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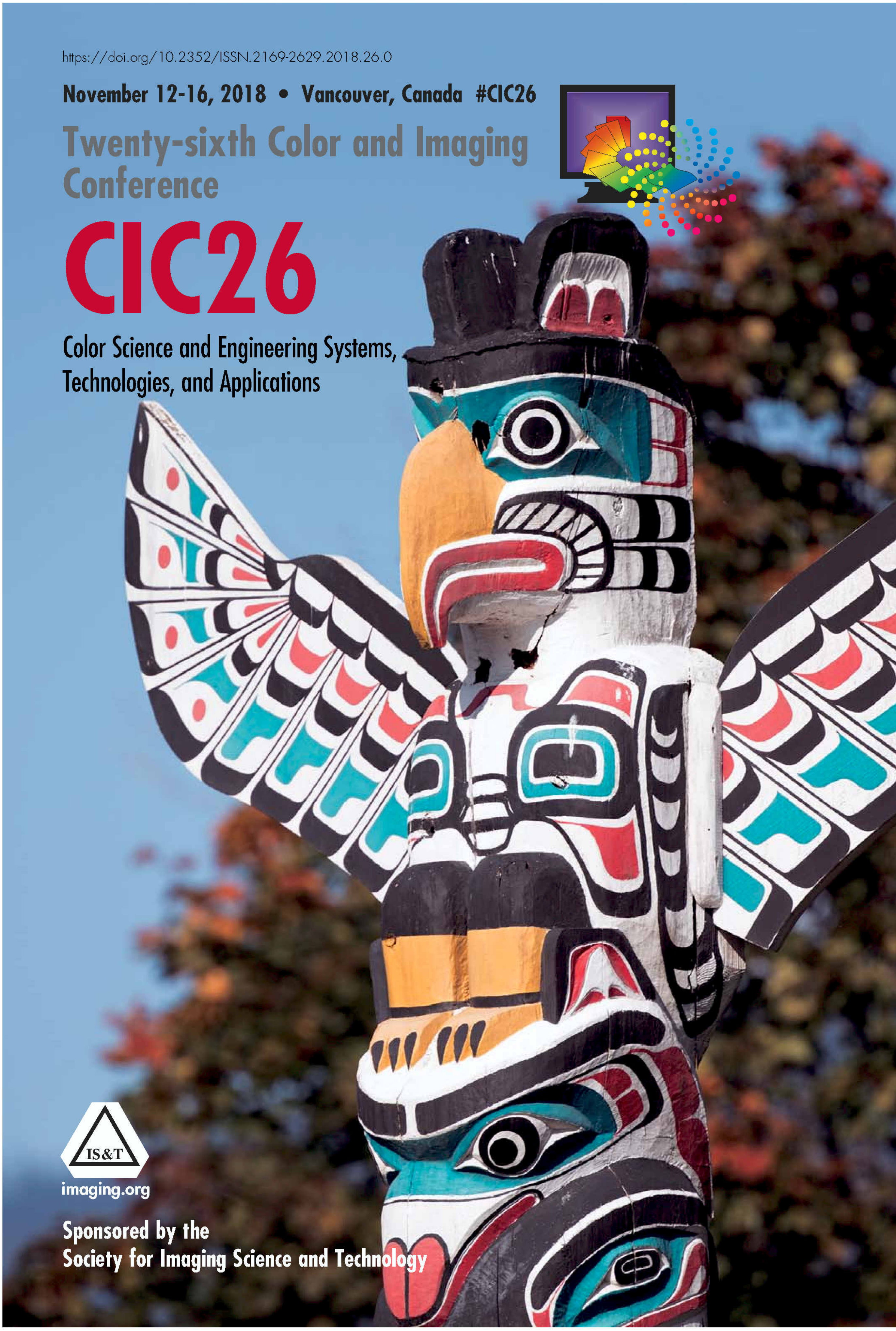
November 12-16, 2018 • Vancouver, Canada #CIC26

Twenty-sixth Color and Imaging Conference

CIC26

Color Science and Engineering Systems, Technologies, and Applications



FINAL PROGRAM AND PROCEEDINGS

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The papers in this volume represent the program of the Twenty-sixth Color and Imaging Conference (CIC26) held November 12–16, 2018, at the Pinnacle Hotel Harbourfront in Vancouver, Canada.

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Welcome to CIC26!

Thank you for joining us at the Twenty-Sixth Color and Imaging Conference (CIC26)—held for the first time in Canada—for an exciting week of courses, workshops, keynotes, and cutting-edge papers from all sides of the color and imaging community. We are excited to bring this conference to Vancouver, where we will have a mix of familiar and new events in beautiful new surroundings.

This year we've made some changes to the conference layout. CIC26 has two tracks of short courses on Monday—our one-day Color and Imaging course plus a track of Advanced Topics—and four tracks on Tuesday until mid-afternoon. Workshops, which have traditionally been held on Friday, have been moved to Tuesday, followed by the Welcome Reception. We then have three full days of keynote talks and technical papers. It is also the first time we are introducing Colleague Connection gatherings during coffee breaks where those interested in discussing a topic can get together informally.

Consistent with the past 25 events, the core of CIC26 is a rich technical program of peer-reviewed papers, including 33 oral, 33 interactive, three keynote talks, an evening lecture, two presentations on the impact research from Vancouver's Simon Fraser University has had on the field of color, and one paper on the color of wine. We continue to have a large number of journal-first papers—8 JIST and 2 JPI—meaning they have been reviewed and accepted for publication in the *Journal of Imaging Science and Technology* or *Journal of Perceptual Imaging*, and are included in the CIC program as reprints. The CIC technical program, assembled by chairs Nicolas Bonnier and Maria Vanrell, represents the state-of-the-art in color science research and application from industry and academia, with topics including image quality, material appearance, lighting, and printing.

We have a very interesting and diverse lineup of keynote speakers. Radhakrishna Achanta (Swiss Data Science Center) provides a brief story of superpixels; Michael Brown (York University) discusses the current state of affairs for color on commodity cameras; and Anders Ballestad (MTT Innovation Inc.) talks about bringing high dynamic range to the big screen. We hope that the range and depth of these speakers instills a deeper understanding, inspires future research, and spurs meaningful conversation during the social breaks.

As Vancouver is one of North America's leading cities for film and TV production, our Wednesday evening lecture is by Andrea Chlebak, a feature film colorist, who discusses color in the process of filmmaking.

One of the most valuable aspects of being at the conference lies in the informal interactions amongst colleagues in the field, which has always been a focus at CIC. This is fostered by bringing everyone together at the Welcome and Conference Receptions. These events, as well as the colleague connections and breaks, are the perfect time to meet new associates, reconnect with old friends and colleagues, and delve into the many exciting topics related to color and imaging.

I would like to acknowledge the contributions of the hard-working people responsible for creating this outstanding conference. These include the technical program, short course, workshop, and interactive paper chairs; the JIST- and JPI-first associate editors; the reviewers; and the tireless staff of IS&T. Thanks also to the exhibitors and sponsors for their help in making the conference possible. I hope you enjoy your time at CIC26! Tell us what you think, and please let us know if you have ideas that can make the next CIC even better.

—Marius Pedersen, CIC26 General Chair

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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)

CIC26 Technical Papers Program: Schedule and Contents

Monday 12 November 2018

8:00 – 17:45
SHORT COURSE PROGRAM

SC01: Color and Imaging
8:30 – 17:45 (8 hours) / **Instructor:** Gaurav Sharma, University of Rochester
SC02: Characterizing Surface Appearance
8:00 – 10:00 (2 hours) / **Instructor:** James A. Ferwerda, Rochester Institute of Technology
SC03: Color Optimization for Displays
10:15 – 12:15 (2 hours) / **Instructor:** Gabriel Marcu, Apple Inc.
SC04: The Role of Color Science in Smartphone Imaging for Brand Protection and Secure Applications
13:30 – 15:30 (2 hours) / **Instructor:** Alan Hodgson, Alan Hodgson Consulting Ltd.
SC05: Variational Color Image Enhancement Inspired by Human Vision
15:45 – 17:45 (2 hours) / **Instructor:** Edoardo Provenzi

Tuesday 13 November 2018

8:00 – 15:30
SHORT COURSE PROGRAM

SC06: Advanced Colorimetry and Color Appearance
8:00 – 12:15 (4 hours) / **Instructor:** Gaurav Sharma, University of Rochester
SC07: Camera Color Characterization: Theory and Practice
8:00 – 12:15 (4 hours) / **Instructors:** Dietmar Wueller, Image Engineering GmbH & Co. Kg, and Eric Walowit, consultant
SC08: Individual Differences in Color Matching and Chromatic Adaptation
8:00 – 10:00 (2 hours) / **Instructor:** Mark Fairchild, Rochester Institute of Technology
SC09: Fundamentals of Psychophysics
10:15 – 12:15 (2 hours) / **Instructor:** James A. Ferwerda, Rochester Institute of Technology
SC10: Fundamentals of Spectral Measurements for Color Science
10:15 – 12:15 (2 hours) / **Instructor:** David R. Wyble, Avian Rochester, LLC
SC11: Colour Difference Perception for Images
10:15 – 12:15 (2 hours) / **Instructor:** Ming Ronnier Luo, Zhejiang University, University of Leeds, and National Taiwan University of Science and Technology
SC12: From Cone Fundamentals to Color Matching Functions to Cone-opponent, Camera Sensor, and Device Color Spaces
13:30 – 15:30 (2 hours) / **Instructor:** Andrew Stockman, UCL Institute of Ophthalmology
SC13: The Art of Making Better Pixels: High Dynamic Range Display Concepts and Technologies
13:30 – 15:30 (2 hours) / **Instructor:** Timo Kunkel, Dolby Laboratories, Inc.
SC14: Color Fundamentals in LED Lighting
13:30 – 15:30 (2 hours) / **Instructor:** Mike Murdoch, Rochester Institute of Technology
SC15: Color Image Quality Assessment
13:30 – 5:30 (2 hours) / **Instructors:** Marius Pedersen and Seyed Ali Amirshahi, Norwegian Colour and Visual Computing Laboratory (NTNU)

15:45 – 18:15
CIC26 WORKSHOPS

W1: VIRTUAL AND AUGMENTED REALITY: CHALLENGES AND PERSPECTIVES

Chair/Convener: Giuseppe Claudio Guarnera, Norwegian University of Science and Technology (Norway)

Speakers/Abstracts:

Over the past few years Virtual Reality and Augmented Reality have become widely available in consumer devices, promising to transform the way we think, learn, and communicate.

The capability of creating photo-realistic, rendered objects within a real-world setting will support sale, promotion, accurate visualization, planning, and marketing purposes more and more in the coming years. A key factor common among all the countless possibilities offered by AR and VR is that all the depicted materials, their reflectance properties, the lighting, etc. must be consistent with human perception, across a range different platforms.

However, photo-realism is still a challenge even on desktop environments, and AR/VR are raising the bar for efficient, realistic, and cost-effective material modelling.

Augmented reality (AR) technology promises to blend virtual rendered objects and overlays with the real world through headmounted displays (HMDs) or other displays. Optical see-through (OST) displays are one way to make this blend, providing a relatively undistorted view of the real world and adding synthetic overlays to it. Current implementations, such as the Microsoft HoloLens, perform spatial tracking of the OST-HMD so that the virtual objects appear to remain fixed in real-world coordinates, allowing the user to look around and view them from different directions. An overview of AR technologies, including non-OST implementations, is provided by van Krevelen and Poelman.

Two use cases for AR can be described: first, adding virtual objects to the real world; and second, manipulating real-world objects with overlaid content. The former case is what many people think of as AR: 3D models floating in real-world space, for example in games or educational experiences. The latter case, in which the color, texture, or geometry of real-world objects appears to be altered by an AR overlay, can be especially useful in medical, education, and retail applications. Different applications in either of these use cases have varied requirements for perceived attributes related to 3D accuracy, spatial resolution, color accuracy.

This workshop presentation focuses on the many challenges and unknowns regarding color reproduction and perception of objects and object color in OST AR applications.

W2: DEEP LEARNING AND COLOR

Chair/Convener: Radhakrishna Achanta, Swiss Data Science Center (Switzerland)

Speakers/Abstracts:

Spectral Image Super-Resolution Via Deep Learning, *Ruofan Zhou, École Polytechnique Fédérale de Lausanne (Switzerland)*

Hyperspectral imaging enhances the solution of many visual problems but suffers from low-resolution image data. Due to the trade-off between spectral and spatial resolution, it is hard and costly to directly get high spectral-spatial resolution data. Recent advances have shown the great power of deep convolutional neural networks (CNN) to learn the relationship between low and high-resolution image patches, leading to state-of-the-art performance. In this talk, I will present our recent works on both network architecture and objective functions on spectral image super-resolution. I will describe our GAN (generative adversarial network) framework for reconstructing spectral image from RGB image: we redefine the objective functions to a step-change in the quality of super resolved spectral images. Moreover, to tackle the problem of limited spectral image datasets, we developed a pipeline for multi-modal spectral image super-resolution. By using domain adaptation techniques, we are able to benefit from different modalities to improve the performance of neural networks on the spectral super-resolution problem. Our proposed deep learning frameworks are economic in terms of parameters and computation time, while still producing state-of-the-art results.

Keyword-based Image Re-coloring, *Fayez Lahoud, École Polytechnique Fédérale de Lausanne (Switzerland)*

We propose to leverage the correlations between images representing similar concepts. Using cross-image statistics, we build a color re-rendering method based on semantic information to enhance an image's colors given a certain keyword. Using similarities across images, we use deep learning to learn semantic segmentation models based on a specified keyword. Later, using the segmentation masks, we generate correlations between the keywords and the color characteristics of the image. The segmentation is then used to indicate the regions for re-coloring, while the correlations guide the operation. Qualitative comparisons show that our method generates visually better results than the state-of-the-art approach, and we further validate with a psychophysical experiment, where the participants prefer the results of our method.

Illuminating Colour via Learning, *Brian Funt, Simon Fraser University (Canada)*

What can deep learning do to further illuminate our understanding of colour perception? Given that the computer vision community has developed very impressive colourization (i.e., luminance image input, full colour image output) methods based on deep learning, one has to wonder how important colour really is to our everyday understanding of the world. In this vein, I will summarize three related learning-based colour projects done in collaboration with Ligeng Zhu. The first colourizes trichromatic images as a method of automatic white balance in scenes with varying illumination. The second colourizes dichromatic images as a way of understanding what dichromats might experience. The third compares learning-based object classification using monochromatic versus trichromatic input as a way to evaluate the importance, or lack thereof, of colour.

Data-driven White Balance: A Cautionary Tale on the Over Reliance on Machine Learning, *Michael Brown, York University (Canada)*
Machine learning, especially deep learning, is a powerful tool that leverages training data to solve a wide range of problems. However, machine learning often cannot reveal new insight into the underlying physical process that generates the data. In this talk, I'll give examples from computational color constancy (white balance) that shows the limitation of relying on data-driven machine learning. The takeaway message—don't replace deep understanding with deep learning.

Color Encoding in CNNs and Some Parallelisms with Human Vision, *Maria Vanrell, Universitat Autònoma de Barcelona (Spain)*
A convolutional neural network (CCN) trained for an object recognition task was dissected to study how color is represented. We defined a color selectivity index to isolate and visualize neuron functionalities. We found a big number of color-tuned neurons and a strong entanglement between color and shape. From the analysis of these color selective neurons, some parallelisms with biological vision system emerged: (a) color opponency clearly comes up in the first layer, presenting 4 main axes (Black-White, Red-Cyan, Blue-Yellow and Magenta-Green), but this is reduced and rotated as we go deeper into the network; (b) in layer 2 color selectivity is tuned to a more dense sampling and opponency is practically reduced to one new main axis, the Bluish-Orangish, that coincides with the dataset bias; (c) in layers 3, 4 and 5 color neurons present similar behavior detecting specific colored patterns, like specific colored objects (e.g., orangish faces), surrounds (e.g., top blue sky) or object-surround configurations (e.g. red blob in a green surround as a ladybug detector). Overall, our work is revealing certain analogies between CNN intermediate representations and evidences reported in studies of color encoding in primate brains.

W3: HDR AND MOVIE PRODUCTION

Chair/Convener: Jérémie Gerhardt, IRYStec Software Inc. (Canda)

Speakers/Abstracts:

VFX/Feature animation: HDR—What Has and Hasn't Changed, *Sean Copper, DoubleNegative (UK)*

HDR Post-production, *Chris Davies, post production consultant (Canada)*

Image Display, *Timo Kunkel, Dolby Laboratories, Inc. (USA)*

The Art of Shaping Color Images, *Dermot Shane, colorist/finishing artist (Canada)*
"Some painters transform the sun into a yellow spot, others transform a yellow spot into the sun," said Pablo Picasso. Shaping the images the director and cinematographer bring to a colorist can get a bit tricky when the ground shifts substantially, and the next generation of HDR seems to be a substantial shift in the thought processes. Typically the camera cannot capture the sun, and we create the "feeling" of having the sun in a frame, Picasso's "transform the sun into a yellow spot" is the thought system embedded in post production. When the day comes that we can display a dynamic range great enough to create the feeling of staring at the sun, we will be challenged to become the painters who "transform a yellow spot into the sun". Ultimately staring into the sun is not a great way to tell a story and keep an audience connected to the plot line, story arc and character development, making the audience turn away is not a typical goal of filmmakers. Much like the early days of stereoscopic 3D, it became apparent that ramping convergence down to flat when cutting from a wide to a tight shot was necessary to avoid causing headaches in the audience, cutting from a night interior shot to a day exterior with a future display system capable of showing 10,000+ nit is very distracting, at a minimum. So when we can see the sun on a display, we will have to think about becoming Picasso's artists that create a "yellow spot representing the sun". And that is in short the focus of what as a colorist working on grading HDR content would like to discuss.

TBA, *cinematographer*

18:15 – 19:30
WELCOME RECEPTION
Pinnacle Harbourfront Hotel, Vista 360, 19th Floor

NOTES

9:00 – 10:00
WELCOME AND OPENING KEYNOTE
Session Chair: Marius Pedersen, Norwegian University of Science and Technology (Norway)

Size uniformity is one of the prominent features of superpixels. However, size uniformity rarely conforms to the varying content of an image. The chosen size of the superpixels therefore represents a compromise—how to obtain the fewest superpixels without losing too much important detail. We present an image segmentation technique that generates compact clusters of pixels grown sequentially, which automatically adapt to the local texture and scale of an image. Our algorithm liberates the user from the need to choose of the right superpixel size or number. The algorithm is simple and requires just one input parameter. In addition, it is computationally very efficient, approaching real-time performance, and is easily extensible to three-dimensional image stacks and video volumes. We demonstrate that our superpixels superior to the respective state-of-the-art algorithms on quantitative benchmarks.

10:00 – 10:40
PICTURE PERFECT
Session Chair: Jonathan Phillips, Google Inc. (USA)

We propose a daltonization method that enhances chromatic edges and contrast for color-deficient people by optimizing the gradient of an image. We rotate and scale the error gradient between the original and its simulation in the color space into the direction of optimal visibility that is orthogonal to both the main direction of information loss and the direction of lightness. Then, we reintegrate the daltonized image version from the modified gradient through an iterative diffusion process. Moreover, we include multiscaling to guarantee optimal daltonization on different scales of the image. Also, we provide an interface for data attachment modules designed to maintain naturalness of memory colors like neutral colors. We evaluate and compare our proposed method to other top-performing daltonization methods in behavioral and psychometric experiments. A visual-search experiment assessing performance of the attentional mechanism of the human visual system before and after daltonization measures the greatest improvement in accuracy for our proposed method compared to the original and all investigated daltonization methods. It also reveals optimal results for both natural and Ishihara images among both protan and deutan color-deficient observers. Furthermore, we can deduce from the results of a pairwise preference evaluation that our proposed method is preferred highest amongst all color-deficient people in total. Our proposed method is also ranked among the most preferred daltonization methods for both protan and deutan color-deficient observers individually.

Texture features can be considered as methods for encoding an image: taking pixel intensities or filter responses and forming them into a description which can be used to solve problems including recognition and matching. In this paper we are considering the inverse problem: given a textural representation of an image, how well can we recover the original.

We show how the LBP method encodes comparative relationships between pixels and relative to these relations we can recover an image with our new method. We extend the recovery method to work with the Sudoku texture representation (an extension of LBP). We show that this method produces a reconstruction more correlated with the original image than the prior art.

10:40 – 11:20 — Coffee Break / Exhibit Open

11:20 – 12:40
WRANGLING COLOR
Session Chair: Abhijit Sarkar, Microsoft Inc. (USA)

OLED display technology is gaining popularity among original equipment manufacturers (OEM). Production costs are decreasing, making this technology more readily available. OLED displays have a better contrast, no backlight and the ability to estimate the contribution of each pixel to the power of the display. This feature allows to experiment spatial algorithms to improve the image quality in relation to its power consumption.

In this article we present a framework to evaluate the performance of spatial algorithms such as just noticeable distortion and saliency maps on OLED displays. We introduce a comprehensive power model that takes into account each pixel value and the display screen brightness. We validate the effectiveness of this model by implementing a power reduction method based on power saving and perceptual quality metric.

Scenes with back-light illumination are problematic when captured with a typical LDR camera, as they result in dark regions where details are not perceivable. In this paper, we present a method that, given an LDR backlit image, outputs an image where the information that was not visible in the dark regions is recovered without losing information in the already well-exposed parts of the image. Our method has three main steps: first, a variational model is minimized using gradient descent, and the iterates of the minimization are used to obtain a set of weight maps. Second, we consider the tone-mapping framework that depends on four parameters. Two different sets of parameters are learned by dividing the image in the darker and lighter parts. Then, we interpolate the two sets of parameter values in as many sets as weighting maps, and tone-map the original image with each set of parameters. Finally, we merge the new tone-mapped images depending on the weighting maps. Results show that our method outperforms current backlit image enhancement approaches both quantitatively and qualitatively.

Color imaging involves a variety of processing operations, from interpolation, via matrix transformation, to smoothing and predictive modeling. Since colors can be represented as coordinates in color space, the general methods of mathematics can be applied to them. However, if color coordinates are treated simply as generic spatial coordinates, their processing can have undesirable consequences, deriving from a disconnect between the coordinates representing a color and the color formation properties resulting in it. E.g., interpolating among colors with very different lightnesses may lead to a grainy result in print, or varying the interpolation support when processing a transition may lead to unwanted cross-contamination of colorants. To address such challenges, the present paper proposes two color processing algorithms that do take the color properties of processed coordinates into account. They can therefore, in some sense, be thought of as "color color" processing algorithms rather than as geometric or mathematical color processing ones. The consequences of making color-native choices when processing color data then are improved transitions, "purity" and grain.

Local Focus: Simon Fraser University and CIC, with introduction by Graham Finlayson, University of East Anglia (UK)

As a computer scientist, I approach questions of colour and colour perception from a computational viewpoint—in other words, as a process rather than a model. From this vantage point, I will first discuss the theoretical and practical limits of metamer mismatching, along with some important conclusions and applications that follow. In particular, I will show how quantifying the extent of metamer mismatching is useful in evaluating both the colour rendering properties of lights and the colour fidelity of cameras; and, as well, how metamer mismatching provides a potential explanation as to why colour discrimination varies throughout colour space. I will then consider how 'colourization' techniques developed by the computer vision community can be applied to trichromatic and dichromatic images, both for automatic white balancing of images obtained under spatially varying illumination, and to gain potential insight into the experience of colour blindness.

12:40 – 14:00

LUNCH ON OWN

14:00 – 15:00

PLAYING WITH COLOR

Session Chair: Susan Farnand, Rochester Institute of Technology (USA)

A method is proposed for appearance reconstruction of 3D fluorescent objects including mutual illumination effect under different conditions of material and illumination. First, we acquire the spectral images of the scene of two fluorescent objects under different illumination directions. The observed images are decomposed into five components of (1) diffuse reflection, (2) diffuse interreflection, (3) self-luminescence by direct illumination, (4) self-luminescence by indirect illumination, and (5) interreflection by fluorescent illumination. Each component is described by the multiplication of the spectral functions and the geometric factors. The surface shape information is estimated from the first geometric factor corresponding to diffuse reflection. Second, the reference geometric factors, independent of illumination direction, are estimated from the observed geometric factors and the surface normals. Third, a new appearance of the two fluorescent object scene is reconstructed under the fixed viewpoint but the arbitrary conditions of fluorescent material and illumination. The spectral image is reproduced by the linear sum of combining the spectral functions and the predicted geometric factors. Finally, the feasibility of the proposed method is shown in experiments using different fluorescent materials and illumination condition.

Psychophysical experiments were conducted to study hue linearity property on an HDR display using a 3-D cube. These constant hue data collected covering larger range lightness and colour areas. This and the other three existing datasets were combined to evaluate the hue linearity performance of four uniform colour spaces (UCSs), including CIELAB, CAM16-UCS, IPT and $J_za_zb_z$. The experimental results indicated that IPT and $J_za_zb_z$ outperformed the other two, especially in blue region. The present HDR dataset and the combined dataset, covered larger colour gamut, are recommended to test hue linearity property of UCSs in future HDR/WCG applications.

The goal of this work is to provide a guideline to produce high quality chromatic contrast sensitivity (CCS) data at low frequencies, and to contrast with the previously published data. An experiment was carried out using forced-choice stair-case method to investigate the CCS just noticeable difference (JND) in different color changing directions at different spatial frequencies. The JND ellipses at different spatial frequencies were fitted and compared with those earlier studies. The results from a white and a green center were reported. They provided theoretical basis and standard practice for the lighting and the imaging industries.

15:00 – 15:35

TWO-MINUTE INTERACTIVE PAPER PREVIEWS I

Session Chairs: Javier Vazquez-Corral, Universitat Pompeu Fabra (Spain), and Youngshin Kwak, Ulsan National Institute of Science and Technology (South Korea)

Raw images are more useful than JPEG images for machine vision algorithms and professional photographers because raw images preserve a linear relation between pixel values and the light measured from the scene. A camera is radiometrically calibrated if there is a computational model which can predict how the raw image is mapped to the corresponding rendered image (e.g., JPEGs) and vice versa. Our method makes use of the observation that the rank order of pixel values is mostly preserved post-color correction. We show that this observation is the key for getting a compact and robust radiometric calibration model. Since our method requires fewer variables, it can be solved for using less calibration data. An additional advantage is that we can derive the camera pipeline from a single pair of raw–JPEG images. Experiments demonstrate that our method delivers state-of-the-art results (especially for the most interesting conversion from JPEG to raw).

Measuring the spectral responsivity of a camera using a monochromator is time-consuming and expensive. This work evaluates a fast responsivity measurement method, where diffraction spectrum images are captured and then used for estimating camera responsivity. An error was noticed in the previously proposed measurement method that was caused by spectroradiometer measurement errors and vignetting effects from the camera's lens and sensor. Therefore, a correction step using chromaticity error minimisation is presented to adjust the initial responsivity estimate. It requires a chart to be captured under a known illumination. The chromaticity error of the improved procedure is approximately one order of magnitude smaller than the original error. This enhanced method was employed to create a dataset of spectral responsivities for machine vision, photographic, and movie cameras, which is presented here.

The two classic image restoration tasks, demosaicing and super-resolution, have traditionally always been studied independently. That is sub-optimal as sequential processing, demosaicing and then super-resolution, may lead to amplification of artifacts. In this paper, we show that such accumulation of errors can be easily averted by jointly performing demosaicing and super-resolution. To this end, we propose a deep residual network for learning an end-to-end mapping between Bayer images and high-resolution images. Our deep residual demosaicing and super-resolution network is able to recover high-quality super-resolved images from low-resolution Bayer mosaics in a single step without producing the artifacts common to such processing when the two operations are done separately. We perform extensive experiments to show that our deep residual network achieves demosaiced and super-resolved images that are superior to the state-of-the-art both qualitatively and quantitatively.

LED-based tunable luminaires are capable of reproducing with high degree of fidelity a variety of constant and time-varying illuminants. The quality of a particular light source is characterized by color-rendering fidelity metrics (CRI, CIE-51, and more recently, TM-30), which quantify the closeness in appearance of a specific set of color evaluation samples under a test light source and a reference source. We present an approach to optimizing the output of a multi-channel light source for any desired illumination spectra and for any given set of color evaluation samples; discuss examples of useful lighting other than thermal and daylight illuminants and the value of time-changing illumination; and describe the basic operation of illumination player.

We present a general multiscale strategy for perceptually-inspired contrast enhancement of color images. The idea behind this methodology comes from a recent wavelet-based variational framework for contrast intensification. We will show that the equations for the wavelet coefficients coming from the variational setting can be re-written in a more general multi-resolution framework, where the only requirement is the existence of an approximation and a detail layer at each different scale. In particular, we will show that a Laplacian pyramid implementation of the variational algorithm performs faster and better than the wavelet-based one. These results open the possibility to efficiently apply the contrast enhancement equations also to video sequences.

New reversible saturation, vividness, blackness and whiteness models were developed based on a visual data. The aim of this study is to develop a model that can be applicable to imaging devices and to enhance the images by controlling one of the scales. It was found that the models gave good predictions with the NCS (Natural Colour System) data. The newly developed models are applicable to colour image evaluation and image enhancement.

The current CIE colour appearance model CIECAM02 and its variant named CAM16 can well predict common colour appearance attributes including lightness, brightness, chroma, colourfulness, saturation, hue angle, and hue composition. These models are complicated as well as have mathematical problems. The current study aimed a new colour appearance model based on $J_za_zb_z$ color space to obtain either better or similar performance compared with CAM16 but the new model should be computationally simple and robust. Such a model will particularly be suitable for color management in high dynamic range and wide color gamut applications. A range of experimental data were collected and a set of equations was derived. Some initial test results are presented in this paper.

Augmented reality (AR) is growing in popularity, blending virtual objects into the real world, and one challenge it demands is the detailed colorimetric study. This research comprises two parts: a model of the displays in a commercial AR optical see-through head-mounted display (OST-HMD) was made using colorimetric measurements and spatial characterization, followed by a color matching experiment to explore the matching criteria when matching nonuniform colors in AR. The OST-HMD model was constructed by combining a traditional display model with camera-measured spatial luminance maps. Data from the color matching experiment were compared with the spatial model in order to infer the observers' matching criteria when matching nonuniform patches. The experimental result suggests that the matching criterion is most likely position- or content-guided and measurably different from other possible criteria. The results can be used to improve uniformity in OST-HMDs and as a reference in modeling color appearance in AR.

Comparative Evaluation of Color Differences between Color Palettes, *Qianqian Pan and Stephen Westland, University of Leeds (UK)* **110**
The difference or distance between two color palettes is a metric of interest in color science. It allows a quantified examination of a perception that formerly could only be described with adjectives. Quantification of these properties is of great importance. The objective of this research is to obtain the dataset for perceptual colour difference between two color palettes and develop color difference metric(s) to correspond well with the perceptual color difference. The psychophysical experiment was carried out using Magnitude Estimation method. Three different color difference metrics, namely Single Color Difference Model (Model 1), Mean Color Difference Model (Model 2), and Minimum Color Difference Model (Model 3), respectively, have been proposed and compared. Data analysis include regression analysis, statistical STRESS analysis, and examination of observer variability using coefficient of variance (CV). The results show that the Minimum Color Difference Model (Model 3) outperformed the other two with a coefficient of determination (R-squared) value of 0.603 and an STRESS value of 20.95. In terms of observer variability, the average intra-observer variability is 17.63 while the average inter-observer variability is 53.73.

Color Quality and Memory Color Assessment, *Anku and Susan Farnand, Rochester Institute of Technology (USA)* **116**
With the rise in high quality displays and cameras following the mainstream adoption of smartphones, the color quality of images is becoming an essential aspect of engaging and attracting consumers. A color quality assessment (CQA) would provide insights into what users perceive and could be put to use when engineering cameras and displays. Twenty cameras were used to capture pictures of common objects like grass, sky, wood, and sand. CQA for common objects was performed using a rank order perceptual testing method, where the observers were asked to rank images of the same object captured by 20 different cameras according to their order of CQA. We confirm the results of the Rank CQA, by performing an Anchored Scaling experiment where the lower anchor is the least ranked and the higher anchor is the highest ranked image from the rank order CQA. The results of this test were generally consistent with the results of the CQA. We also evaluated memory colors using Method of Adjustment. Observers were asked to recreate their memory color for the common objects used in the CQA by adjusting a uniform color patch in CIELAB space. The results for the CQA shows that the preferred camera varies across the images of common objects. The results for the memory color experiment vary across the observers as they can be influenced by geographical locations, cultural backgrounds and other such factors. The results for both the experiments were then combined to compare how the memory color of observers differs from the actual color of the object images.

A Parametric Colour Difference Equation to Evaluate Colour Difference Magnitude Effect for Gapless Printed Stimuli, *Fereshteh Mirjalili and Ming Ronnier Luo, Zhejiang University (China); Guihua Cui, Wenzhou University (China); and Ján Morovic, HP Inc. (Spain)* **123**
In the present study, attempts were made to investigate the effect of colour difference magnitude on colour difference perception of pairs with no separation. To this end, a large number of printed sample pairs with no separation were prepared around 11 CIE recommended colour centres. The sample pairs, representing four colour difference magnitudes of 1, 2, 4 and 8 CIELAB units, were visually evaluated by a panel of 19 observers using the grey scale method. By comparing the present data set with those previously published using pairs with hair-line separation, it was found that separation had a certain impact on colour difference perception. The visual data were used to test the performance of five colour difference formulae: CIELAB, CIE94, CIEDE2000, CAM02-UCS, and CAM16-UCS. A clear effect of colour difference magnitude on total colour difference perception of pairs with no separation was revealed and a generic simple equation was modelled. By introducing this, a new colour difference equation as the modification of CIEDE2000 was proposed for pairs with no separation. The new formula was found to perform much more precise than the original formulae.

The Effect of Surface Texture on Color Appearance of 3D Printed Objects, *Matthew Ronnenberg and Susan Farnand, Rochester Institute of Technology (USA)* **128**
3D printing has become an increasingly popular and affordable technology in recent years due to rapid technological advances. One such advancement is the ability to print a single object with multiple colors. Traditional printers work on the assumption that the surface they are printing to is flat, which further assumes that surface geometry has a negligible effect on appearance. The International Color Consortium (ICC) builds profiles allowing for color communication amongst devices, including traditional 2D printers. The ICC does not currently have practices in place to build profiles for color 3D printers, due in part to several unknown parameters affecting the appearance of 3D printed objects. One such unknown is surface texture. To test the effect of surface texture on the color appearance of 3D printed objects, 3D models were built digitally with goniochromatic effects in mind and then printed using a color 3D printer. Spectral radiance and BRDF measurements of the 3D printed samples were taken to test for changes in appearance. It was found that surface texture does have a measurable effect on the color appearance of 3D printed objects, which is an important first step in creating a characterization space for color 3D printers.

A Robust Algorithm for Computing Boundary Points of the Metamer Mismatch Body, *Tarek Stiebel and Dorit Merhof, RWTH Aachen University (Germany)* **134**
Metamer mismatching is a challenging element of both human and machine color vision. In this work, the theory yielding the description of the metamer mismatch body proposed by Logvinenko is revisited. An algorithm is proposed capable of robustly solving the original equations which precisely describe the boundary of the metamer mismatch body. Additionally and in contrast to before, the requirement for illuminants to be strictly positive is suspended. This is achieved by no longer associating boundary points of the metamer mismatch body with optimal reflectance functions.

The algorithm has been abstracted to deal with sensors of arbitrary dimensionality, making it applicable to multi-spectral imaging.

White Balance under White-Light LED Illumination, *Siyuan Chen and Minchen Wei, The Hong Kong Polytechnic University (Hong Kong)* . . . **140**
Conventional light sources (e.g., fluorescent) contain UV/violet radiations that can excite the fluorescent whitening agents (FWAs) in man-made and natural white objects to enhance whiteness appearance and create different degrees of white. Typical white-light LED sources, however, contain little UV/violet radiation to increase its luminous efficacy. In this study, we

investigated how the failure of white-light LEDs to excite FWAs affect the image color appearance with different white balance algorithms. A same setup, including a Macbeth ColorChecker and three whiteness standards with different amount of FWAs, were illuminated by two 6500 K illuminants with different levels of UV/violet radiation. The captured RAW images were white balanced using 10 algorithms. It was found the failure of FWA excitation produced noticeable color differences, with an average ΔE from 2.9 to 8.1 in the CIELAB color space. The algorithms based on the Gray World assumption were generally less sensitive to the FWA excitation, in comparison to those based on the Retinex theory.

Converting the Images without Glossiness into the Images with Glossiness by Using Deep Photo Style Transfer, *Kensuke Fukumoto[1], Junki Yoshii[1], Yuto Hirasawa[1], Takashi Yamazoe[1], Shoji Yamamoto[2], and Norimichi Tsumura[1]; [1]Chiba University and [2]Tokyo Metropolitan College of Industrial Technology (Japan)* **145**
In this paper, we propose an image conversion method to transfer the images without glossiness into the images with glossiness by using deep photo style transfer technique. The deep style photo transfer can be expected to reproduce a desired image with metallic appearance based on the texture transfer technique. Our practical challenge was performed to create the gold metallic image by transferring a style image of the gold ingot. Two kinds of stile images where one gold ingot and assembled mass of gold ingots were tested to verify how degree of complexity in style image is appropriate for our propose using deep neural network. In order to avoid an excessive loss of color balance, we also applied the YC_rC_b separation technique and used only Y component to learn the only style of gloss appearance. Moreover, the luminance and saturation of the style image were changed to investigate the influence into the converted appearance, since the converted appearances are expected to have the dependence with the contents of the images. These transferred results by changing the luminance and saturation of style image were evaluated by subjective evaluation using semantic differential method. As the results, it is found that the style image with an appropriate amount of contrast change is suitable for appropriate gloss appearance, then showed that there is appropriate selection of contrast in style image depending the contents of original images.

LMMSE Demosaicing for Multicolor CFAs, *Prakhar Amba and David Alleysson, Université Grenoble Alpes (France)* **151**
Digital cameras overlay a Color Filter Array (CFA) over the sensor which sub-samples the color information of the scene. The full color image is then recovered using a class of algorithms known as demosaicing. The color filters used for CFA are predominantly Red, Green and Blue. In this article we propose an algorithm based on Linear Minimum Mean Square Error (LMMSE) which can demosaic images from any color (linear combination of Red, Green and Blue) filter arranged in any order in the CFA. We also propose optimum CFAs based on combination of RGB colors which outperform the state of art CFAs in image reproduction with less computational complexity.

15:35 – 16:20 — Coffee Break / Exhibit Open

16:20 – 17:40

PUTTING COLOR TO WORK

Session Chair: Sabine Süsstrunk, École Polytechnique Fédérale de Lausanne (Switzerland)

16:20 **Comparison of Non-Contact Camera based Methods to Measure the Pulse Rate for Awake Infants,** *Takuma Kiyokawa[1], Kaoru Kiyomitsu[1], Roman Bednarik[2], Keiko Ogawa-Ochiai[3], and Norimichi Tsumura[1]; [1]Chiba University (Japan), [2]University of Eastern Finland (Finland), and [3]Kanazawa University Hospital (Japan)* **157**
Non-contact camera based methods to measure the pulse rate have been introduced in recent years. However, the previous research conducted experiments only for adults and/or sleeping infants, not for awake infants. In this paper, we compare the principal non-contact camera based methods and identify a suitable method for awake infants. We measured the pulse rate of five adults and three infants and obtained the success rate of setting the measurement region and RMSE of estimated pulse rates for several existing methods. The color based method and is the Independent component analysis are the most suitable methods for setting the measurement region and signal processing, respectively.

16:40 **Can Image Enhancement be Beneficial to Find Smoke Images in Laparoscopic Surgery?,** *Congcong Wang[1], Vivek Sharma[2], Yu Fan[1], Faouzi Alaya Cheikh[1], Azeddine Beghdadi[3], Ole Jacob Elle[4,5], and Rainer Stiefelhagen[2]; [1]Norwegian University of Science and Technology (Norway), [2]Karlsruhe Institute of Technology (Germany), [3]University Paris 13 (France), [4]Oslo University Hospital (Norway), and [4]Oslo University (Norway)* **163**
Laparoscopic surgery has a limited field of view. Laser ablation in a laproscopic surgery causes smoke, which inevitably influences the surgeon's visibility. Therefore, it is of vital importance to remove the smoke, such that a clear visualization is possible. In order to employ a desmoking technique, one needs to know beforehand if the image contains smoke or not, to this date, there exists no accurate method that could classify the smoke/non-smoke images completely. In this work, we propose a new enhancement method which enhances the informative details in the RGB images for discrimination of smoke/non-smoke images. Our proposed method utilizes weighted least squares optimization framework (WLS). For feature extraction, we use statistical features based on bivariate histogram distribution of gradient magnitude (GM) and Laplacian of Gaussian (LoG). We then train a SVM classifier with binary smoke/non-smoke classification task. We demonstrate the effectiveness of our method on Cholec80 dataset. Experiments using our proposed enhancement method show promising results with improvements of 4% in accuracy and 4% in F1-Score over the baseline performance of RGB images. In addition, our approach improves over the saturation histogram based classification methodologies Saturation Analysis (SAN) and Saturation Peak Analysis (SPA) by 1/5% and 1/6% in accuracy/F1-Score metrics.

We can employ our enhancement method in replacement of RGB images for classifier training e.g., CNN architectures, which in turn can lead to more accurate classification. Code will be released for public use.

17:00 **JIST-First Dual-Band Infrared Video-based Measurement Using Pulse Wave Maps to Analyze Heart Rate Variability,** *Ryota Mitsuhashi[1], Keiichiro Kagawa[2], Shoji Kawahito[2], Chawan Koopipat[3], and Norimichi Tsumura[1]; [1]Chiba University (Japan), [2]Shizuoka University (Japan), and [3]Chulalongkorn University (Thailand)* **169**

Remote photoplethysmography (rPPG) enables us to capture the vital signs such as pulse rate, respiratory rate, oxygen saturation, and even heart rate variability (HRV) without any contact devises. Although the papers of rPPG mainly focus on the use of standard RGB camera, it cannot used for the cases in night or under the dim light conditions. Therefore, in this paper, we propose a novel noncontact method for monitoring HRV without visible lighting. The proposed method uses dual-band infrared videos to ensure robustness to fluctuations in illumination. The hemoglobin component is extracted via a simple projection from the dual-band pixel values in logarithmic space. We demonstrate the accurate extraction of pulse wave signals using pulse wave maps. As the results, we indicated the effectiveness of HRV monitoring in the situation under the dim light condition.

17:20 **JIST-First Multi-Spectral Pedestrian Detection via Image Fusion and Deep Neural Networks,** *Geoff French, Graham Finlayson, and Michal Mackiewicz, University of East Anglia (UK)* **176**

The use of multi-spectral imaging has been found to improve the accuracy of deep neural network-based pedestrian detection systems, particularly in challenging night time conditions in which pedestrians are more clearly visible in thermal long-wave infrared bands than in plain RGB. In this article, the authors use the Spectral Edge image fusion method to fuse visible RGB and IR imagery, prior to processing using a neural network-based pedestrian detection system. The use of image fusion permits the use of a standard RGB object detection network without requiring the architectural modifications that are required to handle multi-spectral input. We contrast the performance of networks trained using fused images to those that use plain RGB images and networks that use a multi-spectral input.

20:15 – 21:00
WEDNESDAY EVENING TALK

Grab a drink at the bar and join colleagues for an interesting evening talk.
Session Chair: Alex Forsythe, Academy of Motion Picture Arts and Sciences (USA)

Color in Narrative, *Andrea Chlebak, feature film colorist (Canada)**

Color is an often subtle layer in the process of filmmaking. It adds dimension by enhancing or creating atmosphere, calling attention to certain details, or adding meaning by establishing a palette to a certain character. As a supervising colorist for feature, documentary, and commercial films, the speaker sheds light on the process of coming to a final look for a film; she'll discuss her use of experimentation, intuition, and perception as a toolset to determine how blue, dark, or saturated to make an image, and how she collaborates with directors and cinematographers to enhance the narrative through color.

**No proceedings paper.*

Thursday 15 November 2018

9:00 – 10:00
THURSDAY KEYNOTE

Session Chair: Maria Vanrell, Universitat Autònoma de Barcelona (Spain)

Sponsored by HP Inc.

9:00 **Colour and Consumer Cameras: The Good, the Bad, the Ugly,** *Michael Brown, York University (Canada)**

Cameras are now used for many purposes beyond taking photographs. Example applications include remote medical diagnosis, crop monitoring, 3d reconstruction, document recognition, and many more. For such applications, it is desirable to have a camera act as a sensor that directly measures scene light. The problem, however, is that most commodity cameras apply a number of camera-specific processing steps to the captured image in order to produce visually pleasing photos. As a result, different cameras produce noticeably different colors when imaging the exact same scene. This is problematic for applications relying on color because algorithms developed using images from one camera often will not work with images captured on another camera due to color differences. In this talk, I'll discuss the current state of affairs for color on commodity cameras, common incorrect assumptions made in the scientific literature regarding image color, and recent developments that are helping to improve the situation.

10:00 – 12:00
EXPOSING COLOR

Session Chair: Eric Wallowit, consultant (USA)

Recipient of the CIC26 Best Paper Award

10:00 **Using a Simple Colour Pre-Filter to Make Cameras more Colorimetric,** *Graham Finlayson, Yuteng Zhu, and Han Gong, University of East Anglia (UK)* **182**

The idea of placing a coloured filter in front of a camera to make it more colorimetric has been previously proposed. However, this prior art approach sought to increase the dimensionality of the capture—*i.e.,* to take an image with and without a filter—rather than to change the spectral characteristics of the sensor itself.

In this paper, we set out a new method for finding the filter that, in a least-squares sense best achieves the Luther condition. That is, the filter multiplied by the camera spectral sensitivities is 'almost' a linear combination from the colour matching functions of the human visual system. We show that for a given sensor set the best filter and best linear mapping can be found together by solving an alternating least-squares problem.

Experiments demonstrate that placing an optimal filter in front of a camera can result in a dramatic improvement in its ability to see the world colorimetrically.

10:20 **Efficient Multispectral Facial Capture with Monochrome Cameras,** *Chloe LeGendre, Kalle Bladin, Bipin Kishore, Xinglei Ren, Xueming Yu, and Paul Debevec; USC Institute for Creative Technologies (USA)* **187**

We propose a variant to polarized gradient illumination facial scanning which uses monochrome instead of color cameras to achieve more efficient and higher-resolution results. In typical polarized gradient facial scanning, sub-millimeter geometric detail is acquired by photographing the subject in eight or more polarized spherical gradient lighting conditions made with white LEDs, and RGB cameras are used to acquire color texture maps of the subject's appearance. In our approach, we replace the color cameras and white LEDs with monochrome cameras and multispectral, colored LEDs, noting that color images can be formed from successive monochrome images recorded under different illumination colors. While a naive extension of the scanning process to this setup would require multiplying the number of images by number of color channels, we show that the surface detail maps can be estimated directly from monochrome imagery, so that only an additional n photographs are required, where n is the number of added spectral channels. We also introduce a new multispectral optical flow approach to align images across spectral channels in the presence of slight subject motion. Lastly, for the case where a capture system's white light sources are polarized and its multispectral colored LEDs are not, we introduce the technique of multispectral polarization promotion, where we estimate the cross- and parallel-polarized monochrome images for each spectral channel from their corresponding images under a full sphere of even, unpolarized illumination. We demonstrate that this technique allows us to efficiently acquire a full color (or even multispectral) facial scan using monochrome cameras, unpolarized multispectral colored LEDs, and polarized white LEDs.

10:40 – 11:20 — Coffee Break / Exhibit Open

11:20 **JIST-First Demosaicing of Periodic and Random Color Filter Arrays by Linear Anisotropic Diffusion,** *Jean-Baptiste Thomas and Ivar Farup, Norwegian University of Science and Technology (Norway)* **203**

The authors develop several versions of the diffusion equation to demosaic color filter arrays of any kind. In particular, they compare isotropic versus anisotropic and linear versus non-linear formulations. Using these algorithms, they investigate the effect of mosaics on the resulting demosaiced images. They perform cross analysis on images, mosaics, and algorithms. They find that random mosaics do not perform the best with their algorithms, but rather pseudo-random mosaics give the best results. The Bayer mosaic also shows equivalent results to good pseudo-random mosaics in terms of peak signal-to-noise ratio but causes visual aliasing artifacts. The linear anisotropic diffusion method performs the best of the diffusion versions, at the level of state-of-the-art algorithms.

11:40 **Demosaicing Using Dual Layer Feedforward Neural Network,** *Prakhar Amba, David Alleysson, and Martial Mermillod, Université Grenoble Alpes (France)* **211**

Color demosaicing is the problem of recovering full color/spectral channel from a subsampled image captured by single-chip digital cameras covered by Color Filter Array (CFA). Several algorithms have been proposed in the literature, however most of them are tuned to a particular arrangement of color filters. In this paper, we propose a generic algorithm based on a simple Neural Network (NN) architecture, which is trained on a small image database and which gives competitive results. To prove our statement, we test our network on several state of art CFAs and a 5 channel Spectral Filter Array (SFA). We demonstrate our result both on simulated images coming from standard image databases and also RAW images for a 5 channel SFA camera.

12:00 – 12:35

TWO-MINUTE INTERACTIVE PAPER PREVIEWS II

Session Chairs: Javier Vazquez-Corral, Universitat Pompeu Fabra (Spain), and Youngshin Kwak, Ulsan National Institute of Science and Technology (Korea)

Evaluation of High Dynamic Range TVs Using Actual HDR Content, *Sungjin Kim, Yongmin Park, Dongwoo Kang, Jongjin Park, Jangjin Yoo, Jonguk Bae, and Sooyoung Yoon, LG Display Co., Ltd. (South Korea)* . **219**

High Dynamic Range (HDR) content standards such as HDR10, Dolby Vision, HLG (Hybrid Log Gamma) have been presented over a last couple of years, and these standards commonly have both wider dynamic range and color gamut than that of the legacy content. However, it is practically hard to fully satisfy the HDR content standards with the current TV technology. Although various standards for display metrology regarding HDR content standards have been released to evaluate the performance of HDR TVs, it has been controversial whether the performance obtained from measurements using artificial test patterns is well consistent with the actual performance of HDR TVs from which viewers are expecting. For this reason, we examined how the performance of HDR TVs is varied in case measurements are made using actual HDR contents instead of artificial test patterns in terms of peak luminance, black level, and Electro-Optical Transfer Function (EOTF) accuracy. Our investigation was carried out using two different types of TV, an Organic Light Emitting Diode (OLED) and a Liquid Crystal Display (LCD). As a result, while the measurements of the OLED TV were quite coincided with the measurements made from artificial test patterns, those of the LCD TV were not.

Colour Image Gradient Regression Reintegration, *Graham D. Finlayson, University of East Anglia (UK), and Mark S. Drew and Yasaman Etesam, Simon Fraser University (Canada)* **225**

Suppose we process an image and alter the image gradients in each colour channel R,G,B. Typically the two new x and y component fields p,q will be only an approximation of a gradient and hence will be nonintegrable. Thus one is faced with the problem of reintegrating the resulting pair back to image, rather than derivative of image, values. This can be done in a variety of ways, usually involving some form of Poisson solver. Here, in the case of image sequences or video, we introduce a new method of reintegration, based on regression from gradients of log-images. The strength of this idea is that not only are Poisson reintegration artifacts eliminated, but also we can carry out the regression applied to only thumbnail images. The novel approach here is to regress derivatives (using only thumbnails) and then replace reintegration itself by the much simpler use of the resulting regression coefficients on non-derivative, full-size images. We investigate the utility of the method by applying it to the intrinsic-image problem as a first test, and then also to the night-to-day problem as a second test. We find that the new algorithm performs well, and is fast. Moreover eliminating Poisson artifacts results in clearer, more sharp output images that can show far less ghosting.

Effective Boundary for White Surface Colour, *Yuzhao Wang[1], Xi Lv[1], Shining Ma[2], Minchen Wei[3], and Ming Ronnier Luo[1]; [1]Zhejiang University (China), [2]KU Leuven (Belgium), and [3]The Hong Kong Polytechnic University (Hong Kong)* **231**

Fluorescent whitening agents (FWA) are used in the surface colour industry to increase whiteness perception. This study was aimed to define whiteness boundary according to different CCTs under different UV levels. Three sets of data were accumulated. One approach was to refine the limit of the current CIE Tint formula and the other is to apply data to fit ellipsoids in CAM02-UCS space to define whiteness boundary under different lighting conditions by minimizing the measure of 'wrong decision'. The results showed that the size and centre of ellipsoids shifted in a systematic fashion according to different CCT and ultra-violet radiation level.

The most common and popular display used with desktop personal computers and workstations is the flat-panel LCD, primarily because of low-power consumption. These devices present challenges in terms of color fidelity because of channel interaction and non-constancy of channel chromaticities. Therefore, the development of models to establish accurate color characterization is still a research problem. The main purpose of color characterization of a device is to define the transformation between RGB (the device color space) and CIEXYZ or CIELAB (reference color space). There are three different common characterization models which have been widely used in the literature for device characterization: GOG, PLCC and PLVC. All three models require the use of measured samples to characterise the non-linear response of the display. The objective of this research was to determine the effect of varying the number of linearization samples on the characterization performances for a set of 20 displays. For small numbers of linearization samples the GOG model frequently gave the best performance. However, performance using PLVC and PLCC improved markedly as the number of linearization samples increased. Improvement gains when using more than about 18 linearization samples were modest. For 18 or more linearization samples the best performance was usually obtained using PLVC although for some displays PLCC gave better performance.

Objective Image Quality Metrics (IQMs) are introduced with the goal of modeling the perceptual quality scores given by observers to an image. In this study we use a pre-trained Convolutional Neural Network (CNN) model to extract feature maps at different convolutional layers of the test and reference image. We then compare the feature maps using traditional IQMs such as: SSIM, MSE, and PSNR. Experimental results on four benchmark datasets show that our proposed approach can increase the accuracy of these IQMs by an average of 23%. Compared to 11 other state-of-the-art IQMs, our proposed approach can either outperform or perform as good as the mentioned 11 metrics. We can show that by linking traditional IQMs and pre-trained CNN models we are able to evaluate image quality with a high accuracy.

This paper proposes a unified framework for capsule video endoscopy image enhancement with an objective to enhance the diagnostic values of these images. The proposed method is based on a hybrid approach of deep learning and classical image processing techniques. Given an input image, it is decomposed spatially into multi-layer features. We estimate the base layer with pre-trained deep edge aware filters that are learned on the flicker dataset. The detail layers are estimated by the spatio-temporal retinex-inspired envelope with a stochastic sampling technique. The enhanced image is computed by a convex linear combination of the base and the detail layers giving detailed and shadow surface enhanced image. To show its potential, performance comparison between with and without the proposed image enhancement technique is shown using several video images obtained from capsule endoscopy for different parts of the digestive organ. Moreover, different learned filters such as Bilateral and L_0 norm are compared for enhancement using an objective image quality metric, BRISQUE, to show the generality of the proposed method.

In this study, we analyzed the visual difference between dry skin and wet skin for non-contact sweat detection. Recently, there are many researches on emotion recognition using some indexes related to emotion such as electrocardiogram, respiratory, skin temperature, and so on. This is because using some indexes is said to make the accuracy of emotion recognition higher and to help to recognize more various and complex emotions. Also, non-contact method is needed from view point of infection, simplicity when using, and so on. In this paper, we focused on the sweating because detecting the sweating is expected to give us important information on emotion and sympathetic nerve system. For instance, feeling nervous makes palm sweating. Therefore, we considered sweating detection may be useful for emotion recognition. Sweating is conventionally evaluated based on electrodermal activity as known as skin conductance, and that is obtained with a contact method such as attaching electrodes. However, contact methods can cause infection and prevent subjects from concentrating on stimulus to evoke emotion when sweating is used as index of emotion for emotion recognition. Then, we focused on color change caused by wetness. Because total reflection is occurred at water-air interface by water on a material and it makes the light paths longer, the color of material is changed as getting darker and more saturated by wetness. Therefore, we thought that the color change can be useful index for non-contact sweat detection. In this study, we obtained feature values with respect to color using image processing and compared those feature values of dry palm and wet palm. As a result, we found that wetness makes the mean of luminance component smaller, the mean of saturation larger, and the entropy of hue smaller.

With the development of tablet display technology, using tablet has become more and more popular for people to read news and messages. For enhancing visual comfort, many tablets are designed to change display brightness or color with surrounding conditions. Few studies, however, investigated how text-background lightness combination of a tablet should change when the color and light level of a surround change simultaneously, especially under very high light level (e.g., under daylight). In this study, twenty observers evaluated visual comfort of 20 text-background lightness combinations on an iPad Air 2 through paired comparisons under five surrounds—a dark surround and four ambient lighting conditions, comprising two levels of CCT (*i.e.*, 3500 and 6500 K) and illuminance (*i.e.*, 300 and 3000 lx). The observers judged the combination of black text with a light grey background (i.e., $L^*_{background} = 75.33$ and $L^*_{text} = 1.6$) the most comfortable when there was ambient light regardless of CCT and illuminance. This combination was also evaluated as the third most comfortable under the dark surround.

An Extension of CAM16 for Predicting Size Effect and New Colour Appearance Perceptions, *Changjun Li[1], Xiaoxuan Liu[1], Kaida Xiao[2], Yoon Ji Cho[3], and Ming Ronnier Luo[2,4]; [1]University of Science and Technology Liaoning (China), [2]University of Leeds (UK), [3]Yonsei University (South Korea), and [4]Zhejiang University (China)* **264**
CAM16 colour appearance model has been extended to predict the appearance for stimulus of varying sizes and to provide new scales to evaluate saturation, vividness, whiteness and blackness.

Does Colour Really Matter? Evaluation via Object Classification, *Brian Funt and Ligeng Zhu, Simon Fraser University (Canada)* **268**
Colour is important, but how important? This study addresses the question by testing a deep learning approach, ResNet-50, on the task of object classification based on using full-colour, dichromatic, and grayscale images as inputs and comparing the recognition performance as the amount of colour information is reduced. The results show that colour is useful, but far from crucial for object classification. The error rate increases by only 12% for the grayscale case over the full-colour case. A examination of some of the cases in which the full-colour classifier succeeds, but the grayscale classifier fails, reveals the interesting trend that while the in some cases the colour features of an object are crucial, colour may be perhaps even more important for understanding occlusion ordering and figure-ground separation.

JIST-First Effects of Material Pairs on Warmth Perception in Interiors, *Begüm Ulusoy, University of Huddersfield (UK), and Nilgün Olguntürk, Bilkent University (Turkey)* **272**
The study is the second part of a previous study which explored the effects of color pairs on warmth perception in interiors. The main aim of this study is to investigate the effects of material pairs and their single materials on warmth perception in interiors with the same methodology, since paired materials have not been investigated yet. Each material pair and their two single materials were assessed by 32 different participants, thus 96 different participants assessed three group of material models (Fabric and Timber material pair, Fabric and Plasterboard material pair, Timber and Plasterboard material pair, and their single materials) under controlled conditions. Results indicated that as single materials Timber and Fabric have the same level of warmth and are warmer than Plasterboard whereas there is no difference between their pairs. Findings revealed that these two natural materials are perceived to be warmer than the artificial one and pairing them on interior walls provides similar level of warmth.

The Effect of Neighboring Colors on Color Appearance, *Semin Oh and Youngshin Kwak, Ulsan National Institute of Science and Technology (South Korea)* **281**
This research aimed to investigate the effect of neighboring colors on color appearance. The psychophysical experiment was carried out in a dark room by using D65 standard lighting booth. Total of 5 different neighboring color conditions were used in the experiment and those were 'Reference', 'Desaturated', 'Saturated', 'Dark', and 'Light'. Total of 20 participants were invited to each neighboring color condition. Each participant evaluated hue, colorfulness, and lightness of 22 test colors by using magnitude estimation method. Result found that colors shown with the low chroma neighboring colors look more colorful and when the neighboring colors have high lightness, colors look less colorfulness and darker.

Color-based Data Augmentation for Reflectance Estimation, *Hassan Ahmed Sial, Sergio Sancho-Asensio, Ramon Baldrich, Robert Benavente, and Maria Vanrell, Universitat Autònoma de Barcelona (Spain)* **284**
Deep convolutional architectures have shown to be successful frameworks to solve generic computer vision problems. The estimation of intrinsic reflectance from single image is not a solved problem yet. Encoder-Decoder architectures are a perfect approach for pixel-wise reflectance estimation, although it usually suffers from the lack of large datasets. Lack of data can be partially solved with data augmentation, however usual techniques focus on geometric changes which does not help for reflectance estimation. In this paper we propose a color-based data augmentation technique that extends the training data by increasing the variability of chromaticity. Rotation on the red-green blue-yellow plane of an opponent space enable to increase the training set in a coherent and sound way that improves network generalization capability for reflectance estimation. We perform some experiments on the Sintel dataset showing that our color-based augmentation increase performance and overcomes one of the state-of-the-art methods.

The Preferred Type of Tone-Curve in a Transparent OLED Display, *Hyosun Kim, Young-Jun Seo, Seungbae Lee, and Sung-Chan Jo, Samsung Display Co. Ltd., and Youngshin Kwak, Ulsan National Institute of Science and Technology (South Korea)* **290**
In order to improve the image quality of a transparent OLED display, the preferred tone-curve is required to effectively reduce the influence of transmitted background. To develop such gamma correction, we compared two types of tone-curves; 1) the simple gamma correction which had one gamma value in the entire gray range and 2) the 2-gamma correction which had two different gamma values. In the experiment1, we checked the effect of two types of tone-curves on distinguishability between black and low-gray levels. Both types of tone curve were more distinguishable than 2.2 reference gamma. Although simple gamma correction had the highest distinguishability, the difference between two types decreased as the correlated color temperature (CCT) of surround lighting became lower. In the experiment2, the preferred type of tone-curve was investigated in a real transparent OLED display under various ambient surrounds. We analyzed the ratio that participants selected the preferred one between two types of tone-curves. Although simple gamma correction was chosen more, the difference decreased as the CCT of surround lightings became lower. Especially, this trend appeared clearly when the images for Public Information Display were presented. These results showed that natural images with simple gamma correction and images for PID with the 2-gamma correction were preferred.

Behavioral Investigation of Visual Appearance Assessment, *Davit Gigilashvili, Jean-Baptiste Thomas, Jon Yngve Hardeberg, and Marius Pedersen, Norwegian University of Science and Technology (Norway)* **294**
The way people judge, assess and express appearance they perceive can dramatically vary from person to person. The objective of this study is to identify the research hypotheses and outline directions for the future work based on the tasks observers perform. The eventual goal is to understand how people perceive, judge, and assess appearance, and what are the factors impacting their assessments. A series of interviews were conducted in uncontrolled conditions where observers were asked to describe the appearance of the physical objects and to complete simple visual tasks, like ranking objects by their gloss or translucency. The interviews were filmed with the consent of the participants and the videos were subsequently

analyzed. The analysis of the data has shown that while there are cross individual differences and similarities, surface coarseness, shape, and dye mixture have significant effect on translucency and gloss perception.

JIST-First Lightweight Estimation of Surface BRDFs, *James A. Ferwerda, Rochester Institute of Technology (USA)* **300**
In this article, we introduce a method for using a smartphone to estimate the bi-directional reflectance distribution functions of real-world surfaces. Specifically, we use a combination of image-based and visual techniques to determine a surface's diffuse and specular reflectance parameters in the Ward light reflection model. We test the accuracy of the method by comparing our estimates to instrumental measurements of color and gloss standards. We demonstrate its utility by rendering synthetic images of method-estimated surfaces and comparing the renderings with photographs of the real surfaces. The method provides a lightweight approach to surface reflectance measurement.

Effect of Stimulus Luminance and Adapting Luminance on Viewing Mode and Display White Appearance, *Minchen Wei and Siyuan Chen, The Hong Kong Polytechnic University (Hong Kong), and Ming Ronnier Luo, Zhejiang University (China)* **308**
Past studies found that displays and surface colors needed very different chromaticities to produce white appearance and attributed such a difference to the different degrees of chromatic adaptation caused by the viewing media. This study aimed to test whether the different chromaticities for producing white appearance were caused by viewing medium or viewing mode. Observers were asked to adjust the stimuli at different luminance levels on an iPad display until they appeared white under different adapting conditions (i.e., adapting luminance and adapting chromaticities). The results clearly suggested that the different chromaticities for producing white appearance were due to the viewing mode of the stimulus, which was jointly affected by the stimulus luminance and adapting luminance, rather than viewing medium. It also suggested the necessity to develop a comprehensive color appearance model and uniform color space for self-luminous stimuli, which will be important to the color reproduction in HDR imaging systems.

12:20 – 13:50
LUNCH ON OWN

13:50 – 15:20
DO YOU SEE WHAT I SEE?

Session Chair: Po-Chieh Hung, Apple Inc. (USA)

13:50 **Investigating Chromatic Adaptation via Memory Colour Matching Method on a Display,** *Yuechen Zhu[1], Qiyan Zhai[1], and Ming Ronnier Luo[1,2]; [1]Zhejiang University (China) and [2]University of Leeds (UK)* **313**
An experiment was carried out to investigate the incomplete chromatic adaptation on a self-luminous display using memory colour matching method. The goal was to distinguish between the chromatic adaptation and simultaneous colour contrast and develop models to predict each effect. Five adapting fields derived from a pilot visual matching experiment corresponding to four CCTs (2856K, 4500K, 6500K, 9000K) and fourteen familiar objects were studied. Twenty normal colour vision observers participated in the experiment. In total, 1400 matches were accumulated. Seventy corresponding pairs were obtained. The dataset was also conducted to test various CATs and to verify the D function in CAT02. The results showed that the chromatic adaptation for self-luminous display is more incomplete than that in the real scene, but the trend between CCT and degree of adaptation is consistent with our previous study.

14:10 **Can Trichromacy Equal Tetrachromacy?,** *Thomas Bangert and Ebroul Izquierdo, Queen Mary University of London (UK)* **318**
Although our distant ancestors once had the same visual sensor arrangement as extant birds and reptiles, colour vision in most mammals is very limited; essentially reduced to a single dimension of information produced by a pair of colour sensors, each with a fairly broad spectral response. Humans belong to a small subset of mammals that have re-developed some of the ability that was lost by their distant ancestors. They have done this by stretching the natural variation of the light absorbing pigments in one of the visual sensors, thereby adapting it toward a third colour sensor. It is generally assumed that due to the differences and limitations of this solution that colour perception in humans is fundamentally different to that of our distant relations; animals which have been able to continually extend and refine their colour vision over a period of more than two hundred million years. However, over that extended period of time the fundamentals of their colour vision have remained largely unchanged; a system of four visual sensors, each with a specific colour filter that systematically narrows the spectral response. In this paper we demonstrate that a three-sensor system with a broad spectral response (similar in spectral profile to that of the human colour sensors) can in certain conditions be equivalent to a four-sensor system (broadly similar to bird and reptile colour sensors). This suggests that human colour perception (sometimes referred to as a 'trichromatic' system) may be broadly equivalent to colour perception found in a variety of other animals such as birds or reptiles (whose colour vision is generally referred to as 'tetrachromatic'). The difference between a sensor system that uses four spectrally narrow colour sensors arranged into two opponent pairs and a three-sensor system is that the former relies on a simple difference measurement whereas the later requires the use of complex trigonometric functions—which are at least two orders of magnitude greater in computational complexity.

14:30 **Modelling Contrast Sensitivity for Chromatic Temporal Modulations,** *Xiangzhen Kong[1,3], Mijael R. Bueno Pérez[1], Ingrid M. L. C. Vogels[1], Dragan Sekulovski[2], and Ingrid Heynderickx[1]; [1]Eindhoven University of Technology (the Netherlands), [2]Signify Research (the Netherlands), and [3]Wuhan University of Technology (China)* **324**
The temporal contrast sensitivity to isoluminant chromatic flicker was measured for three observers using the method of adjustment. The isoluminant stimuli were created for each observer individually, based on a technique similar to heterochromatic flicker photometry. The chromatic flicker stimuli were sinusoidal modulations, defined in the CIE 1976 UCS (u',v') chromaticity diagram. The chromaticity varied around a base color along a certain modulation direction with a certain amplitude at a certain frequency. Nine base colors, four modulation directions and seven frequencies were used, resulting in thirty-six temporal contrast sensitivity curves per observer. An exponential model was fitted to the resulting contrast sensitivity expressed as $1/\Delta(u', v')$, $1/\Delta LMS$ and $1/\Delta lms$. The model resulted in an average R^2 value higher than 0.93 for the three different measures of contrast sensitivity. The two parameters of the model (i.e. the slope β_1 and intercept β_0) were found to significantly depend on the base color and direction of the chromatic modulation. This means that $\Delta(u', v')$, ΔLMS and Δlms are not suitable measures to predict the sensitivity to temporal chromatic modulations in different locations of the color space.

14:50 **JIST-First Quantifying Spectral Sensitivity Mismatch Using a Metameric Color Rule,** *David R. Wyble, Avian Rochester, LLC, and Roy S. Berns, Rochester Institute of Technology (USA)* **330**

A new camera metric is proposed based, in concept, on the vision test devised by Davidson and Hemmendinger. The "D&H Color Rule" is a set of two linear patch arrays containing at most one match for near-normal color observers. The match selected by an observer can provide an indication of how that observer's color vision relates to others. Comparisons may be made to a group of interest, or more commonly, to a CIE Standard Observer. For this research, two image targets have been created, one physical and one virtual, each with a family of spectra related in much the same way as the colors in the original D&H Rule. These targets can be physically imaged or virtually modeled to predict camera RGB, and then CIELAB with a color profile. The camera can then be judged as to what degree its output matches that of a CIE Standard Observer.

15:10 – 17:00

INTERACTIVE SESSION / EXHIBIT OPEN

17:00 – 17:20

A NOSE FOR COLOR

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

One Wine Many Colors, *Mark Fairchild, Rochester Institute of Technology (USA)**

"If Bacchus ever had a color he could claim for his own, it should surely be the shade of tannin on drunken lips, of John Keats's 'purple-stained mouth', or perhaps even of Homer's dangerously wine-dark sea." — Victoria Finlay

But under which illumination? The color measurement and color appearance of wine under various illumination types was examined to assess the importance of illumination in the sensory evaluation of wine. Six wines were measured in eight different spectrophotometric and spectroradiometric geometries, both in analytical cuvettes and ISO tasting glasses. The resulting spectral transmittance data were analyzed colorimetrically using two color spaces (CIELAB and CIECAM02) to examine the effects of both measurement geometry and viewing condition on the appearance of wines. The results indicate that the lighting used to view wines, as well as the lighting levels, can have significant impact on the perceived colors of wines and ultimate quality judgements.

The importance of sensory perception in wine analysis and enjoyment is introduced along with the spectral, colorimetric, and color appearance analyses that support the hypotheses that greater care should be taken in the illumination used. What this really means for the enjoyment of wine is also explored. More details on this work, including full spectral and CIELAB/CIECAM02 analyses and examination of the effects of measurement geometries, has been recently published in a comprehensive journal paper. *(Full paper available at: Fairchild MD. The colors of wine. Int J Wine Res. 2018;10:13-31. <doi.org/10.2147/IJWR.S161891>)*

19:00 – 21:30

CONFERENCE RECEPTION

Bill Reid Gallery of Northwest Coast Art

639 Hornby St, Vancouver

Friday 16 November 2018

9:00 – 10:10

CLOSING KEYNOTE AND IS&T AND CIC AWARDS

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

9:00 **High Dynamic Range on the Big Screen,** *Anders Ballestad, CEO and co-founder, MTT Innovation Inc., a Barco Company (Canada)**

High dynamic range (HDR) is slowly making its way to the big screen after firmly being established in the living room. For the cinema, there is considerable excitement around high-contrast projectors as well as LED walls. MTT has developed an HDR projector based on a new image formation technique we name dynamic lensing. Source light is steered from dark regions to bright image areas, with dramatic results: deep black levels and a peak luminance exceeding TVs and LED-walls using similar strength light sources as conventional projectors. The perceptual impact of drastically enhanced colour volume technologies will be discussed, as well as a number of open questions around the creative workflow and the potential for new experiments in color science.

10:10 – 10:50

BRIGHT IDEAS

Session Chair: Laurens Orij, Crabsalad (the Netherlands)

10:10 **Assessing Color Discernibility in HDR Imaging Using Adaptation Hulls,** *Timo Kunkel, Robert Wanat, Jaclyn Pytlarz, Elizabeth Pieri, Robin Atkins, and Scott Daly, Dolby Labs, Inc. (USA)* **336**

Objectively predicting the discernibility of color differences is a common requirement when assessing the performance of a display device and is the domain of color difference metrics. Metrics commonly used for this task assess the color discriminability of two stimuli based directly or indirectly on the viewing environment with a known, constant adaptation luminance level L_A.

These metrics were originally derived for color assessment of reflective and transmissive media as well as low dynamic range displays, where L_A can both be maintained and estimated with reasonable certainty for any likely stimulus pair. With High Dynamic Range (HDR) and Wide Color Gamut (WCG) displays, using Steady State metrics is becoming increasingly challenging when assessing the discernibility of two similar stimuli over the display's full range of capability. This is especially true if spatially or temporally varying HDR content is displayed, causing the Human Visual System (HVS) to frequently and unpredictably change L_A, and with that visual sensitivity.

To overcome these challenges, we present the concept of an "Adaptation Hull" color difference metric. Rather than using a specified adaptation luminance that is in most cases substantially different than the stimuli under test, an Adaptation Hull metric instead considers an optimal adaptation state where the HVS has the highest sensitivity to color differences.

**No proceedings paper.*

10:30 **Estimation of HDR WCG Display Color Gamut Volume,** *Fu Jiang and Mark D. Fairchild, Rochester Institute of Technology (USA), and Kenichiro Masaoka, NHK Science & Technology Research Laboratories (Japan)* **344**
Triangular gamut area plots on chromaticity diagrams (e.g., CIE xy or CIE u′v′) have long been used in attempts to describe and compare the range of colors that can be produced on displays. This has been done despite the long-established recognition that three-dimensional color gamut volumes in color appearance spaces (e.g. CIELAB or CIECAM02) more appropriately describe display performance. Since three-dimensional color gamut volumes are often difficult to measure and compute, this paper suggests a simple model to estimate color gamut volumes from chromaticity gamut areas, CLO/WLO ratio, peak luminance, and diffuse white luminance for RGB and RGBW wide-color-gamut and high-dynamic-range displays.

10:50 – 11:20 — Coffee Break

11:20 – 12:40

ILLUMINATING COLOR

Session Chair: Farnaz Aghaian, Google Inc. (USA)

11:20 **Rehabilitating the ColorChecker Dataset for Illuminant Estimation,** *Ghalia Hemrit and Graham D. Finlayson, University of East Anglia (UK); Arjan Gijsenij, AkzoNobel (the Netherlands); Peter Gehler, Amazon (Germany); Simone Bianco, University of Milan-Bicocca (Italy); Brian Funt and Mark Drew, Simon Fraser University (Canada); and Lilong Shi, Samsung Semiconductor Inc. (USA)* **350**
In a previous work, it was shown that there is a curious problem with the benchmark ColorChecker dataset for illuminant estimation. To wit, this dataset has at least 3 different sets of ground-truths. Typically, for a single algorithm a single ground-truth is used. But then different algorithms, whose performance is measured with respect to different ground-truths, are compared against each other and then ranked. This makes no sense. We show in this paper that there are also errors in how each ground-truth set was calculated. As a result, all performance rankings based on the ColorChecker dataset—and there are scores of these—are inaccurate.

In this paper, we re-generate a new 'recommended' ground-truth set based on the calculation methodology described by Shi and Funt. We then review the performance evaluation of a range of illuminant estimation algorithms. Compared with the legacy ground-truths, we find that the difference in how algorithms perform can be large, with many local rankings of algorithms being reversed.

Finally, we draw the readers attention to our new 'open' data repository which, we hope, will allow the ColorChecker set to be rehabilitated and once again become a useful benchmark for illuminant estimation algorithms.

11:40 **Light Sources with a Larger Gamut Area Can Enhance Color Preference under a Lower Light Level,** *Wenyu Bao and Minchen Wei, The Hong Kong Polytechnic University (Hong Kong), and Anqing Liu, Shenzhen ChromaTech Lighting Co., Ltd. (China)* . . **354**
Past studies suggested that sources with a high color fidelity may not always be preferred, while sources enhancing color saturation, especially the saturation of red colors, can result in higher preference. These studies, however, were typically carried out between 200 and 1000 lx. The color preference under a low light level was seldom investigated and illuminance was seldom varied in an individual experiment. This paper reports an experiment which was specifically designed to test a prior hypothesis that color preference reduced with illuminance level and sources with a larger gamut area can compensate the low preference caused by the illuminance reduction. Twenty-two observers compared the color appearance of an artwork under nine nearly metameric 3000 K stimuli under two illuminance levels (*i.e.,* 20 and 480 lx). The stimulus with an R_g of 118 was the most preferred under 20 lx, while the stimulus with an R_g of 109 was the most preferred under 480 lx. The findings clearly revealed the importance of illuminance level in evaluating and specifying light source color rendition.

12:00 **Illumination Source Metrics and Color Difference—Selecting Sources for Cinematography,** *Jack Holm, Tarkus Imaging, and Scott Dyer and Dan Sherlock, Academy of Motion Picture Arts & Sciences (USA)* **359**
This paper uses calculated ΔE^*_{ab} values for 730 spectral reflectances, two reference illumination sources, 88 candidate illumination sources, five camera spectral sensitivities and the CIE 1931 observer to determine the degree to which the illumination source metrics CCT, CRI Ra, TM-30 Rf, TLCI and SSI can be used to reliably select candidate sources to avoid color differences with reference sources. The ISO 7589 spectral distribution index and digital camera scene analysis errors are used to determine excellent and very good ΔE^*_{ab} criteria. Correlations between the illumination source metrics and color differences are generally poor, but metric values close to 100 predict the small color differences required for cinematography.

Local Focus: Simon Fraser University and CIC, with introduction by Graham Finlayson, University of East Anglia (UK)

12:20 **Recent Progress on the Role of Illumination in Physics-based Computer Vision (Invited),** *Mark Drew, Simon Fraser University (Canada)**
In this overview paper we discuss some of the more interesting investigations into the effect and manipulation of illumination in physics-based computer vision. The subject of shadow removal in images is introduced and then, remarkably, the underlying mathematical model is copied into the color space of skin lesion malignancy detection. A new characterization of specularity, the zeta-image, is used to either enhance, or diminish highlights in images. For situations where there are sets of images with lighting consecutively fired from different directions, we show how images can be interpolated with correct generation of both specularity and shadows. We show how contrast in higher-dimensional image data can be copied into lower-dimensional image representatives, with resulting striking improvement in image output quality. These techniques generate derivative-space results – not images themselves—so finally we show a clever new method for moving from gradients to images, that eliminates artifacts from the "reintegrated" images.

12:40 – 14:00

LUNCH ON OWN

**No proceedings paper.*

14:00 – 15:00
COLOR MATTERS
Session Chair: Ján Morovic, HP Inc. (Spain)

Given a single reference stimulus, test stimuli can be sorted with respect to perceptual similarity to this anchor stimulus. Aggregated ranks can then be computed from multiple sort sequences. This ordinal scaling provides an estimate of perceptible differences and can be used to develop and test predictive models. In this paper we propose the use of graph-based methods visualizing experimental data and computing aggregated ranks. Specifically, perceptual similarity is expressed as a sort sequence graph in which nodes are stimuli and weighted edges are the frequency of the corresponding ranks. This graph is also oriented in that it has a start, the reference stimuli, and an end, the least similar stimuli. The Schulze method or the 'strongest path' computation is used for rank aggregation. This analysis is explored in the context of two appearance experiments: the first using solid colors and the second using renderings of 3D printed stimuli varying in multiple appearance attributes. For the second experiment with the renderings of 3D printed stimuli we then use Kendall T_b values to assess a simple model based on mean CIELAB color differences. We find that the underlying sorting task is efficient and intuitive. Furthermore, the graph-based formulation of perceptual similarity allows the application of network analysis and graph theory to the study of visual appearance. New analyses are also possible, such as outlier detection using the sort sequences that are the inverse of the Schulze solution or approximately the 'wrongest path'.

In this paper, we proposed a method for measuring surface reflectance under multiple lighting by using simple devices. In order to establish this method, we first applied principal component analysis (PCA) to MERL BRDF database for compact representation. For estimating BRDF under multiple lighting, lighting component is obtained from the image captured by omni-directional camera. Through the optimization process using these basis and lighting component, an appropriate set of vertex data necessary for estimating unknown BRDF are selected. By performing the optimization process, our method allows us to estimate unknown BRDF efficiently. Finally, to obtain weighting coefficient for linear combination, the measured data of selected vertex are projected onto the basis of BRDF. We verified that our method can estimate the surface reflectance with high accuracy by comparing the results between ground truth and estimated data.

Translucency and factors impacting its perception is not yet fully understood. Various studies have examined the correlation between physical material properties and perceived translucency. Furthermore, the concept of translucency constancy has been introduced. However, to the best of our knowledge, no study has been conducted to identify how image quality impacts perceived translucency. In this study, we address to one particular image quality attribute - blurriness. We quantified blur with objective image quality metric and conducted psychometric scaling experiments to identify how blurring impacts the perceived degree of translucency. The analysis of the results show some indications that blur impairs translucency perception.

15:10 – 15:40 — Coffee Break

15:40 – 17:20
SUBTRACTIVE ADDITIONS
Session Chair: Ingeborg Tastl, HP Labs (USA)

We introduce a thread-safe color management library, LittleCMS-MT. It is a fork of the popular LittleCMS color management library. The issues with LittleCMS are described and the approach used to create LittleCMS-MT is discussed. The architectural design of using a thread-safe color management library with open source projects used for rendering page description languages is covered. Performance results using Ghostscript with LittleCMS-MT vs. LittleCMS and standard test files are provided.

Look-up tables (LUTs) are frequently used in ICC profiles to establish relationships between a Profile Connection Space (e.g. CIELAB) and a device space (e.g. CMYK). The accuracy of an ICC profile is significantly influenced by the sampling method used to populate its LUTs. This paper investigates using polar coordinates for sampling of LUTs in the B2Ax tags of an iccMAX profile to convert from Profile Connection Space to device space. Additionally, a new sampling approach is proposed to achieve better perceptual uniformity of sampling between grid points using adjustment to LCH coordinates. The method uses DIN99d formula and CIEDE2000 color difference equation to sample grid points along C* and H* dimensions in a way that the distance between the grid points along these dimensions is much more perceptually uniform. Using such a strategy to build an iccMAX profile improves roundtrip accuracy while keeping the CLUT size unchanged compared to V4 ICC profiles with some cost in application performance.

We propose and discuss a color-managed workflow for 3D fine-art imaging based on a lookup-table-based transformation to match colors from a laser-scanned 3D image to those from a photographic reference image. We show the significant color errors from shaded, shadowed and specular pixels in the reference image can be eliminated using geometric information from the laser scans.

16:40 **JIST-First Calculation of Scalars in Neugebauer-Like Models. II: Final Scalar Function is Copula,** *J. A. Stephen Viggiano, Rochester Institute of Technology (USA)* **402**

Neugebauer-type models for reflectance factor spectra produced by halftone-based color hardcopy rely on the spectra of the so-called Neugebauer primaries, an invertible function of reflectance, and a weight, or scalar, for each Neugebauer primary. This paper discusses the calculation of the third factor. Research has, until now, relied heavily, perhaps exclusively, on just three parameter-less sets of equations to compute these scalars. In the previous paper in this series, it was shown how the scalar for each Neugebauer primary could be computed from the function governing the scalar of the primary consisting of all colorants, the so-called final scalar. In this paper, conditions necessary and sufficient for a function to provide the final scalar are recited. Copulas, an entire class of functions from probability theory, also satisfy these conditions, and therefore may be used for final scalar calculation. Halftone patterns generated by a raster image processor were used to assess potential improvement in final scalar accuracy in two-colorant dot-on-dot printing with a slight amount of misregistration. Using a copula new to this application resulted in a nearly ten-fold improvement in accuracy over the best-performing overlap models in the prior art, indicating significant increases in accuracy are to be expected with actual printed artifacts.

17:00 **Halftone Structure Optimization Using Convex Programming,** *Peter Morovic, Ján Morovic, Victor Diego, Javier Maestro, Hector Gomez, Sergio Etchebehere, Xavier Fariña, and Pere Gasparin, HP Inc. (Spain)* **410**

In a color printing pipeline, the overall properties of a printed pattern depend on how the available inks are used to reproduce a given color. These choices are typically made in ink-space and therefore concern only how much of each ink to use, with halftoning then determining how those ink amounts interact with each other. For a HANS (Halftone Area Neugebauer Separation) pipeline, it is already the color separation—the recipes of how inks are used for a given color—that determines not only ink amounts but also how to combine them, while halftoning only provides their spatial distribution. Hence, with HANS, halftone properties are to a larger extent determined already by the color separation. This is an important change from traditional pipelines and requires different methods of control. This paper describes an approach to achieving new levels of image quality performance, without incurring complexity in the pipeline. It is based on the realization that certain strategies of halftone composition result in less grainy prints, e.g., when minimizing the amount of blank substrate, and more generally minimizing contrast among constituent, at-pixel drop-states (ink combinations). This is achieved through the mathematical technique of convex optimization, where such strategies can be formulated and efficiently computed. Results are shown for node-by-node LUT optimization; calibrating LUTs from ink-channel ratio data; transforming LUTs to take into account changes in drop-sequences, sets of admissible NPs or the number of possible NPs to use in an on-line pipeline and generating color samples that match in color but vary in grain. This approach is deeply embedded in the first HANS commercial product, the HP DesignJet Z6 and Z9+ series, a portfolio of pro-photo/graphics printers.

17:20 – 17:30
CLOSING REMARKS AND BEST STUDENT PAPER AWARD

Marius Pedersen, Norwegian University of Science and Technology (Norway); Nicolas Bonnier, Apple Inc. (USA); and Maria Vanrell, Universitat Autònoma de Barcelona (Spain)

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APPENDIX

Workshop Papers

VR: from Static Cube Maps to Light Fields

Giuseppe Claudio Guarnera; Norwegian University of Science and Technology - NTNU; Gjøvik, Norway

Abstract

Over the past few years Virtual Reality and Augmented Reality have become widely available in consumer devices, promising to transform the way we think, learn, and communicate.

The capability of creating photo-realistic, rendered objects within a real-world setting will support sale, promotion, accurate visualization, planning, and marketing purposes more and more in the coming years. A key factor common among all the countless possibilities offered by AR and VR is that all the depicted materials, their reflectance properties, the lighting, etc. must be consistent with human perception, across a range different platforms.

However, photo-realism is still a challenge even on desktop environments, and AR/VR are raising the bar for efficient, realistic, and cost-effective material modelling.

Introduction

Half a century after the seminal work by Ivan Sutherland [Sut68], Virtual Reality (VR) and Augmented Reality (AR) have found applications in a number of fields, ranging from games to social media, from tourism to the medical industry. An increasing number of industries look with increasing interest at AR/VR, including architecture, interior design and automotive. Such highly effective visualization tools allow to help customers in decision making about a purchase, simply by means of a phone and AR or just wearing some VR goggles. Moreover, such technologies can be used also within the industry context, for instance to preview the appearance of newly designed materials, thus improving the tool chain.

A key challenge is common among all the AR/VR applications: the depicted materials must be consistent with human perception, across a range of different platforms, regardless whether they are high-end Head-Mounted Displays (HMDs) or a simple cardboard frame and a smartphone.

Human Perception of Material Properties

Our principal source of information about the nature of object is visual observation. The retina of the human eye, somewhat like a camera's sensor, captures signals representing what we see and encodes/transmits these via the optic nerve to the brain for further processing.

Much of our current understanding of visual perception has arisen from studies involving animals and/or human subjects. Studies have ranged between invasive techniques, psychophysical experiments, eye-tracking studies and more recently brain imaging. Although our understanding of vision has developed through psychophysics and physiological experiments, computational models of neural processing have become increasingly important to enhance our understanding.

Over a century of research on perception has made clear that our perceptual system does not attempt to create an exact representation of the world. Instead, it makes a number of shortcuts which lead to perceive things sometimes very differently from reality, for instance, it is enough to think about the huge variety of visual illusions that contradicts the physics of a scene [TBL*09]. Some of these principles have been exploited in image processing and computer graphics for instance, for applications which range from image/video compression to selective rendering. The latter relies on the incapability of the human visual system to spend equal amounts of processing power on all modalities and cues it receives from its sensory systems at any given time, thus enabling a huge reduction in the computational resources required to render a VR experience (VRE) [BCFW08].

As for the properties of the material of an object, to resolve the visual input into an estimate many factor are involved, including the illumination and the shape of the object itself. However, our current knowledge of this influence is limited and it appears to be high-dimensional in nature, without a clear pattern [VLD07, Van09].

A better understanding of human perception would allow a more realistic and efficient material representation for use in VR.

Material Acquisition and Representation

Realistic material representation is still a challenge not only in VR, but also for computer graphics in general. In fact, even for common everyday materials on a standard desktop environment, current methods for material representation and acquisition do not offer a widely adopted solution, good enough for a range of commercial applications without significant labour and money [GGH*17]. Current material models are hard to edit by artists and have a high memory footprint, thus limiting their applicability. Moreover, they are are limited to a small set of parameters, which results in the ability of each model to represent only a specific material group.

VR is raising the bar for efficient, realistic and cost effective material modelling, due to:

- technology related factors: *e.g.* mobile VR graphics memory footprint, device performance and the need for speed;
- user related factors: *e.g.* clients demand perceived high quality, since visual artifacts are distracting and flat textures look worse in a 3D environment;
- deployment related factors: currently there is a trade off between accuracy and practicality of deployment, since making a VREs is labour intensive due to material and model creation, whereas rapid deployment is required; moreover, there is a need to balance user experience against the commercial realities.

Given that material assets must be renderable in high quality on a mobile device, even everyday materials such as woven cloth might require ad-hoc, fast approaches for both acquisition and rendering [GHCG17].

Another interesting gap is that many materials may not have been rendered in computer graphics, due to difficulties in their acquisition and representation. This is particularly true for newly designed materials, and materials which can change their appearance due to external *stimuli* (*i.e. smart materials*).

Besides material reflectance properties, faithful acquisition of colors is also an issue. Nowadays, image-based acquisition setups are common in computer graphics [GHCG17], since they allow to reduce costs and increase the speed of material measurements. The core of such setups are consumer cameras, hence, a careful characterization is required in order to convert acquired RGB values into accurate radiometric and colorimetric data [GBS18a]. As shown in [GBS18b], radiometric compensation (and hence some Augmented/Mixed reality applications) can greatly benefit from a thorough camera characterization.

Conclusions

The wide range of consumer VR headsets, and the limitations deriving from mobile devices, often limit VREs to omnidirectional stereo rendering, delivered by means of static cube maps in which there is no freedom to move around in the scene.

Recently, Overbeck *et al.* [OEED18] presented a spherical light field capture system, along with a set of algorithms for compression, streaming and multi-view geometry reconstruction, which allow the deployment and rendering of light field VREs on common consumer HMDs. Such a technology demonstrates how the sense of presence can be improved by more realistic reflections, lighting and motion parallax.

However, there is still a long way to go, in order to deliver high level of realism while accounting also for the freedom of movement in a VRE. A number of research questions are still open:

- Can our understanding of human visual perception enable us to suggest more effective material models?
- How can we faithfully capture the reflectance properties of a material, despite of its inherent structure (*i.e.* microstructure properties, glossiness, etc.)?
- Once the material data is acquired, how can we represent it in order to enable the possibility to edit the properties, without losing on the perceptual accuracy and at the same time keeping a low memory footprint?
- How can we visualize a material consistently with our understanding of human perception, despite of the wide range of display technologies and the use of cost effective hardware to deploy VREs?

Beneficiaries of future algorithms and pipelines include several multi-billion dollar industries, but also cultural heritage and ultimately the Computer Graphics field.

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Author Biography

Giuseppe Claudio Guarnera received his PhD in computer science from the University of Catania (Italy), with a doctoral dissertation in computer vision and pattern recognition. He began his research in computer graphics while at the USC Institute for Creative Technologies (USA). He is currently a research associate at NTNU (Norway). His research interests include colorimetry, virtual material acquisition and representation, and human perception of materials.

Color and Object Appearance in Optical See-Through AR Applications

Michael J. Murdoch; Munsell Color Science Laboratory, Rochester Institute of Technology; Rochester, NY, USA

Workshop Presentation Abstract

Augmented reality (AR) technology promises to blend virtual rendered objects and overlays with the real world through head-mounted displays (HMDs) or other displays. Optical see-through (OST) displays are one way to make this blend, providing a relatively undistorted view of the real world and adding synthetic overlays to it. Current implementations, such as the Microsoft HoloLens, perform spatial tracking of the OST-HMD so that the virtual objects appear to remain fixed in real-world coordinates, allowing the user to look around and view them from different directions. An overview of AR technologies, including non-OST implementations, is provided by van Krevelen and Poelman [1].

Two use cases for AR can be described: first, adding virtual objects to the real world; and second, manipulating real-world objects with overlaid content. The former case is what many people think of as AR: 3D models floating in real-world space, for example in games or educational experiences. The latter case, in which the color, texture, or geometry of real-world objects appears to be altered by an AR overlay, can be especially useful in medical, education, and retail applications. Different applications in either of these use cases have varied requirements for perceived attributes related to 3D accuracy, spatial resolution, color accuracy.

This workshop presentation focuses on the many challenges and unknowns regarding color reproduction and perception of objects and object color in OST AR applications.

Background blending

One challenge with OST AR is that, with present technologies, selectively occluding the background is impossible. Virtual content rendered on a see-through display is additively blended with the background, meaning real-world background objects and colors simply bleed through the virtual content [2]. This has the expected consequence that a lighter virtual object on a darker background is more visible and less distorted than a darker virtual object on a lighter background.

Ongoing research addresses the perceptual implications of background blending and color appearance [3]. One recent finding is that the CAM16 color appearance model can be modified to account for chromatic surrounds to improve its fit, and another finding is that even with the same patch/surround configuration, color appearance in AR is different than on a normal LCD [4].

Further work in this area should address the cognitive differences between purely virtual objects and manipulated real-world objects. An initial study partly verified the "lightness constancy" hypothesis: that an AR overlay is partly discounted by observers making lightness matches, depending on its spatial extent with respect to the real-world object [5].

Mixed adaptation

Another challenge for modeling color appearance is that it can be difficult to accurately assess an observer's state of adaptation. An adaptation white point may be assumed to be a mixture of the white one would assume looking at the real world only, along with that of the AR display system and/or the displayed AR objects. Some literature has addressed mixed adaptation in cross-media comparisons, but not yet in AR [6]. Systematic study of observers' responses to AR-specific situations should be performed, to both more accurately model mixed adaptation and to better choose and responsively adjust AR display white points.

Lighting consistency

Related to mixed adaptation, a more complex problem is that of the consistency between real-world lighting environments and the lighting and material models used in generating graphical virtual content. There is evidence that observers can tolerate inconsistencies in shadow direction, specular reflection, and other geometric characteristics [7][8][9]. However, further study is required of inconsistencies in lighting color and geometry between AR-displayed virtual objects and real-world objects.

Temporal response

Practical AR systems must be responsive to temporal changes in both virtual content and in the user's environment. In fact, all of the aforementioned challenges have a temporal dimension: background blending changes as the user's head motions put different objects behind AR virtual overlays; adaptation naturally changes as a user moves through different spaces; and lighting models on virtual objects must be continually updated to match the changing real world.

Responsive rendering and display algorithms must be done at high frame rate with minimal lag or latency, sufficient to stay perceptually in sync with real world. Graphics pipelines have been proposed [10], but a general approach is still needed.

AR displays and optics

AR display systems include many components that together determine their visual characteristics and image quality. Besides color accuracy and consistency, consider optical distortion, chromatic aberration, luminance dynamic range, spatial resolution, visual field of view, spatial and temporal uniformity, etc. As with most imaging systems, the most objectionable components tend to dominate the impression of image quality. Thus, system-wide improvement of the AR experience necessitates work on all components. At present, one distracting color artifact is color breakup, which can occur in sequential-color displays.

HMD metrology

Colorimetric, spectral, and spatial measurement and characterization of HMDs is complicated by their form factor: for example, a typical spectroradiometer doesn't fit within the head-band of an HMD. Measurements should be made to mimic the position of the human eye, given the displays' small eye box and angular field of view [11]. Metrology must be extensive as AR display technologies evolve, because assumptions of channel independence, additivity, and uniformity (which typically hold for backlit LCDs), should be verified before models are used [12]. Commercial measurement devices designed for HMDs are already starting to appear, but further research and testing should aim for consensus on measurement methodologies.

Call to Action

Certainly, there exist plenty of interesting research questions for color and object appearance in AR. Hopefully this list and the workshop discussions can help prioritize research topics and inspire collaboration between laboratories. Understanding color perception in an AR OST-HMD requires expertise in nearly all aspects of contemporary color science: displays, optics, adaptation, appearance modeling, graphics, and lighting. Let's get to work!

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Author Biography

Michael J. Murdoch is an Assistant Professor in RIT's Munsell Color Science Laboratory. His current research interests include the effects of temporally dynamic lighting on visual adaptation and color appearance and visual adaptation in Augmented/Mixed Reality (AR/MR). His education includes a BS in chemical engineering from Cornell, MS in computer science from RIT, and PhD in human-technology interaction from Eindhoven University of Technology in The Netherlands.

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