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Scottsdale, Arizona

CIC 30th COLOR & imaging CONFERENCE

Color Science and Engineering Systems, Technologies, and Applications

FINAL PROGRAM AND PROCEEDINGS



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IS&T: Society for Imaging Science and Technology
7003 Kilworth Lane
Springfield, VA 22151 USA
703/642-9090; 703/642-9094 fax
info@imaging.org
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WELCOME TO CIC30!

Welcome to the 30th Color and Imaging Conference!

This will be a special one! After two years of CIC held as an online conference due to the pandemic, we finally return to a full, in-person experience and we could not be happier. On top of this, we are celebrating the 30th anniversary of CIC and the 75th anniversary of the Society of Imaging Science and Technology—we are returning to Scottsdale (AZ) where it all began, back in 1992.

Thirty years of color and imaging research is a long time and we have seen many important developments over the years. Major milestones in our understanding and modelling of color vision, metamerism, color appearance, color constancy, and dynamic range perception, as well as important developments in gamut mapping, color correction, tone mapping, ICC and illuminant standards, and many others can all trace their roots to a CIC. Importantly, CIC is home to a unique balance of academia and industry working in tandem to advance fundamental science and come up with practical engineering solutions. But, as always, we look ahead and this year we continue to be the place where color science and imaging research is shared in support of the latest technologies and newest applications.

To that end, we put together an exciting program for you, even before the technical program kicks off. Our short courses, many new or updated, cover topics at levels from introductory to advanced, during the first two days. The second day also sees 3 workshops with 12 panelists who will engage the audience on topics such as facial appearance and rendering, material appearance, and digital cinema color grading.

Then, over three intense days we have 34 oral presentations and 20 interactive posters, as well as 3 great keynotes and an evening talk.

The exciting topics of this year's keynotes push CIC further into fields that require a deeper understanding of how we perceive our environment and what we do with that knowledge. I am particularly pleased that we are giving sustainability and diversity the spotlight. Specifically the talks are:

- Dr. Vien Cheung, "Nothing without us about us?"
- Prof. Roland Fleming, "A Theory of Material Appearance: How Learning Structures Surface Perception"
- Dr. Erik Reinhard, "Green Color Science"

Our evening talk takes us further afield as well, with a visually stimulating lecture from *National Geographic* Photographer Babak Tafreshi, who speaks on night photography.

Finally, we can look forward to the welcome and conference receptions and a robust social program—from contests and competitions to designated times to meet with experts in our community—all with appropriate health measures so everyone is safe as we make the most of being in-person again.

Looking forward to talking with you in Scottsdale and wishing everyone a great conference!

—CIC30 General Chair Peter Morovic

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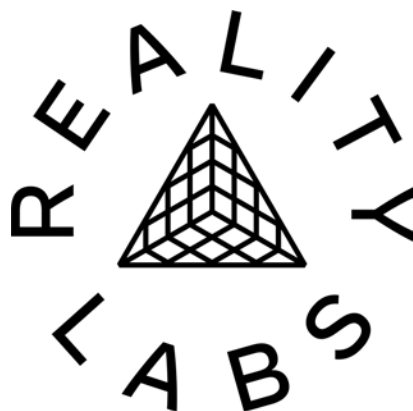
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TECHNICAL PROGRAM: SCHEDULE AND ABSTRACTS



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, CIEC30 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 Hellwig¹, Dale Stoltzka², and Mark Fairchild¹; ¹Rochester Institute of Technology and ²Samsung 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 Zhu¹ and Ming Ronnier Luo^{1,2}, ¹Zhejiang University (China) and ²University 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 significant 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 Dumortier², Sophie Jost², Herve Drezet¹, and Marie-Laure Avenel¹; ¹Technocentre Renault and ²ENTPE (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/m²), stimulus luminance (up to 49000 cd/m²), 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) **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 sub-tense, 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) **277**

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.

Relating Color Associations to Pill Colors and Expected Efficacy,

Rema Amawi, Rochester Institute of Technology – Dubai Campus (United Arab Emirates), and Michael Murdoch, Rochester Institute of Technology (US) . . . 52

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.

A Noise-robust Pulse Wave Estimation from NIR Video using Wiener

Estimation Method, Yuta Hino, Koichi Ashida, and Norimichi Tsumura, Chiba University (Japan) 58

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.

Measurement of Gloss Unevenness with Different Reflection Angles,

So Nakamura¹, Shinichi Inoue², Yoshinori Igarashi³, Takeyuki Hoshi³, Hiromi Sato¹, and Yoko Mizokami¹; ¹Chiba University, ²Tokyo Polytechnic University, and ³Chuo Precision Industrial Co., Ltd. (Japan) 63

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.

Pseudocolor Analysis of Glare's Paradox in Illusions, John McCann,

McCann Imaging (US) 69

Glare introduces a complex scene-dependent 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 (LUTs) 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.

HDR Multispectral Imaging-based BRDF Measurement using a Flexible

Robotic Arm System, Yoko Arteaga^{1,2}, Clotilde Boust^{1,3}, and Jon Hardeberg²;

¹Centre of Research and Restoration of the Museums of France (France),

²Norwegian University of Science and Technology (Norway), and

³PSL-PCMTM UMR8247 CNRS (France) 75

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 than 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.

Constant Hue Loci in Rec. 2020 Gamut under an HDR Condition, Hongbing

Wang and Minchen Wei, The Hong Kong Polytechnic University (Hong Kong), and Xinchao Qu, Dajiang Innovations Technology Co., Ltd. (China) 81

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., IC₁C₂ and J₂a₂b₂). 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



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
- Kaide 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) see JIST 66(5)/DOI: 10.2352/J.ImagingSci.Technol.2022.66.5.050402

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 ΔE 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 Bourrier¹, Martial Mermillod¹, Marina Reyboz², and David Alleysson¹; ¹LPNC, Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS and ²Univ. 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 Estribeau², Cédric Virmontois¹, Pierre Magnan², Justin Plantier⁴, and Edoardo Cucchetti¹; ¹Centre National d'Études Spatiales (France), ²ISAE-SUPAERO (France), ³Rochester Institute of Technology (US), and ⁴French 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

Session Chair: 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.

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 frame rates, 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.

CIC30 WORKSHOPS

Workshop 1

Facial Appearance, Rendering, Perception, and Measurement



WORKSHOP SPONSOR



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



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

MATERIAL APPEARANCE: IMAGE CAPTURE AND ANALYSIS



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) see JIST 66(5)/ DOI: 10.2352/J.ImagingSci.Technol.2022.66.5.050406

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 Compo-





ment 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) see JIST 66(5)/ DOI: 10.2352/J.ImagingSci.Technol.2022.66.5.050403

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) see JIST 66(5)/ DOI: 10.2352/J.ImagingSci.Technol.2022.66.5.050404

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) see JIST 66(5)/ DOI: 10.2352/J.ImagingSci.Technol.2022.66.5.050405

Spatially varying bidirectional reflectance distribution functions (SVBRDFs) play an important role in appearance modeling of real-world surfaces. Au-

tomatic 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 Brendel², ¹Stuttgart Media University and ²ARRI 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.



A0 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 demonstrating the potential of using an off-the-shelf commercial camera to operate as a 360° luminance meter. Our method uses the Ricoh Theta Z1 camera, which provides a full 360° omnidirectional field of view and an API to access the camera's minimally processed RAW images. Working from the RAW images, we describe a calibration method to map the RAW images under different exposures and ISO settings to luminance values. By combining the calibrated sensor with multi-exposure high-dynamic-range imaging, we provide a cost-effective mechanism to capture dense luminance maps of environments. Our results show that our luminance meter performs well when validated against a significantly more expensive spot photometer.

Analysis of Individual Quality Scores of Different Image Distortions,

Olga Cherepkova, Seyed Ali Amirshahi, and Marius Pedersen, Norwegian University of Science and Technology (Norway) 129

In this paper, we study individual quality scores given by different observers for various image distortions (saturation, contrast, and color quantization) at different levels. We created a database that contains a total of 232 images, derived from 21 pristine images, three distortions, and five levels. The database was rated by 31 participants collected through an online platform. The study shows that observers have distinguishable patterns with respect to different distortions. Using quadratic regression models, we visualized the behavior patterns of different groups of observers. The database and the individual scores collected are publicly available and can be further used for quality assessment research.

Three Dimensional Surface Preserving Smoothing, Ali Alsam and Hans

Jakob Rivertz, Norwegian University of Science and Technology (Norway) 135

We propose a new anisotropic diffusion process for removing noise from MRI images without distorting the edges. The method is based on a simple principle: any diffusion that increases a gradient at neighbouring pixels should be prohibited. From this principle, we deduce an inequality that allows diffusion along the edges but not across them. We introduce promising results using synthetic data with various types of noise as well as real MRI scans.

Spectral Reflectance Estimation with Smoothness Constraint, Shoji

Tominaga, Norwegian University of Science and Technology (Norway) and Nagano University (Japan), Shogo Nishi, Osaka Electro-Communication University (Japan), Ryo Ohtera, Kobe Institute of Computing (Japan), and Hideaki Sakai, Kyoto University (Japan) 141

We consider the problem of estimating surface-spectral reflectance with a smoothness constraint from image data. The total variation of a spectral reflectance over the visible wavelength range is defined as the measure of smoothness. A penalty on roughness, equivalent to smoothness, is added to the performance index to estimate the spectral reflectance functions. The optimal estimates of the spectral reflectance functions are determined to minimize a total cost function consisting of the estimation error and the roughness of the spectral functions. An RGB camera and multiple LED light sources are used to construct the multispectral image acquisition system. We model the observed images using spectral sensitivities, illuminant spectrum, unknown spectral reflectance, a gain parameter, and an additive noise term. The estimation algorithms are developed for the two estimation methods of PCA and

LMMSE. The optimal estimators are derived based on the least-square criterion for PCA and the mean squared error minimization criterion for LMMSE. The feasibility of the proposed method is shown in an experiment using three mobile phone cameras. It is confirmed that the optimal estimators improve the accuracy for both original PCA and LMMS estimators.

Improving Naturalness in Transparent Augmented Reality with Image

Gamma and Black Level, Zilong Li and Michael Murdoch, Rochester Institute of Technology (US) 147

In this study, we used a custom-built Optical See-Through Augmented Reality (OST AR) system to conduct a psychophysical experiment to determine the preferred gamma and black level for high naturalness perception in OST-AR. We utilized 6 different fruit stimuli and 11 different backgrounds to do this experiment. We used two-way ANOVA to analyze the data and concluded that only the effect of different fruits on virtual objects' gamma preference for high naturalness is considered statistically significant. Surprisingly, all ANOVA analyses indicate background's color does not contribute to observers' gamma or black level preference for naturalness. We found that gamma preference has a strong correlation with the average lightness of the virtual stimuli. There is no clear correlation between chroma, hue, and gamma preference in terms of naturalness perception. This finding suggests that the background can be ignored in future imaging pipelines emphasizing high naturalness appearance in Augmented Reality.

Reversibility of Corresponding Colors in Sensory Chromatic Adaptation,

Mark Fairchild, Rochester Institute of Technology (US) 153

In colorimetry and color appearance modeling it is assumed that chromatic adaptation is reversible. Recent experimental results suggest that this might not be the case and that bidirectional models of chromatic adaptation might be needed. This paper describes a series of experiments designed to collect very-high precision corresponding colors data for sensory chromatic adaptation to test the hypothesis that chromatic adaptation is reversible for individual observers. The results indicate that there are small, but statistically significant, differences in corresponding colors due to changes in the previous state of adaptation. However the effect sizes are small and the number of repeated observations required to detect these differences is very large. Thus it is concluded that these differences are, while interesting, not problematic for practical colorimetry. In addition the application of the vk20 chromatic adaptation model for predicting such effects is further explored and its 15000K reference adaptation state is validated.

The Regularised Epsilon-derivative for Image Reintegration, Graham

Finlayson, University of East Anglia (UK), and Mark Drew, Simon Fraser University (Canada) 159

Many image-editing tasks are carried out in the gradient domain. Suppose that for an image I the gradient ∇I consists of a pair of fields (p,q) ; then some image "reintegration" scheme is tasked with converting derivative fields (p,q) back to imagespace I ; typically, a Poisson equation solver is used for this task. But what if we have altered (p,q) so that this pair (p,q) is no longer integrable? Then we have to project onto integrable gradient data that will indeed reintegrate to an approximation of the original image. For example, we may wish to alter (p,q) so as to emphasize or de-emphasize some aspects of the image, e.g. ameliorating wrinkles in skin images (or indeed enhancing them in the case of ageing a face image).

Here, we propose a new gradient kernel that retains part of the original image, regularising the reintegration back into the image domain. We compare our approach with the Screened-Poisson method which includes a term λ times a "screen" term that moves the solution image back closer to the input





image. Effectively, we are doing a similar adjustment, but we show that the results are a good deal better than using Screened-Poisson, which tends to overly blur the output. Moreover, in Screened-Poisson one must choose a value for λ , which may be different for every image—here we determine that our new kernel method does not need to adapt to each image yet delivers comparable or better results.

Effect of Polarization on RGB Imaging and Color Accuracy/Fidelity, Tarek Abu Haila^{1,2}, Reimar Tausch¹, Martin Ritz¹, Pedro Santos¹, and Dieter Fellner^{1,2,3}; ¹Fraunhofer IGD (Germany), ²Darmstadt University of Technology (Germany), and ³Graz 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: Minjung Kim, Meta Reality Labs (US)

14:00 An Exposure Invariant Neural Network for Colour Correction, Abdullah Kucuk¹, Graham D. Finlayson¹, Rafal Mantiuk², and Maliha Ashraf³; ¹University of East Anglia, ²University of Cambridge, and ³University 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) 3x3 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. Comacitantly, 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) **A-3**

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 narrow-band 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 Yang¹, Hassan Ahmed Sial², Ramon Baldrich¹, and Maria Vanrell¹; ¹Universitat Autònoma de Barcelona and

²Barcelona 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 Cucchetti¹, Emilie Robert^{1,2,3}, Alexandre Delahaye⁴, Mathieu Bouillier¹, Christophe Latry¹, Karine Mathieu¹, Nicolas Théret¹, and Cédric Virmontois¹; ¹Centre National d'Etudes Spatiales (France), ²ISAE Supaero (France), ³Rochester Institute of Technology (US), and ⁴Magellium (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 Ashraf¹, Rafal Mantiuk², Jasna Martinovic³, and Sophie Wuerger¹; ¹University of Liverpool, ²University of Cambridge, and ³University 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/m²) were matched in perceived contrast to reference stimuli presented on a background at a fixed 200 cd/m² luminance level. We found that approximate contrast constancy holds at photopic luminance levels (20 cd/m² 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. Murray¹, David H. Brainard², Jaykishan Y. Patel¹, Ethan Weiss¹, and Khushbu Y. Patel¹; ¹York University (Canada) and ²University 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 Xu¹, Qichen Ye¹, Rafal Mantiuk², and Ming Ronnier Luo¹; ¹Zhejiang University (China) and ²University 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 Lu¹, Kaida Xiao¹, Jie Yang², Michael

Pointer¹, Changjun Li³, and Sophie Wuerger⁴; ¹University of Leeds (UK), ²Beijing Institute of Graphic Communication (China), ³University of Science and Technology Liaoning (China), and ⁴University of Liverpool (UK) A-5

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) see JPI vol 5/

DOI: 10.2352/J.Percept.Imaging.2022.5.000409

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 Ciortan¹, Tina Grette Poulsson², Sony George¹, and Jon Yngve Hardeberg¹; ¹Norwegian University of Science and Technology and ²National 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 life-cycle. 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 microfadeome-





ter, 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 Nagasawa¹, Kamui Ono¹, Wataru Arai², and Norimichi Tsumura¹; ¹Chiba University and ²Mimaki 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 Javed 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

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 Wüeller, 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

SC16 Advanced Colorimetry and Color Appearance

Instructor: Gaurav Sharma, University of Rochester

SC17 Fundamentals of Spectral Measurements for Color Science

Instructor: David R. Wyble, Avian Rochester, LLC

CIC30 APPENDIX A

EXTENDED **ABSTRACTS**



Color-Difference Ellipsoids Follow from Metamer Mismatching

Emitis Roshan and Brian Funt; School of Computing Science, Simon Fraser University, Vancouver, Canada

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. [1] [2], have been developed based on fits to the data obtained from psychophysical experiments (e.g., Li et al. [3] [4]). However, such models do not explain why the color difference thresholds vary across color space as they do. Funt et al. [5] 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.

Metamer mismatching results from the fact that the relationship between cone triples and surface reflectances is one-to-many. Under some fixed illuminant, there are many different surface reflectances leading to the same cone response triple. Such reflectances are generally referred to as metamers. Under a second illuminant these different reflectances will usually lead to quite distinct cone response triples. The set of all such cone triples is known as the metamer mismatch body [6]. This phenomenon is referred to as metamer mismatching. Because of the one-to-many relationship between a cone response triple and surface reflectances, the eye cannot uniquely identify a surface's reflectance and so might, for example, misidentify a poisonous plant as an edible one. The likelihood of this misidentification depends on the extent of metamer mismatching, which varies across color space. The more serious the metamer mismatching, the more precisely colors need to be discriminated from one another to avoid mistakes; and hence, the need for an inverse relationship between the extent of metamer mismatching and color discrimination thresholds.

Color difference thresholds are usually represented by ellipses in a 2D chromaticity space or ellipsoids in 3D color space. Funt et al. [5] show that the volume, M , of the Metamer Mismatch Body (MMB) normalized by the cube of the distance, C , between a color center and the origin of the coordinate system is inversely proportional to the volume of the color discrimination ellipsoid (E_{vol}). In other words, $C^3/M \propto E_{vol}$. This relationship—based solely on the hypothesis that the uncertainty created by metamer mismatching underlies color difference thresholds—predicts the experimental data on the volume of color discrimination ellipsoids better than CAM16-UCS, even though CAM16-UCS is based on a direct fit to similar experimental data.

Although the relationship $C^3/M \propto E_{vol}$ based on metamer mismatching is effective in predicting the volume of color discrimination ellipsoids, can metamer mismatching predict the shape and orientation of the color discrimination ellipsoids as well?

To model the general shape of an MMB, we use its equivalent ellipsoid as proposed by Roshan et al. [7]. The radii and principal axes of the equivalent ellipsoid represent the MMB's size and orientation respectively. Let the radii of its equivalent ellipsoid be

r_1 , r_2 and r_3 . Based on the inverse relationship between the normalized MMB volume and the discrimination ellipsoid volume (i.e., strong correlation coefficients between C^3/M and E_{vol}) it is reasonable to expect an ellipsoid with radii C/r_1 , C/r_2 and C/r_3 , to be similar to the discrimination ellipsoid.

The proposed theory predicts the shape and orientation of color discrimination ellipsoids based on metamer mismatching. In order to evaluate the accuracy of the method's predictions, an ellipsoid similarity measure is needed. One such measure is that defined by Merritt [8]. The Merritt similarity measure varies from 0 to 1, with 1 indicating two identical ellipsoids.

The MMBs for the 19 color centers in the Melgosa dataset [9] (derived from the original data in RIT-DuPont dataset [10]), the 17 color centers in Huang dataset [11], the 5 color centers in Cheung dataset [12] and the 4 in Witt dataset [13] are calculated for illuminant change D65 to A using the algorithm of Logvinenko et al. [14]. The equivalent ellipsoids corresponding to these MMBs are then calculated and compared to the experimental data using the Merritt similarity measure (Table 1).

Dataset	Merritt
Melgosa	0.79
Huang	0.78
Cheung	0.80
Witt	0.84

Table 1 Merritt similarity measure comparing the predicted color discrimination ellipsoids to the measured ellipsoids from four datasets.

Color discrimination thresholds are known to vary throughout color space. The degree of metamer mismatching (which reflects the underlying degree of uncertainty as to the actual reflectance producing the color) also varies throughout color space. Hence, color discrimination thresholds and the degree of metamer mismatching are inversely related. This principle can be used to predict the orientation and dimensions of color discrimination ellipsoids quite well.

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The NCL-MI image dataset for benchmarking color constancy algorithms: Multiple illuminations and multiple ground truths

Jan Kučera¹, Gaurav Gupta² and Anya Hurlbert²; ¹School of Computing, ²Institute of Biosciences, Newcastle University, Newcastle upon Tyne, UK

Abstract

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.

Motivation

Color constancy algorithms for digital images typically aim to make the image look as if a neutral light illuminated the scene, removing the chromatic bias of the actual illumination. The assumption is that this processing - “color correction” - will not only achieve constant color descriptors for objects in the image but also match the color appearance of the original scene for a human viewer completely adapted to the scene.

Color constancy algorithms are typically evaluated by metrics that compare the estimated illumination chromaticity with a ground-truth illumination chromaticity, supplied as part of a standard benchmarking image dataset (e.g. the reproduction angular error [1]). Most available image datasets for evaluating color constancy algorithms are of scenes with a single illumination source, and ground truths are typically provided in the form of a single (linear) RGB triplet specifying the illumination chromaticity, obtained from a known achromatic reference surface in the scene (e.g. the Gehler-Shi dataset [2]). The assumption is that the illumination estimate obtained from the single reference surface in these scenes accurately represents the illumination at every location in the scene. This assumption is generally not valid, as in many scenes there is more than one direct light source (e.g. outdoor scenes, with a mixture of sunlight and skylight, or indoor scenes lit by both artificial light and natural light through a window), or there are substantial indirect reflections from chromatic surfaces that add to the direct illumination, or both. Illumination maps that provide illumination estimates at each pixel in the scene, allowing for spatial variations, are generally more realistic even for ostensibly single-source images.

Problem: The need for image datasets for scenes with diverse contents illuminated by multiple sources, with accompanying ground truths, is generally acknowledged by the community. Existing such datasets include the MIMO dataset [3], the subset of two-illumination images in the Cube++ dataset [4], as annotated within the 2nd International Illumination estimation challenge (https://chromaticity.iitp.ru/iec_2.html), and the Flying Grey Ball dataset [5], the latter including on average 100 illumination measurements in the form of RGB triplets from an achromatic surface at different locations in the scene.

The assumption underlying the ground-truth illumination chromaticities provided for the images in such datasets is that the image produced by “de-lighting” via the inverse of the estimated

illumination chromaticity will yield the color appearance of the scene under neutral illumination. This assumption is not generally proven.

Approach

Here we present an image dataset of multiple-illumination scenes with three forms of ground-truths: illumination chromaticities (linear RGB) from multiple achromatic reference surfaces within the scene; images of the same scene under neutral illumination (either D65 or EEW); and images derived from human observer-adjusted color matches to the same scenes (“human perceptual ground-truth”).

The dataset contains 50 raw RGB images, taken by a Panasonic DMC-G7 camera, of indoor scenes under controlled lighting from four spatially separated ceiling fixtures, each an independently spectrally tuneable multi-channel LED lamp. Indoor scenes consist either of all “white” surfaces (see Fig. 1a), or multiple chromatic surfaces. Some of the latter scenes include a live human model facing the viewer (see Fig. 1b). For each scene, multiple images are provided, with and without grey reference balls and with varying combinations of distinct light sources, including single-source EEW and D65 neutral illuminations.

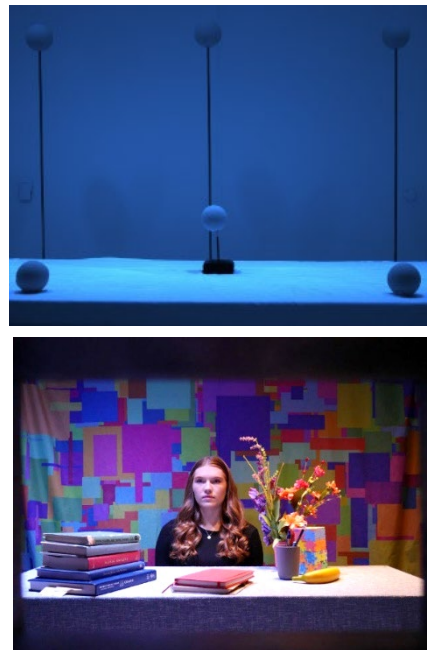


Figure 1. Sample images from NCL-MI dataset. Upper: Single illuminant (“blue”), uniformly neutral scene; Lower: Two-illuminants (“cool/warm”), complex scene.

To obtain the human perceptual ground-truth images, we performed a psychophysical color matching experiment. Participants viewed the chromatic scenes (with and without human models) through a porthole and adjusted the chromaticity of a digital image of the scene, presented on an adjacent monitor, to match. To adjust the chromaticity of the image, participants altered the global scaling factors on the pixel RGB values by navigating in CIELUV (u^*v^*) space. No other light sources were present, and adaptation times were controlled. Human perceptual ground-truth images for each of a series of single- and multiple-illumination scenes were derived from the global scaling factors averaged over all participants for each condition.

Results

Participant matches were compared with outputs of 11 color correction algorithms, including standard single-source (e.g. Grey World [6]; Weighted Grey Edge [7]) and multiple-source algorithms (e.g. Grayness Index [8]). In each of 12 illumination conditions on three distinct scenes, algorithm outputs deviated from human perceptual ground truth images, with highest deviations for scenes containing human models, and lowest for algorithms designed to correct for multiple illuminations. Algorithm performance in terms of metrics based on comparisons of the chromaticity of the estimated illumination and illumination chromaticity ground truth, or on global image differences with neutral illumination ground truth image, did not predict performance based on comparisons with the human perceptual ground truth images.

Conclusions

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. The ground-truths included with this image dataset provide starting points for new benchmarks.

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Author Biography

Jan Kučera received his BSc in Mathematics and MSc in Computer Graphics from the Charles University in Prague. He obtained his MRes and PhD in Human-Computer Interaction from Newcastle University (UK) in 2021. Since then he has worked as a research associate in the Institute of Biosciences at Newcastle University and research fellow at University College London. His research interests include cross-media color perception and novel display technologies.

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Colour predictors of facial preference differ in Caucasian and Chinese populations

Yan Lu¹, Kaida Xiao¹, Jie Yang², Michael Pointer¹, Changjun Li³, and Sophie Wuerger⁴; ¹University of Leeds (UK), ²Beijing Institute of Graphic Communication (China), ³University of Science and Technology Liaoning (China), and ⁴University of Liverpool (UK)

Abstract

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.

Motivation

Facial preference judgement has a profound impact on diverse important social outcomes, such as mate choices and social decision-making, thus it has been studied from various facial perspectives[1], [2]. Compared to non-colour-related facial traits (facial symmetry, averageness, sexual dimorphism, etc.), the colour appearance of a human face has been relatively less investigated but has gained increasing attention in recent years, which may suggest an important role for facial colour characteristics in any of the preference-related evaluations including facial attractiveness, perceived healthiness, and perceived ageing. Colour is a perceptual stimulus which is essential in daily life and is often considered in terms of aesthetics. As a consequence, skin colour preference has been a subject of great interest in many fields including cosmetology, image capture and reproduction, computer graphics, lighting engineering, etc., where effort has been made to satisfy people's desire to have a beautiful, healthy-looking or youthful facial appearance.

Problem

Different facial colour characteristics have been assessed by previous work, including average facial skin colour[3], [4], local skin colour[5], skin colour variation[6], and facial colour contrast[7], in terms of their role in facial preference judgements. With a few notable exceptions, these studies generally examined the role of a single colour characteristic in predicting facial preference. The results are mixed, and none considered all the different colour characteristics together. It is not known how these colour characteristics taken together would affect facial preference, whether they are correlated themselves, and which characteristics are more important in terms of predicting facial preferences including attractiveness, healthiness, and visual age. More importantly, the majority studies have used manipulated facial

stimuli and changed a single colour variable in controlled experiments. The method may overstate the importance of the single colour variable that is being changed in the experiments and meanwhile could not reflect the role of various colour cues in the real situation of attractiveness evaluation in daily life. The weakness of the image manipulating method and the necessity of using real facial images has been discussed in our previous work[8].

Approach

Considering all the above, the present study aims to discuss facial colour preference within an evolutionary meaningful parameter space and to provide a useful and repeatable methodology for skin colour research based on a realistic skin model. Figure 1 shows the schematic diagram of the methodology used in this study. We have used a set of high-resolution images of real human faces without changing the original colour. Facial colour analysis was performed on each of the real facial images and colour characteristics including average/local skin colour, skin colour variation, and facial colour contrast were measured. A rating study was conducted, using both Caucasian and Chinese observers, to obtain preference evaluations including facial attractiveness, perceived healthiness, and visual age. Separate analyses of multiple regressions were carried out for each ethnic group to examine the role of colour in predicting the preference rating of their own faces. We provided a comprehensive assessment of various facial colour characteristics that predict facial attractiveness, perceived healthiness, and perceived age in the two ethnic groups.

Results

Using the non-manipulated real facial images, our study revealed the moderate role of facial colour characteristics in determining facial preference judgements. The average skin colour (L^* , a^* , b^*) explained 9%~31% of the variation in facial preference across different regression models and was a more important predictor than local skin colour (cheek a^* and periportal L^*) in all conditions. Skin colour variation explained 11%~24% of the variation in facial preference across models and, especially, was the most important predictor of perceived age for Caucasians (24% of the variation explained). The overall skin colour variation was a more important colour cue than skin colour variation within the cheek area in predicting any of the facial preferences. Overall, facial colour contrasts explained 10% ~55% of the variation in facial preference and were more important predictors for Chinese than Caucasians in any of the perceptual ratings, including attractiveness, healthiness, or perceived age. Different facial colour cues are utilized by different observers and according to different preference attributes they were accessing. Cultural difference was not only restricted to the utilization of the average facial skin colour as we previously revealed. Actually, the cultural differences included the opposite preference for facial lightness, the utilization of skin colour

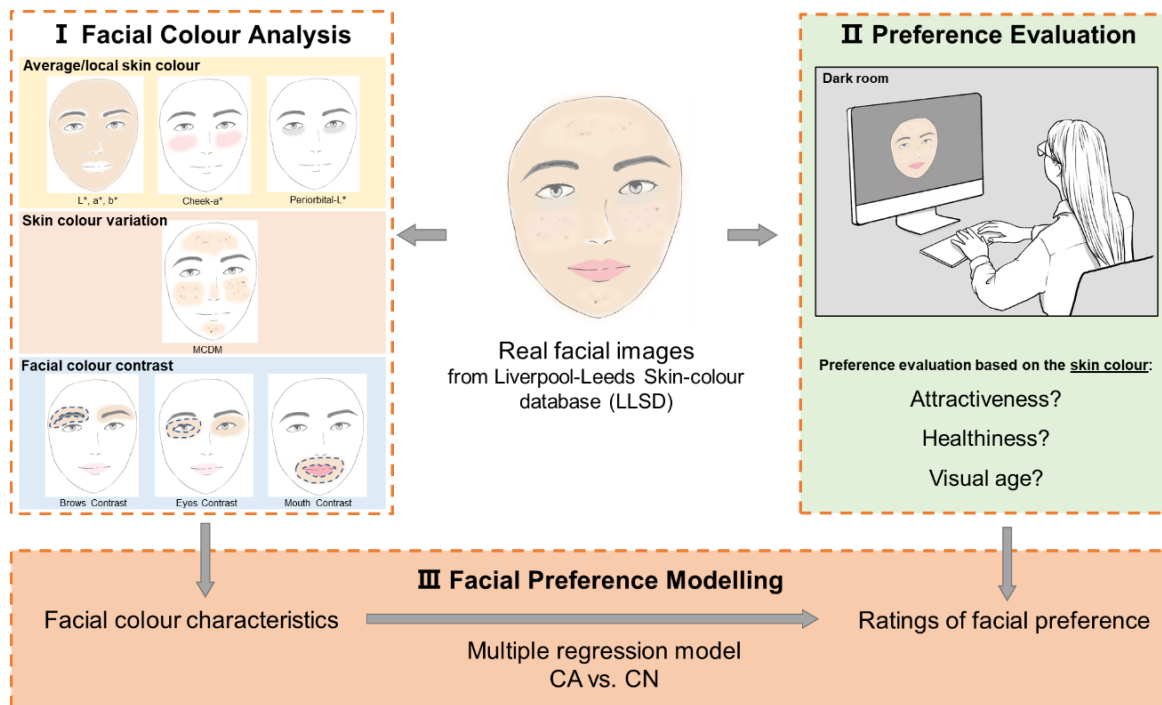


Figure 1. A schematic diagram of the key idea in this study.

variation in judging different preference attributes, and the different colour contrast cues used in preference evaluation.

Conclusions

Our results reveal a moderate role for colour characteristics in determining facial preference within an evolutionary meaningful parameter space. Although the averaged skin colour of facial areas plays limited role, together with colour variation and contrast, there are stronger links between colour and facial preference than previously revealed. Moreover, different facial colour cues are found to be utilized by different observers according to the different preference attributes they are accessing. Interestingly, Chinese observers tend to rely more heavily on colour cues to judge all facial preference attributes than Caucasian observers. The results highlight the importance of examining various facial colour cues to obtain the full picture of colour predictors utilized in facial preference evaluation and demonstrate the large cultural difference between Caucasian and Chinese populations. Our study provides a useful and repeatable methodology that is based on a realistic skin model and thus could be effectively adopted in the future for skin colour research related to preference evaluation.

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Author Biography

Yan Lu received her BEng in Electrical Engineering and Automation (2016) and her MSc in Electric-Optical Measurement and Control Technology (2019) from Fudan University. Currently, she is a PhD student supervised by Kaida Xiao and Stephen Westland at the University of Leeds. Her work focuses on modelling facial colour appearance and facial attractiveness for human complexions. She is also a Research Fellow working on appearance measurement at Leeds Institute of Textile and Colour (LITAC).

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