Host: Michael Murdoch, Rochester Institute of Technology (US)

19:10 (New York)
00:10 (Paris) / 08:10 (Tokyo)
A Study on Memory Colours, *Mingkai Cao and Ming Ronnier Luo, Zhejiang University (China)* **362**
Memory colour has generated a sustained interest in the colour world. Previous studies mainly focused on the reflection colour chips and colour samples on real scenes or displays. Less attention was paid to the specific attributes of memory colour. In this paper, the forced choice psychophysical experiment method was used to study the preference, the colourfulness and the naturalness memory colours of 29 familiar objects on mobile displays by Chinese observers. The experiment collected the memory colours data and the representative memory colour was specified by CIELAB L*, a*, b* value. The intra-observer and inter-observer variations were analyzed by mean colour difference from the mean values, which was compared with other similar studies. An ellipsoid model was established to represent results in terms of memory colour centre and colour range in CIELAB a*b* space. At the same time, the results of this experiment were compared with those of previous experiments.

19:30 (New York)
00:30 (Paris) / 08:30 (Tokyo)
Accumulation of Corresponding Colours under Extreme Chromatic Illuminations and Modification of CAM16, *Yuechen Zhu[1] and Ming Ronnier Luo[1,2]; [1]Zhejiang University (China) and [2]University of Leeds (UK)* **368**
The goal of this study was to investigate the chromatic adaptation under extreme chromatic lighting conditions using the magnitude estimation method. The locations of the lightings on CIE1976 u'v' plane were close to the spectrum locus, so the colour purity was far beyond the previous studies, and the data could test the limitations of the existing models. Two psychophysical experiments were carried out, and 1,470 estimations of corresponding colours were accumulated. The results showed that CAT16 gave a good prediction performance for all the chromatic lightings except for blue lighting, and the degree of adaptation was relatively high, that is, D was close to 1. The prediction for blue lightings was modified, the results showed the performance of CAM16 could be improved by correcting the matrix instead of the D values.

19:50 (New York)
00:50 (Paris) / 08:50 (Tokyo)
The Threshold of Color Inconstancy, *Che Shen and Mark Fairchild, Rochester Institute of Technology (US)* **374**
Color inconstancy refers to significant changes in the perceived color of an object across two or more different lighting conditions, such as daylight and incandescent light. This research focusses on defining the threshold of color inconstancy between generated D65 and A illumination through a psychophysical experiment. Although modern color appearance models provide equations to calculate the degree of adaptation, a neutral grey match experiment was completed to produce a more accurate D values for the experimental viewing conditions. Like setting an instrumental color tolerance experiment, a second, sorting, experiment was used to define the threshold of color inconstancy. This threshold is the color shift, expressed in color difference terms, required for observers to notice a color change across changes in illumination. In addition, the tolerance ellipsoid for each Munsell principal hue group was also established.

3 Nov: 20:10 – 20:30 (New York)
4 Nov: 01:10 – 01:30 (Paris) / 09:10 – 09:30 (Tokyo)
SESSION BREAK / POSTERS AVAILABLE FOR VIEWING
Join speakers and other attendees in the CIC29 Gather.town.

DESCRIBING APPEARANCE

Session Chair: Javier Vazquez-Corral, Universitat Autònoma de Barcelona (Spain)

3 NOV: 20:30 – 21:10 NY
4 NOV: 01:30 – 02:10 PARIS / 09:30 – 10:10 TOKYO

20:30 (New York)
01:30 (Paris) / 09:30 (Tokyo)
Testing Colour Appearance Model based UCS using HDR, WCG, and COMBVD Datasets, *Qiang Xu[1], Muhammad Safdar[2], and Ming Ronnier Luo[1,3]; [1]Zhejiang University (China), [2]Avient Corporation (Singapore), and [3]Leeds University (UK)* **381**
Two colour appearance models based UCSs, CAM16-UCS and ZCAM-QMh, were tested using HDR, WCG and COMBVD datasets. As a comparison, two widely used UCSs, CIELAB and ICTCP, were tested. Metrics of the STRESS and correlation coefficient between predicted colour differences and visual differences, together with local and global uniformity based on their chromatic discrimination ellipses, were applied to test models' performance. The two UCSs give similar performance. The luminance parametric factor k_L, and power factor γ, were introduced to optimize colour-difference models. Factors k_L and γ of 0.75 and 0.5, gave marked improvement to predict the HDR dataset. Factor k_L of 0.3 gave significant improvement in the test of WCG dataset. In the test of COMBVD dataset, optimization provide very limited improvement.

20:50 (New York)
01:50 (Paris) / 09:50 (Tokyo)
Comparison of Remote and In-person Tutorials of Color Appearance Phenomena, *Dorukalp Durmus, Pennsylvania State University (US)*. . . . **387**
Accurately describing the effect of lighting on color appearance phenomena is critical for color science education. While it is ideal to conduct in-person tutorials to demonstrate the color appearance fundamentals, laboratory tutorials have been limited due to COVID-19. The limitation of in-person gatherings and the increase popularity of remote teaching help evoke alternative methods to demonstrate color appearance phenomena. Here, a remote tutorial method is described, and results are compared to in-person tutorials. While the remote tutorial had weaker result in representing observers' color experience compared to the in-person lab tutorial, remote demonstrations can be used to demonstrate and discuss the limitations of color imaging, and the difference between the human visual system and digital imaging systems.