30th Color and Imaging Conference 2022 (CIC30)

Color Science and Engineering Systems, Technologies, and Applications

Scottsdale, Arizona, USA
13 - 17 November 2022

ISBN: 978-1-7138-7107-1

Printed from e-media with permission by:

Curran Associates, Inc.
57 Morehouse Lane
Red Hook, NY 12571

Some format issues inherent in the e-media version may also appear in this print version.

Society for Imaging Science & Technology
7003 Kilworth Lane
Springfield, Virginia 22151
USA

Phone: 703-642-9090
Fax: 703-642-9094

info@imaging.org

Additional copies of this publication are available from:

Curran Associates, Inc.
57 Morehouse Lane
Red Hook, NY 12571 USA
Phone: 845-758-0400
Fax: 845-758-2633
Email: curran@proceedings.com
Web: www.proceedings.com

TECHNICAL PROGRAM: SCHEDULE AND ABSTRACTS

TUESDAY 15 NOVEMBER

COLORFUL CONNECTIONS
07:30 – 08:45

During breakfast join one of the following members from the community to talk about their experiences and areas of expertise:

- Timo Kunkel, Dolby: HDR and Displays
- Anya Hurlbert, Newcastle University: Vision, Perception, and Neuroscience
- Vien Cheung, University of Leeds: Color and EDI (equality, diversity, and inclusion)

WELCOME AND OPENING KEYNOTE
Session Chair: Jon Hardeberg, Norwegian University of Science and Technology (Norway)
09:00 – 10:00

SESSION SPONSOR

Welcome Remarks
Suzanne Grinnan, IS&T executive director (US), and Peter Morovic, CIC30 general chair, HP Inc. (Spain)

09:00 **A Theory of Material Appearance: How Learning Structures Surface Perception,** *Roland Fleming, Justus Liebig University of Giessen and Center for Mind, Brain and Behavior of the Universities of Marburg and Giessen (Germany)* [Abstract only]

Humans are very good at visually recognizing materials and inferring their properties. Without touching surfaces, we can usually tell what they would feel like, and we enjoy vivid visual intuitions about how they typically behave. This is impressive because the retinal image that the visual system receives as input is the result of complex interactions between many physical processes. Somehow the brain has to disentangle these different factors. This talk presents some recent work which shows that an unsupervised neural network trained on images of surfaces spontaneously learns to disentangle reflectance, lighting, and shape. However, the disentanglement is not perfect, and we find that as a result the network not only predicts the broad successes of human gloss perception, but also the specific pattern of errors that humans exhibit on an image-by-image basis. This has important implications for thinking about appearance and vision more broadly.

COLOR APPEARANCE: METRICS
10:00 – 11:00
Session Chair: Yoko Mizokami, Chiba University (Japan)

10:00 **Why Achromatic Response is not a Good Measure of Brightness,** *Luke Hellwig[1], Dale Stolitzka[2], and Mark Fairchild[1]; [1]Rochester Institute of Technology and [2]Samsung Display America Lab (US)* **1**

Luminance underestimates the brightness of chromatic visual stimuli. This phenomenon, known as the Helmholtz-Kohlrausch effect, is due to the different experimental methods—heterochromatic flicker photometry (luminance) and direct brightness matching (brightness)—from which these measures are derived. This paper probes the relationship between luminance and brightness through a psychophysical experiment that uses slowly oscillating visual stimuli and compares the results of such an experiment to the results of flicker photometry and direct brightness matching. The results show that the dimension of our internal color space corresponding with our achromatic response to stimuli is not a scale of brightness or lightness.

10:20 **Representing Color as Multiple Independent Scales: Brightness versus Saturation,** *Hao Xie and Mark Fairchild, Rochester Institute of Technology (US)* [Abstract only]

The concept of color space has served as a basis for vast scientific inquiries into the representation of color including colorimetry, psychology, and neuroscience. However, the ideal color space that can both model color appearance attributes and color difference as a uniform Euclidean space is still not yet available. In this work, based on the alternative representation of independent one-dimensional color scales, the brightness and saturation scales for five Munsell principal hues were collected via partition scaling, where the MacAdam optimal colors served as anchors. Furthermore, the interactions between brightness and saturation were evaluated using maximum likelihood conjoint measurement. For the average observer, saturation as constant chromaticity is independent of luminance changes, while brightness receives a small positive contribution from the physical saturation dimension. This work further supports the feasibility of representing color as multiple independent scales and provides the framework for further investigation between other dimensions.

10:40 **A Revised Formulation based on CIECAM16 for Cross-media Colour Reproduction via Real Scene Experiment,** *Yuechen Zhu[1] and Ming Ronnier Luo[1,2], [1]Zhejiang University (China) and [2]University of Leeds (UK)* **6**

In order to reproduce the colour appearance between real scene and images on self-luminous display, this study conducted a series of psychophysical experiments using threshold method. Three types of real scenes were built up in a lighting room, including painting, fruit and vegetable, skin colour chart. Sixteen adapting conditions were designed including four CCTs (3000K, 4500K, 6500K, 8000K) and 4 luminance levels (10lux, 100lux, 500lux, 1000lux). Four displays with different sizes were studied. The result indicated that the colour appearance of real scene and the image on the display were different, especially for low CCT and luminance level. The contents of scene and size of display didn't show a significate impact. The prediction performance of CIECAM16 was tested, and a revised formulation was proposed with high accuracy.

COFFEE BREAK AND EXHIBIT
11:00 – 11:40

COLOR APPEARANCE: APPLICATIONS

11:40 – 13:00

Session Chair: Carol Payne, Netflix (US)

11:40 **Testing the Performance of Color Difference Formula for a Mixed Display Technology Setup,** *Pooshpanjan Roy Biswas[1,2], Dominique Dumortier[2], Sophie Jost[2], Herve Drezet[1], and Marie-Laure Avenel[1]; [1]Technocentre Renault and [2]ENTPE (France)* **11**

Automotive cockpits are becoming more and more digital day by day and this is evident by the increase in the number of displays inside the cockpit. With the advent of OLED displays, automotive cockpits not only have LCD but have started having mixed display technologies. A recent example of such a cockpit display is the MBUX Hyperscreen in Mercedes EQS.

A general situation is most mid ranged cars from Renault includes several displays inside the cockpit. These displays are placed at different locations inside the cockpit and go through various changes in external environmental condition during day and night. A vehicle cockpit experiences a wide range of illumination change during the day, from 35 kLux in bright sunlight to a few Lux during the night. The displays are generally used in high luminance range during the day and very low luminance during the night.

Traditional color difference formulae like the CIEDE76 or CIEDE2000, the latter being the current industry standard, are defined for a specific set of evaluation conditions. For the myriad of different conditions that the displays undergo inside the cockpit, there isn't a recommended color difference formula which can be used to quantify the color difference between any two chosen displays inside the cockpit. An attempt has been made to include various real time parameters involving color difference evaluation between two displays, one of which is an LCD and other OLED. The motive of this study is to find out which color difference formula is the most representative of the perceived color difference between two mixed technology displays for a group of observers. The metric used for this the study is the CIE recommended STRESS index. The outcome of this research is to serve as a reference regarding the choice of color difference metric by display manufactures and OEM suppliers.

12:00 **Adaptive Display White Point for Enhancing Viewing Experience of Mixed Reality Headsets,** *Minchen Wei, Wenyu Bao, and Zheng Huang, The Hong Kong Polytechnic University (Hong Kong), and Jan Oberländer, Stefan Rüffer, and Jerry Jia, Meta Reality Labs (US)* . . . **18**

The development of various new imaging systems introduces new viewing conditions that did not exist in the past. Mixed reality systems, which capture the real environment and renders the captured image on display with virtual objects superimposed, require more immersive and realistic feeling than virtual and augmented reality systems, especially when users just put on the headsets. Therefore, the rendering shown on the display needs to be carefully adjusted to match the appearance in the real environment. In this study, we specifically focus on reproducing the overall color tone of the real environment under different ambient illumination color by shifting the white point of the display. The human observers viewed a real environment under different ambient illumination conditions, in terms of CCT and chromaticities, and evaluated the rendering of the captured scene with 44 white points. The results clearly suggested that the display white point should be adaptive to the ambient illumination color, especially when the ambient illumination had a CCT below 4000 K, to provide a good user experience.

12:20 **Luminance, Brightness, and Lightness Metrics for HDR,** *Charles Poynton, Independent consultant (Canada)* **24**

High dynamic range (HDR) technology enables a much wider range of luminances—both relative and absolute—than standard dynamic range (SDR). HDR extends black to lower levels, and white to higher levels, than SDR. HDR enables higher absolute luminance at the display to be used to portray specular highlights and direct light sources, a capability that was not available in SDR. In addition, HDR programming is mastered with wider color gamut, usually DCI P3, wider than the BT.1886 ("BT.709") gamut of SDR. The capabilities of HDR strain the usual SDR methods of specifying color range. New methods are needed.

A proposal has been made to use CIE LAB to quantify HDR gamut. We argue that CIE L* is only appropriate for applications having contrast range not exceeding 100:1, so CIELAB is not appropriate for HDR. In practice, L* cannot accurately represent lightness that significantly exceeds diffuse white—that is, L* cannot reasonably represent specular reflections and direct light sources. In brief: L* is inappropriate for HDR. We suggest using metrics based upon ST 2084/BT.2100 PQ and its associated color encoding, IC_TC_P.

12:40 **Color Appearance Characterization of Highlight Stimuli in HDR Scenes Across a Wide Range of Diffuse White Luminance,** *Hongbing Wang and Minchen Wei, The Hong Kong Polytechnic University (Hong Kong)* **30**

Various uniform color spaces and color appearance models were mainly developed for characterizing stimuli under a low dynamic range condition. Real scenes in daily life, however, are commonly high dynamic range (HDR), containing highlights with luminance beyond the diffuse white, whose color appearance characterization was never investigated in the past. This study was carefully designed to investigate the color appearance characterization of highlights in HDR scenes, covering extremely wide ranges of diffuse white luminance (up to 11000 cd/m^2), stimulus luminance (up to 49000 cd/m^2), stimulus chromaticities (reach Rec. 2020 gamut), and scene luminance contrast (up to 72045). The observers viewed two stimuli, including one highlight and one dark stimulus, in a viewing booth, and were asked to adjust the color appearance of another stimulus, so that the color differences between the adjusted stimulus to each of the other two stimuli appeared the same. The results clearly showed that none of the existing models, including the one (i.e., IC_TC_P) that was recently designed for HDR scenes, has a good performance. The models using a power function to characterize the non-linear compressive responses of the human visual system (i.e., CIELAB and IPT) had a slightly better performance. The findings provided some guidance for performing tone mapping and chroma/saturation adjustments, and clearly suggest the necessity to carry out further work to develop a better model for HDR scenes.

GROUP LUNCH

13:00 – 14:20

Join other attendees for a buffet lunch on the terrace.

COLOR DIFFERENCE

14:20 – 15:20

Session Chair: David Alleysson, Université Grenoble Alpes (France)

14:20 **Color-difference Ellipsoids Follow from Metamer Mismatching,** *Emitis Roshan and Brian Funt, Simon Fraser University (Canada)* . . . . . **Appendix A-1**

Many psychophysical experiments have shown that color discrimination thresholds vary as a function of the color center under consideration, MacAdam ellipses being a prime example. Color discrimination thresholds are usually modelled either as ellipses in chromaticity space or ellipsoids in 3D color space. Various color difference models, such as those of Luo et al., have been developed based on fits to the data obtained from psychophysical experiments (e.g., Li et al.). However, such models do not explain why the color difference thresholds vary across color space as they do. Funt et al. show that the uncertainty created by metamer mismatching provides a very interesting explanation. Extending that theory as described below enables it to predict, not only the ellipsoid volumes, but the shapes and orientations of the ellipsoids as well, thereby providing further evidence of its validity.

14:40 **The Perceptibility of Color Differences between Thin Lines and its Application to Printing Imaging Pipelines,** *Ján Morovic, HP Inc. (UK), and Peter Morovic, HP Inc. (Spain)* **36**

Imaging is enabled by the limitations of the human visual system, which is blind to certain physical differences. The trichromacy of human vision, e.g., allows for very different materials to be combined in a way that results in the same signals triggered by the eye's cones. As a result a print can elicit the same response as a display, or a projection can yield colors like those in a painting. The limits of spatial acuity too allow for discrete patterns, e.g., those resulting from halftoning, to appear continuous. This paper turns its attention to the limits of color difference perception in stimuli with a very small subtense, such as thin lines or fine features of 3D objects. A first set of psychophysical data, obtained in an on-line visual experiment, indicates a dramatic relaxation of perceptibility thresholds when comparing very thin with thicker lines. The second half of the paper then presents printer imaging pipeline strategies that take advantage of these experimental findings to successfully render fine lines while taking advantage of the more limited sensitivity with which their specific colors are perceived.

15:00 **A Parametric Colour-difference Study on the Separation and CMF Effects,** *Qiang Xu, Keyu Shi, and Ming Ronnier Luo, Zhejiang University (China)* **42**

An experiment was carried out to investigate separation and CMF effects on colour-difference evaluation using display colours. In total, 1120 sample pairs around 5 CIE recommended colour centres were assessed 20 times using the grey-scale method. Sample pairs were selected to have colour-difference of 4 and 8 CIELAB units, include or exclude separation between two colours on a pair, have four fields of view (FoVs), 2°, 4°, 10° and 20°. The experiment results were used to test 3 colour-difference equations or uniform colour spaces, CIELAB, CIEDE2000 and CAM16-UCS. For separation (S) sample pairs, CIEDE2000 performed the best, followed by CAM16-UCS and CIELAB the worst. For no-separation (NS) sample pairs, all models gave worse performance than separation (S) sample pairs. The parametric formula derived earlier was verified to predict colour-difference for sample pairs to have no-separation line. Five colour matching functions (CMFs), CIE 1931, CIE 1964, CIE 2006-2°, CIE 2006-10° and 2006-4° were tested and the results indicated very small CMF effect on calculating colour-difference.

INTERACTIVE PAPER PREVIEWS I

15:20 – 15:50

Session Chair: Minjung Kim, Meta Reality Labs (US)

Trendlines: Evaluation of Consistent Color Appearance, *Yasuki Yamauchi, Yuta Terashima, and Yukiya Konnta, Yamagata University (Japan)* [Abstract only]

Usually images reproduced on different devices have different colors. In some settings, it is desirable for images reproduced on various devices to have a similar color impression. The degree of similarity of color impression among this set of images can be defined as consistent color appearance (CCA). If the CCA is high, colors appear similar (or consistent). To evaluate whether the colors have CCA, it is necessary to develop a metric to describe CCA. Although several color difference metrics, such as CIEDE2000, have been often used to evaluate color difference, they do not necessarily represent subjective differences in color impression. To solve this problem, the concept of a color trendline has been proposed. The degree of deviation from a trendline might be used to evaluate CCA, i.e., a set of prints from different printers whose colors have a smaller deviation from the trendline would have more consistent colors. In this study, we conducted several psychophysical experiments to verify this approach. Color patches were used to determine whether deviations from a trendline correlates with CCA. Psychophysical testing was used to find the CCA between sets of natural images and these results are used to determine whether deviations from a set of trendlines can explain the degree of CCA.

Color Matching between Regular Display and LED Lighting Tiles in Automotive, *Jérémie Gerhardt, Greg Ward, Hyunjin Yoo, and Tara Akhavan, Faurecia IRYStec Inc. (Canada)* **47**

For a few years, the automotive industry has produced new cars with continuous changing display models, this by combining display sizes, forms, and technologies all together to bring new experiences to the users. In this paper we will present the color matching solution implemented for a new car display system where regular LCD display technology and LED lighting tiles are mixed together. The solution we proposed is based on accepted display model providing the transformation device RGB space to CIE XYZ independent color space and in reverse. The approach we followed choose the LCD display as reference, then transformation matrix is derived to modify the RGB LED control values. Once the color matching operation is applied, the color difference between the two display areas is greatly reduced.

Revising CAM16-UCS, *Luke Hellwig and Mark Fairchild, Rochester Institute of Technology (US)* . . . . . **Appendix A-3**

Recently-proposed modifications to the CIECAM16 color appearance model require an update to its corresponding uniform color space, CAM16-UCS, in order to ensure that the formulas continue to predict the available color difference data. Theoretical and statistical inconsistencies in the current CAM16-UCS formulas are also discussed and addressed by the proposed revisions. The STRESS metric is used to derive new formulas for CAM16-UCS and to evaluate the performance of these formulas in comparison to existing uniform color spaces or color difference formulas on a common color difference dataset.

Colors, generally, have effects on human interpretations that can manifest in a variety of emotions, reactions, and behaviors. The objective of this study is to understand the reasoning behind the choices of pill colors in relation to expected efficacy of drugs, as well as the color associations made by participants. The research was conducted at several university campuses in USA, UAE, Croatia, Kosovo, and China, and focused on different age brackets, gender, ethnic backgrounds, educational levels, and pill usage frequency. Understanding the reasoning and color associations helps us better comprehend the expected efficacy of drugs, and can therefore support pharmaceutical companies in designing and manufacturing drugs, thereby maximizing the potential effect on patients' adherence rates.

In this paper, we propose a noise-robust pulse wave estimation method from NIR video. Pulse wave estimation in the near-infrared region is expected to be applied to non-contact monitoring in dark areas. Conventional method cannot consider noise when performing estimation, so the accuracy of pulse wave estimation in noisy environment is not very high. This may adversely affect the accuracy of heart rate and other data obtained from pulse waves. Therefore, the objective of this study is to perform pulse wave estimation robust to noise. The Wiener estimation method was used in this study. The Wiener estimation method is a simple linear computation that can consider noise. The proposed method is expected to enable non-contact and accurate estimation of pulse wave from near-infrared video images. Experimental results show that the proposed method estimates the pulse wave more robustly to noise than the conventional method. Furthermore, the heart rate was estimated from the estimated pulse wave and the proposed method was able to obtain a value closer to the ground truth.

In this study, we introduced a measurement method for gloss unevenness as a function of reflectance angles. Gloss is one of the most important qualities of materials, and it is evaluated subjectively by the intensity of reflected light and gloss unevenness. People can estimate the texture of a material using gloss unevenness, which is found in the small peripheral part of the gloss area and can easily be recognized by observing the reflected light while moving the object or eyes. However, it is not easy to photograph and quantify gloss unevenness. One reason is the area where gloss unevenness is observed is a small area near specular reflection. Second, the appearance of gloss unevenness changes depending on the reflection angle. We developed a measurement apparatus to measure gonio-photometric gloss unevenness. We introduced two solutions: a wide-area gloss unevenness measurement technology using telecentric imaging and a rotating mirror optical system that defects reflected light at an angular resolution of 0.02°. We analyzed three materials—mirror, plastic, and paper—and proposed three indicators as a quantitative evaluation method for gloss: intensity of reflected light at the specular angle, full width at half maximum (FWHM) of Bidirectional Reflectance Distribution Function (BRDF), and gloss unevenness image at the FWHM.

Glare introduces a complex scene-depended transformation of the array of "All Scene Luminances" making a different spatial pattern in the array of light on all receptors, called "Retinal Contrast". The spatial convolution of "All Scene Luminances" with Vos and van den Berg's CIE 1999 Glare Spread Function calculates high-resolution arrays of "Retinal Contrasts". The results show that uniform-luminance scene segments become low-slope gradients that are nearly invisible, or invisible. Visual inspection of these arrays is misleading. Plots of calculated "Retinal Contrast" values, histograms, and other numerical techniques are needed to analyze the effects of glare. Pseudocolor Look-up Tables (LUT)s are very helpful in visualizing the complexity of glare's spatial transformation that controls the amount of light falling on rods and cones.

This article studies Lightness Illusions that contain two identical scene-luminance segments that are identified as the "Regions-Of-Interest"(ROI). Following receptor responses, neural spatial processes generate a second spatial-image transformation that leads to appearances. Contrast, Assimilation, and Natural Scene Illusions demonstrate [Appearance ≠ scene luminance]. Analysis of Illusion's patterns of light on receptors shows that: Contrast Illusions, Edwin Land's B&W Mondrian, Adelson's Checkershadow all exhibit Glare's Paradox. Namely, that vision's second neural transformation overcompensates the effects of glare. Illusions' GrayROIs appear darker despite large amounts of glare light on receptors. GrayROIs that appear lighter have smaller amounts of glare. Assimilation Illusions adds light to GrayROI's that appear lighter. The combination of intraocular glare and Lightness Illusions shows complex-spatial-image-processing transformations following receptor responses in normal scenes.

Materials with special appearance properties such as goniochromatic materials require complex bidirectional measurements to properly characterise their colour and gloss. Normally, these measurements are performed by goniospectrophotometers which are expensive and not commonly available. In this paper a flexible imaging system composed of a snapshot multispectral camera and a light source attached to a robotic arm, is used to obtain HDR BRDF measurements of patinas commonly used in cultural heritage objects. The system is evaluated by comparing the results to those of a commercially available goniospectrophotometer. It is found that with a known uncertainty, the system is capable of producing accurate measurements of samples with a roughness equal or lower than 6.19 μm. For roughnesses higher that 12.48 μm, the accuracy of the system decreases. Moreover, it is found that the size and orientation of the region of interest plays a great influence on the precision of the imaging system.

Hue linearity is critically important to uniform color spaces and color appearance models. Past studies investigating hue linearity only covered relatively small color gamuts, which was generally acceptable for conventional display technologies. The recent development of HDR and WCG display technologies has motivated the development of new color spaces (e.g., IC_TC_P and $J_za_zb_z$). The hue linearity of these new color spaces, however, was not verified

for the claimed HDR and WCG conditions, due to the lack of constant hue loci data. In this study, an experiment setup was carefully developed to produce HDR and WCG conditions, with the stimulus luminance of 3400 cd/m² and the diffuse white luminance of 1000 cd/m² and the stimulus chromaticities almost covering the Rec. 2020 gamut. The human observers performed a hue matching task, adjusting the hue of the test stimulus, with a hue angle step of 0.2°, at various chroma levels to match that of the reference stimulus at 21 different hues. The derived constant hue loci were used to test the various UCSs and suggested the need to improve the hue linearity of these spaces.

Visibility Improvement in Air Pollution Scene by Joint Sharpness—Contrast Enhanced Dehazing, *Hiroaki Kotera, Kotera Imaging Laboratory (Japan)* . . . **85**
In the latter half of the 1980s, PM2.5 pollution in Beijing became a serious problem, and there were concerns about health hazards. It was expected that China's emissions must be reduced from 2013 to 2016, and the lockdown effect of Covid-19 would bring about an end, but it is still reluctant to regulate CO2 emissions. Again, in Beijing in November 2021, a visibility of 500 m or less has been observed, then road traffic is dangerous in addition to health.

After that, the center of pollution has moved from India to Mongolia, and now Nepal, Qatar and Saudi Arabia. The situation is still serious in developing countries.

Image restoration to remove the effects of haze and fog has been a long-standing concern of NASA, and their original Visual Servo has been put into practical use. Though the mainstream moved to the technique based on atmospheric physics. He et al.'s Dark Channel Priority (DCP) logic has had a certain effect on heavily polluted PM 2.5 scenes , but there is a limit to the restoration of detailed visibility. The observed images are affected by two spatial inhomogeneities of 1) atmospheric layer and 2) illumination.

As a countermeasure, we have improved DCP process with the help of Retinex and introduced the veil coefficient as reported in CIC24. Recently, a variety of improvements in single image Dehazing, using FFA-net, BPP-net, LCA-net, or Vision-based model are in progress. However, in each case, visibility of details is still a common problem.

This paper proposes an improvement in detail visibility by (1) joint sharpness-contrast preprocess and (2) adjustment in Dehaze effect with veil coefficient v.

Lastly, we challenge numerical evaluation of improvement in detail visibility by the two ways of attenuation of high-frequency Fourier spectrum and the expansion rate of the color gamut.

HALSTEAD-GRANVILLE TEA, EXHIBIT, AND COLORFUL CONNECTIONS

15:50 – 16:30

HALSTEAD-GRANVILLE TEA SPONSOR

THE COLOUR GROUP (GB)
PERCEPTION • MEASUREMENT • REPRODUCTION • ARTISTIC EXPRESSION

COLORFUL CONNECTIONS

During the break join one of the following members from the community to talk about their experiences and areas of expertise:

- Peter Morovic, HP Labs: Color in Print
- Kaida Xiao, University of Leeds: Skin and Appearance
- Susan Farnand and Mark Fairchild, RIT: Color Perception

IMAGE CAPTURE

16:30 – 17:50

Session Chair: Erik Reinhard, InterDigital (France)

16:30 **JIST-first: Evaluation of Figures of Merit for Colorimetric Cameras,** *Michael Vrhel, Artifex Software, and H. Joel Trussell, North Carolina State University (US)* . . . . . **Appendix B**
We investigate the relationship between goodness measures of spectral sensitivities to actual ΔE performance in the presence of signal dependent noise. We show that the Vora value does not perform as well as Sharma's figure of merit (FOM). In addition, we show that Sharma's FOM has issues when the spectral samples include lower luminance data. We introduce an FOM that accounts for signal dependent noise and has a linear relationship to E performance. The improvement introduced by including signal dependent noise in the FOM results in closer relationships of the FOM to colorimetric accuracy in all cases but is especially important when the ensemble under investigation has a wide range of luminance values.

16:50 **CNN Color Demosaicking Generalizes for any CFA,** *Lise Yannick Bourrier[1], Martial Mermillod[1], Marina Reyboz[2], and David Alleysson[1]; [1]LPNC, Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS and [2]Univ. Grenoble Alpes, CEA, LIST (France)* **92**
A convolutional neural network is trained in auto/hetero-associative mode for reconstructing RGB components from a randomly mosaicked color image. The trained network was shown to perform equally well when images are sampled periodically or with a different random mosaic. Therefore, this model is able to generalize on every type of color filter array. We attribute this property of universal demosaicking to the network learning the statistical structure of color images independently of the mosaic pattern arrangement.

17:10 **Hue-specific Color Correction for Raw-RGB Images,** *Emilie Robert[1,2,3], Magali Estribeau[2], Cédric Virmontois[1], Pierre Magnan[2], Justin Plantier[4], and Edoardo Cucchetti[1]; [1]Centre National d'Études Spatiales (France), [2]ISAE-SUPAERO (France), [3]Rochester Institute of Technology (US), and [4]French Military Health Service (France)* **96**
Some natural scenes show a reduced set of colors. These scenes are often encountered in space imaging, for instance for ocean observation which deals with hues of blue and for Mars exploration which deals with hues of "yellowish-brown". In this context the interest of performing hue-specific (or scene-specific) color corrections for the reconstruction of these images is tested. The study is performed on the Next Generation Target (Avian Rochester, LLC - 130 color patches) for both the color correction matrix computation and efficiency testing. The results show that such hue-specific corrections are efficient on the hues of interest, and evaluate the impact on subsidiary hues.

17:30 **Comparison of LED-based and Reflective Colour Targets for Camera Spectral Sensitivities Estimation,** *Hui Fan and Ming Ronnier Luo, Zhejiang University (China)* **103**
Spectral sensitivities represent the spectral property of a digital camera. Most of the prior art spectral sensitivities estimation algorithms were applied to reflective colour charts, while some algorithms used a LED-based target. In this study, the spectral sensitivities of camera were estimated from both the LED-based and reflective colour targets. Four algorithms including Tikhonov Regularization based on Derivatives, Fourier basis function, Principal Component Analysis (PCA) and Singular Value Decomposition (SVD), were implemented. The estimated accuracy was compared between different types of colour

targets, and between different algorithms. It was found that the optimal algorithm was different when using LED-based and reflective colour targets.

EVENING TALK

20:00 – 21:00

SessionChair: Paul Hubel, Apple Inc. (US)

Night Reveals a Universe in Colors

Babak Tafreshi, National Geographic photojournalist and founder of The World at Night (TWAN) [Abstract only]

Striking colors appear in the images of night skies, from golden Milky Way to red nebulosities, and a colorful aurora. Human eyes can not visually see colors of diffuse faint objects, but the colors do exist and each represents fascinating physical information. However a rapidly growing interest to digital astro-photography and image processing, without learning about the nature of the night sky, has also caused a notable misrepresentation in the natural forms and colors of the universe. Learn more about this fascinating topic during this year's evening talk.

CIC30 WORKSHOPS

Workshop 1
Facial Appearance, Rendering, Perception, and Measurement

MANER

WORKSHOP SPONSOR

LIFC Leeds Institute of Textiles and Colour

Convener: Kaida Xiao, University of Leeds
Confirmed speakers: Tushar Chauhan, MIT; Susan Farnand, Rochester Institute of Technology; Yan Lu, University of Leeds; Yoko Mizokami, Chiba University; and Norimichi Tsumura, Chiba University

Workshop 2
Research and Education in Material Appearance

MANER

Convener: Aditya Suneel Sole, NTNU
Confirmed speakers: Davit Gigilashvili, Jon Yngve Hardeberg, and Aditya Suneel Sole, NTNU

Workshop 3
Color Grading for Digital Cinema

Conveners and Speakers: Laurens Orij, Crabsalad, and Charles Poynton, independent consultant

WEDNESDAY, 16 NOVEMBER

COLORFUL CONNECTIONS

07:30 – 08:45

During breakfast join one of the following members from the community to talk about their experiences and areas of expertise:

- Minjung Kim and Lili Zhang, Meta: Perception in XR
- Paul Hubel, Apple Inc.: Digital camera systems
- Charles Poynton, independent researcher: Display technology

WEDNESDAY KEYNOTE

09:00 – 10:00

Session Chair: Jérémie Gerhardt, DNEG (Canada)

09:00 **Green Color Science,** *Erik Reinhard, InterDigital (France)* [Abstract only]

This keynote makes the case that color science can and should make a meaningful contribution to sustainability. All along a video pipeline, from production to transmission and finally to display, energy is spent. It turns out that one of the most costly aspects of video is simply the production of light in the displays that we use. The introduction of novel display technologies, including a wider gamut, higher dynamic range, higher resolutions, and higher framerates, for the moment tends to increase the energetic impact. The tendency of viewers to migrate to smaller displays, on the other hand, helps to counteract this problem. But what else can be done, and where does color science come in? This presentation outlines the problem and begins to answer some of these questions.

The talk concludes with a discussion of the next phase of color measurement requirements needed to take color reproduction to the point where color communication and control become a universal measurement, much like the voltmeter or the mass balance.

MATERIAL APPEARANCE: IMAGE CAPTURE AND ANALYSIS

MANER

10:00 – 10:40

Session Chair: Aditya Suneel Sole, Norwegian University of Science and Technology (Norway)

datacolor

SESSION SPONSOR

10:00 **JIST-first: Visual Cortex based Material Appearance Transfer Model,** *Hiroaki Kotera, Kotera Imaging Laboratory, and Norimichi Tsumura, Chiba University (Japan)* . . . . . **Appendix B**

MA (Material Appearance) is a perceptual phenomenon that our brain deciphers from the retinal image. What features of retinal image are most closely related to the stimulus inside the visual cortex of V1 ~ V5? The function of V1 is the most well-studied. V1 has the function of seeing fine in the fovea and rough in the periphery, and is mathematically described by LPT (Log-Polar Transform). Since LPT samples the retinal image at a higher rate in the fovea but at lower rate peripherally, the color information tends to gather in center of V1. Paying attention to this LPT features in V1, we reported a novel method to transfer MA from one to another scenes. After LPT, PCM (Principal Component Matching) is applied to match the color distribution between source and

target scenes. By just showing the target scene as an example, our previously reported LPT-PCM model can transfer the MA of target to that of source without any a priori information. However, this model had drawbacks such as changes in appearance depending on the background margins and unpredictable results for the scenes consisting of multiple color clusters. This article explores measures to overcome such drawbacks and discusses the applicability of proposed LPT-PCM. Finally we propose a new numerical index to evaluate the similarity between the target and the transferred with the examined samples.

10:20 **JIST-first: Bumpy Appearance Editing of Object Surfaces in Digital Images,** *Yusuke Manabe, Midori Tanaka, and Takahiko Horiuchi, Chiba University (Japan)* . . . . . **Appendix B**

Objects in nature have diverse appearances, and appearance is one of the elements constituting the unique visual aspect of an object. However, previous studies have shown that when an object is represented as a digital image, its appearance can change compared to the real object depending on the material. In this study, the focus was on the "bumpiness" of the object surface, whereby a method was proposed to edit the bumpiness of the object in the image. First, the statistics obtained from images were analyzed in relation to the sensibility value of the bumpiness perceived by humans. Since the statistics on the original image could not fully explain the perception of bumpiness, analyses were conducted on multiscale images. The results suggested that the mean, standard deviation, and top, defined as the average of the luminance values within the top 10 [percentile], were highly influential as cues for bumpiness perception. The results also indicated that the components in the range of 5–65 [cycles per image-width] were highly influential. Based on these analysis results, a method is proposed to edit bumpiness perception by modulating components in the low and medium frequency bands. The effectiveness of the proposed method is demonstrated by image modulation experiments on objects of various materials.

COFFEE BREAK, EXHIBIT, AND DEMONSTRATION SESSION

10:40 – 11:20

11:20 **JIST-first: Statistical Analysis of Sparkle in Snow Images,** *Mathieu Nguyen, Jean-Baptiste Thomas, and Ivar Farup, Norwegian University of Science and Technology (Norway)* . . . . . **Appendix B**

Sparkle from snow is a common phenomenon in Nature but not well studied in the literature. We perform a statistical study on digital snow images captured in-situ to analyze sparkle events by using contrast and density of sparkle spots descriptors. The method for measuring sparkles by Ferrero et al. is adapted, tested, and verified to the case of snow. The dataset is divided into three categories representing the type of snow acquired: dense snow, fresh snow, and old snow. Our analysis highlights the link between the sparkle of snow, the nature of snow, and its grain structure. Sparkle could thus be a feature used for snow classification.

11:40 **JIST-first: SVBRDF Estimation using a Normal Sorting Technique,** *Snehal Padhye, David Messinger, and James A. Ferwerda, Rochester Institute of Technology (US)* . . . . . **Appendix B**

Spatially varying bidirectional reflectance distribution functions (SVBRDFs) play an important role in appearance modeling of real-world surfaces. Automatic capture of these surface properties is highly desirable, but many techniques only partially capture these properties or use complicated setups to do so. Micro surface roughness variations are especially difficult to capture using image-based methods. In this paper, we propose a novel approach towards estimating the complete SVBRDFs of surfaces using a portable projector-camera system made of standard consumer-grade components. Our approach uses insights about the relations between the illumination and viewing geometry and captured image statistics to estimate surface reflectance properties. Our technique should be of great value to practitioners seeking to model and render the geometric and reflectance properties of complex real-world surfaces.

INTERACTIVE PAPER PREVIEWS II

12:00 – 12:25

Session Chair: Minjung Kim, Meta Reality Labs (US)

Color Reproduction in LED Wall Virtual Production Stages, *Laurent Gudemann[1,2], Jan Fröhlich[1,2], and Harald Brendel[2]; [1]Stuttgart Media University and [2]ARRI Munich (Germany)* **109**

Virtual production stages with LED walls utilize illumination, display, and camera equipment which was not designed with this use case in mind. Because the spectral sensitivity of a camera is different from a human observer, a device specific calibration is required. Furthermore, the illumination spectrum emitted by the display contains large gaps in the cyan and yellow wavelength ranges and is dissimilar to the light sources for which cameras are designed. This causes object colors to be reproduced by the camera in an unnatural manner, making cinematographers hesitant to use LED walls as their primary light source.

In this paper, a display calibration and camera color correction workflow for LED wall virtual production stages is proposed. A linear color correction matrix and the spectrum of a multi-channel LED fixture are jointly optimized to better reproduce object colors simultaneously illuminated by an LED display and the multi-channel fixture as they would appear under high CRI (Color Rendering Index) light sources. An alternative color correction method using root polynomials is found to further improve color reproduction. It is shown that the camera's response to the display can be characterized by a linear 3×3 matrix and the display can be calibrated using the inverse of the color correction, allowing for a color accurate reproduction of a virtual environment.

Digital Restoration of Lost Art: Applying the Colorization Transformer to the Ghent Altarpiece Panels, *Milan Kresovic and Jon Yngve Hardeberg, Norwegian University of Science and Technology (Norway)* **118**

In recent years, image processing has proven to be a great tool to help document, preserve, and restore art pieces, especially visual art. One example is using colorization techniques when the original color information of the image has been lost or is unavailable. To expand on that, we used Ghent Altarpiece as the study case. One of the panels of this polyptych has been lost, and only an archival photograph exists. Using the state-of-the-art colorization method, we want to digitally restore what has been lost in its original form. In this work, we proposed a pipeline that consists of a colorization transformer (ColTran) trained on the captured patch-based imaging data of the Ghent Altarpiece. We evaluated the proposed pipeline and addressed its strengths and weaknesses. Moreover, we presented planned future steps and improvements for this project.

A 360° Omnidirectional Photometer using a Ricoh Theta Z1, *Ian MacPherson, Richard F. Murray, and Michael S. Brown, York University (Canada)* . . . **124**

Spot photometers measure the luminance that is emitted or reflected from a small surface area in a physical environment. Because the measurement is limited to a "spot," capturing dense luminance readings for an entire environment is impractical. In this paper, we provide preliminary results

Effect of Polarization on RGB Imaging and Color Accuracy/Fidelity, *Tarek Abu Haila[1,2], Reimar Tausch[1], Martin Ritz[1], Pedro Santos[1], and Dieter Fellner[1,2,3]; [1]Fraunhofer IGD (Germany), [2]Darmstadt University of Technology (Germany), and [3]Graz University of Technology (Austria)* **165**

The use of polarization while trying to keep the digital color reproduction accuracy at its finest is very challenging due to how polarization is interacting and affecting the light spectrum itself and due to the quality of the used polarization materials. Our study on RGB imaging and color reproduction's fidelity with and without polarization shows that a cross circular polarization (on a camera lens and light source) will have a major impact on how a linear grayscale, whether it has a semi-glossy or matt finishing, would be reproduced in contrast to no polarization at all. A major loss in deep black shades in the case of a semi-glossy grayscale is unmistakable. In addition to a noticeable shift in both lightness and Chroma components regardless of the grayscale's finishing but depending rather on the used color target for correction. DE00 could not paint the full picture about color fidelity despite its low conformant reported values. Whereas, a closer visual inspection of the color components separately (lightness and Chroma) reveals color reproduction problems caused by polarization.

GROUP LUNCH

12:25 – 14:00

Join other attendees for a buffet lunch on the terrace.

COLOR IN COMPUTER VISION: ILLUMINATION ESTIMATION AND INVARIANCE

14:00 – 16:10

Session Chair: Richard Murray, York University (Canada)

14:00 **An Exposure Invariant Neural Network for Colour Correction,** *Abdullah Kucuk[1], Graham D. Finlayson[1], Rafal Mantiuk[2], and Maliha Ashraf[3]; [1]University of East Anglia, [2]University of Cambridge, and [3]University of Liverpool (UK)* **176**

Colour correction is the process of converting camera dependent RGB values to a camera independent standard colour space such as CIE XYZ. Regression methods—linear, polynomial, and root-polynomial least-squares—are traditionally used to solve for the colour correction transform. More recently neural net solutions for colour correction have been developed.

This paper begins with the observation that the neural net solution—while delivering better colour correction accuracy compared to the simple (and widely deployed) 3×3 linear correction matrix approach—is not exposure invariant. That is to say, the network is tuned to mapping RGBs to XYZs for a fixed exposure level and when this exposure level changes, its performance degrades (and it delivers less accurate colour correction compared to the 3x3 matrix approach which is exposure invariant). We develop two remedies to the exposure variation problem. First, we augment the data we use to train the network to include responses for many different exposures. Concomitantly, the trained network is robust to a changing exposure. Second, we redesign the network so, by construction, it is exposure invariant.

Experiments demonstrate that, by adopting either approach, Neural Network colour correction can be made exposure invariant.

14:20 **The NCL-MI Image Dataset for Benchmarking Color Constancy Algorithms: Multiple Illuminations and Multiple Ground Truths,** *Jan Kucera, Gaurav Gupta, and Anya Hurlbert, Newcastle University (UK* . . . . . **Appendix A-6**

An image dataset of multiple-illumination scenes with three forms of ground-truths, including human perceptual ground truths, is presented, together with benchmarking results of single- and multi-illumination color constancy algorithms. The results demonstrate the need for new benchmarks for color correction algorithms based on the spectral and spatial non-uniformities of chromatic adaptation in complex scenes.

14:40 **Laplacian of Logarithm as Illuminant-Invariant Input Space,** *Brian Funt and Ligeng Zhu, Simon Fraser University (Canada)* . . . **182**

An object's color is affected by the color of the light incident upon it, and the illuminant-dependent nature of color creates problems for convolutional neural networks performing tasks such as image classification and object recognition. Such networks would benefit from illuminant-invariant representation of the image colors. The Laplacian of the logarithm of the image is introduced as an effective color invariant. Applying the Laplacian in log space makes the input colors approximately illuminationinvariant. The illumination invariance derives from the fact that finite-difference differentiation in log space is equivalent to ratios of neighboring pixels in the original space. For narrowband sensors, rationing neighboring pixels cancels out their shared illumination component. The resulting color representation is no longer absolute, but rather is a relative color representation. Testing shows that when using the Laplacian of the logarithm as input to a Convolutional Neural Network designed for classification its performance is: (i) approximately equal to that of the same network trained on sRGB data under white light, and (ii) largely unaffected by changes in the illumination.

10-MINUTE STRETCH BREAK

15:10 **Image Editing of Light and Color from a Single Image: A Baseline Framework,** *Yixiong Yang[1], Hassan Ahmed Sial[2], Ramon Baldrich[1], and Maria Vanrell[1]; [1]Universitat Autònoma de Barcelona and [2]Barcelona Institute for Global Health (ISGlobal) (Spain)* **188**

Smart image editing is drawing attention and a wide range of edit operations have been investigated. We address the problem of creating new image versions where light conditions and object colors can be altered while maintaining physical coherence across the scene. We propose a baseline framework comprised of a surreal dataset with a large Ground-Truth on light effects and a set of basic deep architectures relying on intrinsic decomposition. Our proposal is evaluated for image relighting and outperforms the state-of-the-art on the previous VIDIT dataset. The codes and datasets are available: https://github.com/ liulisixin/ImageEditingSI

15:30 **Approximating Planckian Black-body Lights using Wien's Approximation,** *Rada Deeb and Graham Finlayson, University of East Anglia (UK), and Michael Brill, Datacolor (US)* **194**

Planck's law and Wien's approximation of this law are both widely used to calculate the spectral radiation of a black-body based on its color temperature. The Wien approximation is a slightly simpler equation and has the advantage that the logarithm of a Wien light can be written as a linear sum of two basis vectors plus an offset (a fact that is exploited in some computer vision algorithms).

In this paper, we show that the Wien formulation can, in general, be used to approximate Planckian lights assuming there is a mapping function taking Planckian to corrected Wien temperature. Significantly, we show that

a correction function *f*() exists and for the range of color temperatures of interest the Wien spectrum calculated for *f*(T) has a very similar shape to the actual spectrum of a Planckian light with temperature T. We find that defining *f*() as a polynomial-type function models to a good extent the relationship between the color temperatures of Planckians and their closest Wien-Planckians lights both in terms of the angular error between their two respective spectral functions and their projections to u'v' coordinates.

15:50 **Dive into Illuminant Estimation from a Pure Color View,** *Shuwei Yue and Minchen Wei, The Hong Kong Polytechnic University (Hong Kong)* **200**

Illuminant estimation is critically important in computational color constancy, which has attracted great attentions and motivated the development of various statistical- and learning-based methods. Past studies, however, seldom investigated the performance of the methods on pure color images (i.e., an image that is dominated by a single pure color), which are actually very common in daily life. In this paper, we develop a lightweight feature-based Deep Neural Network (DNN) model—Pure Color Constancy (PCC). The model uses four color features (i.e., chromaticity of the maximal, mean, the brightest, and darkest pixels) as the inputs and only contains less than 0.5k parameters. It only takes 0.25ms for processing an image and has good cross-sensor performance. The angular errors on three standard datasets are generally comparable to the state-of-the-art methods. More importantly, the model results in significantly smaller angular errors on the pure color images in PolyU Pure Color dataset, which was recently collected by us.

INTERACTIVE POSTER SESSION

16:10 – 17:40

Meet with Interactive (poster) paper authors to discuss their work over a beverage of your choice and help select the CIC30 Cactus Award winner.

CONFERENCE RECEPTION/DINNER AND DRINK THE ΔE CONTEST

19:00 – 22:00

Join other attendees for a night of fun. We begin with cocktails and the Drink the ΔE Contest where you use the base of your choice and food-safe dyes to match a color to the closest ΔE, followed by a buffet dinner.

THURSDAY, 17 NOVEMBER

COLORFUL CONNECTIONS

07:30 – 08:45

During breakfast join one of the following members from the community to talk about their experiences and areas of expertise:

- Carol Payne, Netflix, and Jeremie Gerhardt, DNEG: Color management for film and media
- Roland Fleming, Justus Liebig University of Giessen and Center for Mind, Brain and Behavior of the Universities of Marburg and Giessen: Vision / neuroscience, computer graphics, and machine/deep learning
- Erik Reinhard, InterDigital: HDRI, Sustainability

KEYNOTE AND AWARDS

09:00 – 10:10

Session Chair: Anya Hurlbert, Newcastle University (UK)

09:00 **Nothing About Us Without Us?,** *Vien Cheung, University of Leeds (UK)* [Abstract only]

Facial recognition, an artificial-intelligence-based technology, aims to map and analyze facial features from images—photographs, videos, or in real time—so as to identify and confirm a subject. This technology has been increasingly deployed by law enforcement and border control to secure access, improve surveillance, and minimize in-person contact, especially during the crucial pandemic times. However, such efficient advancement is not without controversies. There have been significant concerns on privacy risk, data leak, discrimination, and color (racial) and gender bias. This talk discusses the state-of-the-art of facial recognition and presents a philosophical analysis on the balance of technology and diversity.

IMAGE QUALITY AND INTERPRETATION

10:10 – 10:50

Session Chair: Susan Farnand, Rochester Institute of Technology

10:10 **Image Quality of Spectral Filter Arrays for Planetary Rover Applications: From Demosaicing to Color Correction,** *Edoardo Cucchetti[1], Emilie Robert[1,2,3] Alexandre Delahaye[4], Mathieu Boutillier[1], Christophe Latry[1], Karine Mathieu[1], Nicolas Théret[1], and Cédric Virmontois[1]; [1]Centre National d'Etudes Spatiales (France), [2]ISAE Supaero (France), [3]Rochester Institute of Technology (US), and [4]Magellium (France)* **205**

The exploration of the Solar System using unmanned probes and rovers has improved the understanding of our planetary neighbors. Despite a large variety of instruments, optical and near-infrared cameras remain critical for these missions to understand the planet's surrounding, its geology but also to communicate easily with the general public. However, missions on planetary bodies must satisfy strong constraints in terms of robustness, data size, and amount of onboard computing power. Although this trend is evolving, commercial image-processing software cannot be integrated. Still, as the optical and a spectral information of the planetary surfaces is a key science objective, spectral filter arrays (SFAs) provide an elegant, compact, and cost-efficient solution for rovers. In this contribution, we provide ways to process multi-spectral images on the ground to obtain the best image quality, while remaining as generic as possible. This study is performed on a prototype

SFA. Demosaicing algorithms and ways to correct the spectral and color information on these images are also detailed. An application of these methods on a custom-built SFA is shown, demonstrating that this technology represents a promising solution for rovers.

10:30 **Evaluating the Performance of Different Cameras for Spectral Reconstruction,** *Yi-Tun Lin and Graham D. Finlayson, University of East Anglia (UK)* **213**

Spectral Reconstruction (SR) algorithms seek to map RGB images to their hyperspectral image counterparts. Statistical methods such as regression, sparse coding, and deep neural networks are used to determine the SR mapping. All these algorithms are optimized 'blindly' and the provenance of the RGBs is not considered.

In this paper, we benchmark the performance of SR methods—in order of increasing complexity: regression, sparse coding, and deep neural network—when different RGB camera spectral sensitivity functions are used. In effect, we ask: "Are some cameras better able to recover spectra from RGBs than others?". In our experiments, RGB images are generated by numerical integration for a fixed set of hyperspectral images using 9 different camera response functions (each from a different camera manufacturer) plus the CIE 1964 color matching functions. Then, we train SR methods on the respective RGB image sets. Our experiments show three important results. First, different cameras **do** support slightly better or worse spectral reconstruction but, secondly, that changing the spectral sensitivities alone does not change the ranking of different algorithms. Finally, we show that sometimes switching the used camera for SR can give a greater performance boost than switching to use a more complex SR method.

COFFEE BREAK
10:50 – 11:20

COLOR VISION: ADAPTATION AND MODELS

11:20 – 12:40

Session Chair: Michael Brill, DataColor (US)

11:20 **CIC30 Best Paper: Suprathreshold Contrast Matching between Different Luminance Levels,** *Maliha Ashraf[1], Rafal Mantiuk[2], Jasna Martinovic[3], and Sophie Wuerger[1]; [1]University of Liverpool, [2]University of Cambridge, and [3]University of Edinburgh (UK)* **219**

We investigated how perceived achromatic and chromatic contrast changes with luminance. The experiment consisted of test and reference displays viewed haploscopically, where each eye sees one of the displays. Test stimuli presented on the test display on a background of varying luminance levels (0.02, 2,20,200,2000 cd/m^2) were matched in perceived contrast to reference stimuli presented on a background at a fixed 200 cd/m^2 luminance level. We found that approximate contrast constancy holds at photopic luminance levels (20 cd/m^2 and above), that is, test stimuli presented at these luminance backgrounds matched when their physical contrasts were the same magnitude as the reference stimulus for most conditions. For lower background luminances, covering an extensive range of 5 log units, much higher physical contrast was required to achieve a match with the reference. This deviation from constancy was larger for lower spatial frequencies and lower pedestal suprathreshold contrasts. Our data provides the basis for new contrast retargeting models for matching appearances across luminance levels.

11:40 **An Intrinsic Image Network with Properties of Human Lightness Perception,** *Richard F. Murray[1], David H. Brainard[2], Jaykishan Y. Patel[1], Ethan Weiss[1], and Khushbu Y. Patel[1]; [1]York University (Canada) and [2]University of Pennsylvania (US)* **225**

Research on human lightness perception has revealed important principles of how we perceive achromatic surface color, but has resulted in few image-computable models. Here we examine the performance of a recent artificial neural network architecture in a lightness matching task. We find similarities between the network's behaviour and human perception. The network has human-like levels of partial lightness constancy, and its log reflectance matches are an approximately linear function of log illuminance, as is the case with human observers. We also find that previous computational models of lightness perception have much weaker lightness constancy than is typical of human observers. We briefly discuss some challenges and possible future directions for using artificial neural networks as a starting point for models of human lightness perception.

12:00 **Weighted Geometric Mean (WGM) Method: A New Chromatic Adaptation Model,** *Che Shen and Mark Fairchild, Rochester Institute of Technology (US)* **231**

The geometric mean has been suggested to be the fundamental mathematical relationship that governs peripheral sensory adaptation. This paper proposes the WGM model, an advanced chromatic adaptation model based on a weighted geometric mean approach that can anticipate incomplete adaptation as it moves along the Planckian or Daylight locus. Compared with two other chromatic adaptation models (CAT16 and vK20), the WGM model shows more accuracy in predicting previous visual data.

12:20 **A Study of Spatial Chromatic Contrast Sensitivity based on Different Colour Background,** *Qiang Xu[1], Qichen Ye[1], Rafal Mantiuk[2], and Ming Ronnier Luo[1]; [1]Zhejiang University (China) and [2]University of Cambridge (UK)* **236**

The goals of this work are to accumulate the experimental data on contrast sensitivity functions and to establish a visual model that incorporates spatial frequency dependence. In addition, the experimental results from fixed-size and fixed-cycles stimuli and from different luminance levels were compared. Such a model is highly desired for applications that rely on image quality and to serve the lighting and imaging industries. The detection thresholds have been measured for chromatic contrast patterns at different spatial frequencies. The experimental parameters included: (1) four colour centres (white, green, yellow, and red), which were recommended by the International Commission on Illumination (CIE), at two different luminance levels for each colour centre; (2) three colour directions for each colour centre, namely luminance, red-green and yellow-blue; (3) five spatial frequencies, 0.06, 0.24, 0.96, 3.84, and 6.00 cycles per degree (cpd) for fixed-cycles stimulation, in which two spatial frequencies, 0.24 and 6.00 cpd, were also chosen for fixed-size stimuli. In this experiment, a 10-bit display characterized by GOG model was used to obtain contrast thresholds of different colour centres by 2-alternative forced choice method and stair-case method. The experimental results revealed different parameter effects (colour centres, luminance, colour direction, fixed cycle/size), and also supported McCann's conclusion that the number of cycles affects the comparative sensitivity. Most importantly, a cone contrast model was successfully developed by fitting the visual test data (fixed number of cycles). The model could accurately predict the contrast sensitivity of different color centers, spatial frequencies and stimulus.

GROUP LUNCH
12:40 – 14:00
Join other attendees for a buffet lunch on the terrace.

COLOR COGNITION: FACES AND CULTURE

14:00 – 15:00

Session Chair: Vien Cheung, University of Leeds (UK)

14:00 **Representative Color of Skin Tones and Natural Objects,** *Dara Dimoff and Susan Farnand, Rochester Institute of Technology (US* **241**

Color enables humans to readily extract features of an object, leading us to describe tomatoes and apples as "red" despite the presence of other colors. How observers accomplish this is not well understood. In this study, we present observers with rapidly presented stimuli at varying levels of context. Observers were asked to select the color that best represents the image from eight options. We found that observers tended to select progressively lighter or darker colors as more context was introduced, although whether the representative color choice became darker or lighter varied from image to image. This is likely a result of observers discounting achromatic cues (i.e.: specular highlights, shadows) as context is revealed, but why images were treated inconsistently requires further investigation. Observer responses were noisily distributed. These results shed light on how observers characterize the color of multicolored objects.

14:20 **Colour Predictors of Facial Preference Differ in Caucasian and Chinese Populations,** *Yan Lu[1], Kaida Xiao[1], Jie Yang[2], Michael Pointer[1], Changjun Li[3], and Sophie Wuerger[4]; [1]University of Leeds (UK), [2]Beijing Institute of Graphic Communication (China), [3]University of Science and Technology Liaoning (China), and [4]University of Liverpool (UK)* . . . . . **Appendix A-8**

Facial colour characteristics convey vital personal information and influence social interactions and mate choices as contributing factors to perceived beauty, health, and age. How various colour characteristics would affect facial preference and whether there is a cultural difference are not fully understood. Here, we provide a useful and repeatable methodology for skin colour research based on a realistic skin model to investigate the effect of various facial colour characteristics on facial preference and compare the role of colour predictors in Caucasian (CA) and Chinese (CN) populations. Our results show that, although the average skin colour of facial areas plays a limited role, together with colour variation and contrast, there are stronger links between colour and facial preference than previously revealed. We also find large cultural differences in facial colour perceptions. Interestingly, Chinese observers tend to rely more heavily on colour cues to judge facial preferences than Caucasian observers.

14:40 **How Koreans Understand Colorfulness, Chroma, Vividness, and Depth,** *Hyesun Han and Youngshin Kwak, Ulsan National Institute of Science and Technology (South Korea)* **246**

In this study, the relationships between chae-do, the commonly used Korean terminology to describe chromatic attributes, CIE definition for colorfulness, Munsell definition for chroma, Berns' definition for CIELAB based vividness and depth are investigated. Although only the definitions were presented, without corresponding terminologies, the observers' responses showed that chae-do is understood very similarly to the definitions of CIE colorfulness and Munsell chroma. Responses for the definitions of vividness and depth also showed high correlation with Berns' CIELAB based vividness and depth predictions, which shows that definitions were well understood. No correlations were found between the definition of CIE colorfulness and the definition of vividness, which shows that the definition of vividness is understood differently to the definition of colorfulness. Comparing the response with color appearance model predictions, the responses showed good correlation with the predictions. Especially, colorfulness definition responses showed the highest coefficient correlation with CIELAB-based Berns' depth prediction, implying the possibility of colorfulness predictor modification for better prediction. The findings can be further investigated to observers from other non-English speaking countries and collect meaningful cross-cultural color appearance data.

COFFEE BREAK

15:00 – 15:30

MATERIAL APPEARANCE: SHINING AND SEEING THROUGH

15:30 – 17:10

Session Chair: Roland Fleming, Justus Liebig University of Giessen and Center for Mind, Brain and Behavior of the Universities of Marburg and Giessen (Germany)

15:30 **JPI-first: Transparency and Translucency in Visual Appearance of Light-Permeable Materials,** *Davit Gigilashvili and Tawsin Uddin Ahmed, Norwegian University of Science and Technology (Norway)* . . . . . **Appendix B**

Light-permeable materials are usually characterized by perceptual attributes of transparency, translucency, and opacity. Technical definitions and standards leave room for subjective interpretation on how these different perceptual attributes relate to optical properties and one another, which causes miscommunication in industry and academia alike. A recent work hypothesized that a Gaussian function or a similar bell-shaped curve describes the relationship between translucency on the one hand, and transparency and opacity, on the other hand. Another work proposed a translucency classification system for computer graphics, where transparency, translucency and opacity are modulated by three optical properties: subsurface scattering, subsurface absorption, and surface roughness. In this work, we conducted two psychophysical experiments to scale the magnitude of transparency and translucency of different light-permeable materials to test the hypothesis that a Gaussian function can model the relationship between transparency and translucency, and to assess how well the aforementioned classification system describes the relationship between optical and perceptual properties. We found that the results vary significantly between the shapes. While bell-shaped relationship between transparency and translucency has been observed for spherical objects, this was not generalized to a more complex shape. Furthermore, how optical properties modulate transparency and translucency is also dependent on the object shape. We conclude that these cross-shape differences are rooted in different image cues generated by different object scales and surface geometry.

15:50 **Predicting Pigment Color Degradation with Time Series Models,** *Irina-Mihaela Ciortan[1], Tina Grette Poulsson[2], Sony George[1], and Jon Yngve Hardeberg[1]; [1]Norwegian University of Science and Technology and [2]National Museum of Norway (Norway)* **250**

The colors of pigments and dyes are affected by light exposure. Light-induced color change has an impact on various industrial and artistic applications where colored materials are frequently exposed to light throughout their lifecycle. For this reason, it is beneficial to understand the fading behaviour of pigments and simulate future degradation. In this article, we are proposing a method to forecast color change of pigments based on time series analysis. To begin with, we collect fading data from real objects with a microfadeometer, which records the color coordinates after every second of light exposure. Then, we treat this data as a time series, test for its stationarity and fit it with

autoregressive integrated moving average (ARIMA) models. Finally, using a train-test split, we validate the accuracy of the ARIMA models in predicting color degradation of pigments and dyes.

16:10 **Perception of the Appearance of Metal-like Package Printing,** *Carl Fridolin Weber, Labeed Ahmad Solangi, Hans Martin Sauer, and Edgar Dörsam, TU Darmstadt; and Martin Schmitt-Lewen, Heidelberger Druckmaschinen AG (Germany)* **258**

A psychophysical study on two series of printed metallized surfaces, which both consisted of ten samples was performed. Two groups participated in the experiment. These were experts, who regularly judge the appearance of printed samples at their daily work, and amateurs who do not regularly visually judge and compare samples. For the experiments, a special light booth for conducting visual experiments with focus on gloss was designed and a ranking experiment was worked out. It was investigated how observers look at these kind of surfaces when asked to judge their glossiness, lightness, roughness, the sharpness of reflected images, and metallicity. All samples had the same size and nearly no hue but differed in gloss and texture. It was examined how the ratings of the targeted characteristics of appearance correlate with each other, and how they correlate with the gloss measured at the specular angles of 20°, 60°, and 85° and the distinctness-of-image measured with an IQ-S gloss meter. Additionally, observers were inquired for their individual understanding of gloss.

16:30 **Reproduction of Perceptual Translucency by Surface Texture in 3D Printing,** *Kazuki Nagasawa[1], Kamui Ono[1], Wataru Arai[2], and Norimichi Tsumura[1]; [1]Chiba University and [2]Mimaki Engineering Co., Ltd. (Japan)* **264**

We propose a method of reproducing perceptual translucency in three-dimensional printing. In contrast to most conventional methods, which reproduce the physical properties of translucency, we focus on the perceptual aspects of translucency. Humans are known to rely on simple cues to perceive translucency, and we develop a method of reproducing these cues using the gradation of surface textures. Textures are designed to reproduce the intensity distribution of the shading and thus provide a cue for the perception of translucency. In creating textures, we adopt computer graphics to develop an image-based optimization method. We validate the effectiveness of the method through subjective evaluation experiments using three-dimensionally printed objects. The results of the validation show that the proposed method using texture is effective in improving perceptual translucency.

16:50 **The Role of Shape in Modeling Gloss,** *Davit Gigilashvili and Akib Jayed Islam, Norwegian University of Science and Technology (Norway)* **271**

Gloss is an important appearance attribute, and its exact perceptual mechanisms are yet to be fully understood. Previous works attempted to model the relationship between optical and perceptual gloss. The state-of-the-art studies demonstrate that the human visual system has a poor ability to recover surface reflectance and perceived gloss rather depends on image cues that are generated by a complex interaction among optical material properties, illumination, object shape, and its surface geometry. Therefore, perceptual models defined on a particular shape, such as a sphere, may not generalize to other objects. To investigate shape-specific differences, we conducted a psychophysical experiment with a simple sphere and complex Lucy shapes. We scaled the magnitude of apparent gloss to study how the shape affects perceived gloss, and how the role of optical material properties varies between the shapes. We observed significant cross-shape differences, which we argue can be explained by the analysis of the image cues.

CLOSING REMARKS AND BEST STUDENT PAPER AWARD

17:10 – 17:20

CIC30 General Chair: Peter Morovic, HP Inc. (Spain)

CIC30 SHORT COURSES

SC01 Color and Imaging and
SC16 Advanced Colorimetry and Color Appearance
Instructor: Gaurav Sharma, University of Rochester

SC02 Digitizing Motion Picture Film
Instructor: Giorgio Trumpy, University of Zurich

SC03 Solving Color Problems using Vector Space Arithmetic
Instructor: Michael Vrhel, Artifex Software, Inc.

SC04 Understanding Quality in the Era of Extended Reality (XR)
Instructor: Chaker Larabi, XLIM - Université de Poitiers

SC06 Measuring, Modeling, and Rendering Surface Appearance
Instructors: James A. Ferwerda and Snehal Padhye, RIT

SC07 High Dynamic Range Imaging and Display—Technologies, Applications, and Perceptual Considerations
Instructor: Timo Kunkel, Dolby Laboratories, Inc.

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

SC09 Human Color Vision and Visual Processing from Optics to Perception
Instructor: Andrew Stockman, UCL Institute of Ophthalmology

SC10 Fundamentals of Translucency Perception
Instructor: Davit Gigilashvili, Norwegian University of Science and Technology

SC11 OLEDs, Quantum Dots, and Color Imaging
Instructors: Charles Poynton and Peter Palomaki, independent consultants

SC12 Fundamentals of Psychophysics
Instructor: James A. Ferwerda, RIT

SC13 HDR Theory and Practice
Instructor: John McCann, McCann Imaging

SC14 Color Calibration and Color Rendition Considerations for LED-Based Virtual Production Stages
Instructors: Carol Payne and Chloe LeGendre, Netflix

SC17 Fundamentals of Spectral Measurements for Color Science
Instructor: David R. Wyble, Avian Rochester, LLC