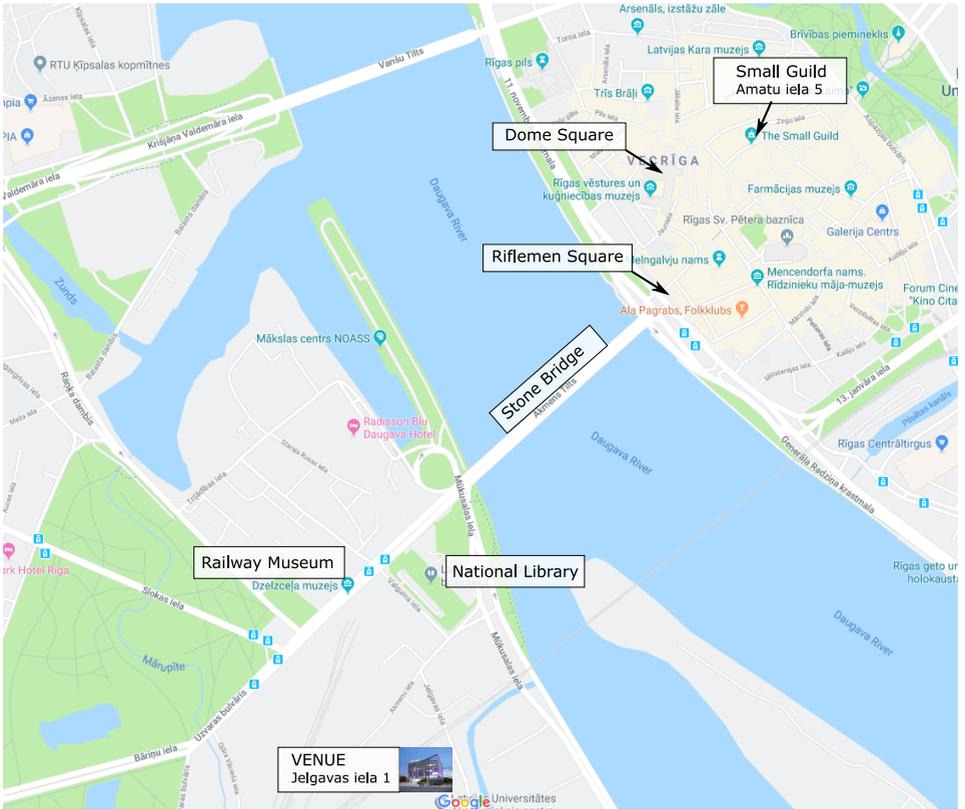




ICVS 2019

University of Latvia, Riga, Latvia

5-9 July 2019



The Patmalnieks Family



IEGULDĪJUMS TAVĀ NĀKOTNĒ



LATVIJAS UNIVERSITĀTES FONDS

The 25<sup>th</sup> Symposium of the  
International Colour Vision Society

Abstract Book

July 5-9, 2019

Riga, Latvia



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University of Latvia

1 Jelgavas Str., Riga, Latvia, LV-1004



## PREFACE

Dear Colleagues,

We are pleased to welcome you to Riga, the host of the 25th Symposium of the International Colour Vision Society. The Society's selection of Latvia provides a wonderful opportunity for all its members to experience new horizons, as well as a great honour for the University of Latvia.

A very warm welcome to new participants in our conference, as well as established friends and colleagues. It is very satisfying to have a high number of abstracts submitted and to see new members being attracted to ICVS. Over 150 attendees from 17 countries will visit ICVS in Riga, giving in total 120 paper presentations. Nearly 40% of the presentations will be given by students and early career researchers.

We hope the meeting in Riga will continue to develop the traditions of the Symposium and foster many friendly exchanges and discussions among attendees.

The social and cultural programme will explore historical and cultural aspects of the architecture, lifestyle and tastes of Latvia's capital and the Vidzeme Region. We are sincere in our desire to provide an atmosphere for informal interactions in order to facilitate conversations, new collaborations and friendships.

We deeply thank all those who have provided support to ICVS2019, in particular, sponsors, foundations, local businesses, private donors, and the ICVS officers and directors.

We wish you a fruitful meeting and a pleasant stay in the Pearl of the Baltics.

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## VERRIEST MEDALIST 2019

Professor Michael Webster

University of Nevada Reno

Professor Webster's interest in color vision is rooted in his undergraduate work at the University of California, San Diego. He went on to a Ph.D. in Psychology at the University of California, Berkeley and then was a postdoctoral research fellow at the University of Cambridge, UK. In 1994 he joined the faculty at the University of Nevada, Reno, where he rapidly rose to a Foundation Professorship in the Department of Psychology with affiliations to graduate programs in Cognitive & Brain Sciences and Integrative Neuroscience, which he helped found and co-directs. He is a fellow of the Optical Society of America.

His research on color vision includes a steady stream of influential papers over the past 30 years. Two themes recur over the decades: adaptation and individual differences. His novel adaptation designs have advanced our understanding of the multiple pathways that mediate color perception, including color constancy and changes across the life span. The comprehensive breadth of his work on individual differences encompasses color matching, unique hues and color naming. Professor Webster is a beloved teacher and mentor. He has made also exceptional contributions to his peers and the field by serving on NSF and NIH grant review panels, as an editor of *Vision Research*, as the color vision editor for the *Journal of the Optical Society of America A*, and as chair of the Color Technical Group of the Optical Society of America. He recently was elected to the board of directors of both the Vision Sciences Society and ICVS, reflecting the high regard of his colleagues.

## The Verriest Medal

In its early years, the mainstay of the IRGCVD (as the ICVS was then known) was the Belgian ophthalmologist Guy Verriest (1927-1988), who acted as both Secretary and Editor. In 1991, a special award was bestowed by the Society to honor long-term contributions to the field of colour vision in his name to recognize his contribution to the Society.



## GENERAL INFORMATION

### Conference venue

1. Talks will be held in the auditorium Magnum, situated on the left side of the central entrance.
2. The Director's meeting will take place at the auditorium Caelum (701) on the 7<sup>th</sup> floor. Please, use lift to access the 7<sup>th</sup> floor.
3. The cloakroom is free service. Please, don't leave valuable objects in the public cloakroom. Belongings can be left at the Optometry and Vision Science Department on the 4<sup>th</sup> floor room 430. Please, ask the conference staff for assistance.
4. Free WIFI is accessible via EDUROAM network. A conference network will be setup and the code will be provided on request at the desk.
5. Smoking is not allowed at the Venue. Information on special smoking cabin outside the building will be provided.
6. Coffee and some local biscuits will be served in the courtyard during the breaks and poster sessions.
6. Food and beverages can be brought to the building, but not to the conference auditorium.
7. The working hours of the House of Nature (Academic Centre of Natural Sciences (DAC)) of the University of Latvia (UL) are from 8.00 to 22.00. During Sunday permission is needed to reach the 4<sup>th</sup> floor.

### Presentations

1. Please prepare your laptop computer for presentation and make a copy of presentation on the USB stick. Analog (VGA, D-sub 15 pins) and digital (HDMI) connections are available. Please, check the connectivity and presentations before the talk.
2. Time slot for general presentations is 15 minutes including questions and discussion.
3. Poster stands are 90,5 (width) x 195 (height) cm portrait orientation. We recommend you prepare your poster in the A0 portrait format. Materials will be provided for fixation of the posters on the poster stands.
4. Poster presenters are asked to put their posters up as soon as they can. Numbered boards will be available from Friday morning. The posters will be on display for the entire meeting.
5. Presenters of odd/even-numbered posters are requested to attend their poster during the allocated session from 14.45 to 17.00 on Saturday 6<sup>th</sup> July (poster session I; odd numbers) and Monday 8<sup>th</sup> July (poster session II; even numbers).

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## Welcome reception (starting 19.00, July 5)

1. Reception will take place at the Mazā Ģilde (Small Guild) situated right in the centre of Old Town near Livs's Square.
2. A short guided walking tour will be provided before the reception. It will start from the symposium Venue and we will walk over the Stone Bridge to Dome Square. After a short introduction about Old Riga the guides will get you to the Mazā Ģilde for Reception. Planned time approximately 30 - 45 min.
3. Reception will be held in mid-century style with original local foods, beverage and entertainment.

## Lunch (July 6 and 8)

1. Lunch on the second and fourth days of Symposium will be served in the courtyard of the Venue. The courtyard is accessible from the 2<sup>nd</sup> floor.
2. Please identify yourself on arrival if you have requested special arrangements for meals.

## Excursion (July 7)

1. Please, pick a lunch box before getting on the bus.
2. We will go to Ligatne area (part of the Gauja National Park) to visit the Vienkoči ("Single-cut") park for an excursion and meet the woodworking master, have a walk and enjoy folk traditions for the first part of excursion. It will be possible to buy some wooden crafts and souvenirs at the place.
3. Local beer and snacks will be served at the Vienkoči park.
4. In the second part of excursion we will visit a Secret Nuclear Bunker placed under the rehabilitation hospital in the picturesque valley of Gauja river. Some original alcoholic drinks and snacks of the historic time will be offered. Please, inform organisers if you are claustrophobic; an alternative route will be provided. Your mobile phone will be out of service while in this area.
5. We will move between sites by bus. The public transportation is limited in this area. Please, don't miss the bus.

## Banquet (July 7)

1. After the excursion we will have a banquet at the restaurant *Santa Villa* near the town of *Cesis* in Vidzeme Region. This place surrounded by Pine forest is an area of historical villas built by nobles for recreation purposes. The place is well beloved by Latvian poets and musicians for its atmosphere and recreative force.
2. After some refreshments in this restaurant area we will have a 4-course banquet in the Bridge House.
3. Both bus and banquet venue are fully booked. Please understand that seating may be a bit tight.
4. Please identify yourself on arrival, if you have requested special arrangement on meals. Also, please, understand that not all meal requests can be fully satisfied.

Enjoy the conference!



- 09.00 – 13.30 *Director's committee meeting*  
 10.00 – 18.00 *Registration desk open*  
 13.30 – 14.00 *Opening*

## Central Processing of Colour

*Chairs: Neil Parry, Barry Lee*

- 14.00 – 14.15 **The neural representation of perceived color**.....2  
 Steven Shevell, Insub Kim, Won Mok Shim and Sang Wook Hong
- 14.15 – 14.30 **Cortically-stimulating gratings reveal non-cardinal colors better than do LGN-stimulating spots**.....3  
 Karen Gunther, Colby Dunigan, Carson Powell and Jorge Rodriguez
- 14.30 – 14.45 **A multivariate approach to the decoding of chromatic and achromatic contrast in the human visual cortex**.....4  
 Kathy T Mullen and Erin Goddard
- 14.45 – 15.00 **Hue selectivity of SSVEP responses**.....5  
 Ichiro Kuriki, Sae Kaneko and Søren K. Andersen
- 15.10– 15.15 **Diagnostic color elicits selective neural responses to grayscale objects**.....6  
 Talia Retter, Bruno Rossion, Fang Jiang and Michael Webster
- 15.15 – 15.45 *Coffee pause*

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*Chair: Barry Lee*

- 15.45 – 16.45 **Form and function in parallel pathways for colour vision**.....7  
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## Retinal Mechanisms of Colour Processing

*Chairs: Kathy Mullen, Rigmor Baraas*

- 16.45 – 17.00 **A new genetic mechanism for tritan color vision deficiency**.....8  
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- 17.15 – 17.30 **Are anomalous pupillary responses to M-cone onsets linked to L:M ratio?**.....10  
 Neil Parry, Ian Murray, Xian Li and Elena Rodrigo-Diaz

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17.45 – 18.00	<b>Responses of macaque ganglion cells to natural scenes: spatial, temporal and chromatic parameters</b> .....	12
	Barry Lee and Manuel Schottdorf	

08.30 Registration desk open

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	Steven Buck and Tanner Delawyer	
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	Robert Ennis and Katja Doerschner	
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	Sara Patterson, Maureen Neitz and Jay Neitz	
9.45 – 10.00	<b>How to make a #theDress.....</b>	<b>17</b>
	Christoph Witzel and Matteo Toscani	
10.00 – 10.15	<b>What is white under coloured lights?.....</b>	<b>18</b>
	Anya Hurlbert, Naomi Gross, Ruben Pastilha and Gaurav Gupta	

10.15 – 10.45 *Coffee pause*

## Colour Vision Testing

*Chairs: John L Barbur, John S Werner*

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	Manca Tekavcic Pompe	
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11.45 – 12.00	<b>Measuring hue discrimination thresholds in infants using inter-observer staircases.....</b>	<b>23</b>
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12.00 – 12.45 *Lunch*

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*Chair: Pablo Barrinuevo*

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	Claudia Feitosa-Santana, Carlo M. Gaddi and Sérgio MC Nascimento	

08.30      *Registration desk open*

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10.00 – 10.30      *Coffee pause*

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12.00 – 20.00      *Lunch and Excursion*

08.30      *Registration desk open*

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*Chair: Anya Hurlbert*

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FRIDAY 5<sup>th</sup> JULY

**THE NEURAL REPRESENTATION OF PERCEIVED COLOR****Steven K Shevell<sup>1</sup>, Insub Kim<sup>2</sup>, Won Mok Shim<sup>2</sup> and Sang Wook Hong<sup>3</sup>**<sup>1</sup> Psychology and Institute for Mind & Biology, University of Chicago, United States<sup>2</sup> Biomedical Engineering, Sungkyunkwan University (SKKU), South Korea<sup>3</sup> Psychology, Florida Atlantic University, United States*Corresponding author: shevell@uchicago.edu*

The distinction between stimulus chromaticity and perception of hue is critical for understanding color vision. A chromatic stimulus has spectral properties that characterize light entering the eye. The colors we experience, on the other hand, are perceptual constructs from neural processing in hierarchically organized cortical visual areas. Previous research, however, often has confounded stimulus chromaticity with perceptual color experience, leaving unsolved the fundamental question of whether the neural responses at each stage of processing represent a physical stimulus or instead a color we see. This question is addressed here by dissociating the physical domain of chromatic stimulation from the perceptual domain of color experience, using a novel approach that causes sustained color percepts to vary over time without altering a rapidly changing temporal stream of retinal stimulation. These measurements show a hierarchical progression of color processing in the ascending human ventral visual pathway, from a representation of the chromatic stimulus in V1 to perceptually experienced color in V4.

**METHODS:** Stimulus chromaticity was dissociated from color appearance with chromatic interocular-switch rivalry (CISR; Christiansen, D'Antona & Shevell, 2017), which uses dichoptic rivalrous chromaticities that are swapped between the eyes every 120 msec. The surprising percept is a single sustained color for about 2 seconds (during which there are 16 eye swaps) followed by a different sustained color. These two sustained color percepts are dissociated from the rapidly changing 4.25 Hz stimulation, which is identical in each eye (except for the eyes' relative temporal phase). Observers reported their sustained color percepts during CISR. At the same time, fMRI BOLD responses were measured at each level of the visual cortical hierarchy. A chromatic representation in DKL space was reconstructed separately for each stage (V1, V2, V3, V4v, VO1, V3A, and MT+) by transforming the fMRI measurements with an inverted encoding model (Brouwer & Heeger, 2009).

**RESULTS & CONCLUSION:** fMRI responses at each moment in time were separated according to the particular sustained color reported by the observer during CISR. Reconstructed color representations from fMRI were qualitatively different in early visual areas V1 and V2 compared to higher visual areas V4v and VO1. In V1, reconstructed colors did not correspond to what observers perceived. Color representations in V4v, on the other hand, aligned closely with the colors perceived. Further, as a control, a separate analysis examined fMRI responses during moments of perceiving mixed or patchy color, or rapid color switching instead of a single sustained color. This analysis showed no consistent reconstructed colors across subjects in any of the visual areas. In sum, neural representations of color became progressively more selective for perceived hue across the ventral visual stream, from responses in V1 and V2 reflecting the chromatic stimulus to responses in V4 and VO1 corresponding to perceived color.

Brouwer G. J. & Heeger D. J. (2009). Decoding and reconstructing color from responses in human visual cortex. *Journal of Neuroscience*, 29, 13992–14003.

Christiansen J. H., D'Antona A. D. & Shevell S. K. (2017). Chromatic interocular-switch rivalry. *Journal of Vision*, 17(5):9, 1–16.

**CORTICALLY-STIMULATING GRATINGS REVEAL NON-CARDINAL COLORS BETTER THAN DO LGN-STIMULATING SPOTS****Karen Gunther, Colby Dunigan, Carson Powell and Jorge Rodriguez**

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We are examining the ability of spots versus gratings to reveal non-cardinal colors. Neurons in the LGN respond better to spots, while cortical neurons respond better to gratings (DeValois, Cottaris, Elfar, Mahon, & Wilson, 2000). In addition, non-cardinal mechanisms are known to not emerge until the cortex (Gegenfurtner, 2003). Thus, non-cardinal mechanisms should be more likely to be revealed with cortically-stimulating gratings than LGN-stimulating spots. This has been shown in the isoluminant color plane in macaque monkeys (Stoughton, Lafer-Sousa, Gagin, & Conway, 2012) and in the RG/LUM color plane in humans (Gegenfurtner & Kiper, 1992). Recent reviews of non-cardinal mechanisms (Eskew, 2009) and S-cone vision (Smithson, 2014) do not report that this has yet been examined in the TRIT/LUM color plane. We are filling in this gap by testing all three color planes, using both spots and gratings, in the same study and in the same species (human). Thresholds to detect spot or grating stimuli are measured in aligned or orthogonal speckled noise. For example, an orange/turquoise grating may be presented in orange/turquoise or purple/lime noise. Evidence for separate underlying neural mechanisms is seen when the threshold to detect the stimulus in aligned noise is greater than in orthogonal noise. All stimuli in the isoluminant plane are individually isoluminant via heterochromatic flicker photometry. Non-cardinal colors are created in equal threshold space. We aim to test 10 subjects in each color plane; preliminary results are largely following predictions.

**A MULTIVARIATE APPROACH TO THE DECODING OF CHROMATIC AND ACHROMATIC CONTRAST IN THE HUMAN VISUAL CORTEX****Kathy T Mullen and Erin Goddard**

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The extent to which specialized chromatic and achromatic stimulus properties are encoded differentially or combined in an integrated response in human visual cortex is controversial. Moreover, different answers to this question are likely to be relevant to different cortical stages. Here we take four different types of stimuli, two achromatic and two chromatic, chosen as representative of the four differential stream of information represented in the subcortical pathways from retina, to LGN, to V1 and we used a multivariate approach with a series of classification analyses to measure how well the pattern of activity across voxels in different cortical areas can be used to decode the stimulus type. The two achromatic stimuli are: a low spatial frequency, high temporal frequency stimulus (0.5cpd, 10Hz, more relevant to the M-cell pathway and a high spatial, low temporal frequency stimulus (5cpd, 2 Hz) more relevant to the P-cell pathway. The two chromatic stimuli isolate the red-green (RG), L/M cone opponent pathway of P-cell origin and the S-cone opponent, blue yellow (BY) pathway of koniocellular origin (0.5 cpd, 2Hz), respectively. All stimuli are radial sinusoidal gratings. Imaging was done using a 3T Prisma scanner, 32-channel head coil 1.5mm isovoxels, TR=3s, with result averaged over 8 subjects. All subjects were mapped using standard methods with 9 regions of interest and the LGN. Our classification analyses show that overall there is robust decoding of these stimulus properties in all visual areas including the LGN. We followed up with a representational similarity analysis (RSA) to ask which pairwise classifications are best driving classifier performance. We find that in the early visual areas (V1-V3), classifier discrimination is best driven by the Ach high spatial frequency stimulus, whereas there is a switch in higher visual areas V4, VO1 and VO2, which are best driven by responses for chromatic vs achromatic stimuli. Successful decoding indicates that the voxel patterns are reliably different for the different stimulus types, with differential neural responses across voxels. Our results imply a greater voxel differentiation for achromatic form-like stimuli in lower visual areas with chromatic vs achromatic properties emerging as more differentiated in higher extrastriate areas, including VO1 and VO2.

## HUE SELECTIVITY OF SSVEP RESPONSES

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Several psychophysical and physiological studies on the representation of color in human visual cortex have revealed the presence of a neural system that selectively responds to intermediate colors of cardinal axes in the cone-opponent color space. Our fMRI study (Kuriki et al., 2015) has demonstrated the presence of hue-selective neurons by measuring the hue selectivity of each voxel and by fMRI adaptation. However, this study left at least two issues unsolved.

First, a strong asymmetry in the voxel population of hue selectivity was observed. Does this reflect large anisotropies in hue selectivity across the neuronal population or a small bias, i.e. the “top of an iceberg” among abundant neurons selective to various hues? This is mainly due to the limitation of spatial resolution and the method of analysis in our fMRI study, which focused on measuring biases in the neural population in a voxel with strictly unilateral hue-selectivity. Another important issue is the difficulty of estimating the tuning bandwidth with our method. Hues were scanned at a rate of 24s per cycle, but the fMRI signal takes 6 s from baseline to maximum, thereby limiting the resolution of this approach.

To address these issues, we used steady-state visual evoked potential (SSVEP). By presenting visual stimulus with a given flicker frequency, VEP response yields its energy at the corresponding temporal frequency. By analyzing changes in the amplitude of the flicker frequency component, it is possible to evaluate changes in brain activity, which is considered to originate mainly in primary and secondary visual cortices. We presented visual stimulus similar to the previous fMRI study. The hue of check pattern was alternated with gray at 5 frames/s and changed along a hue circle at the rate of 24 seconds/cycle. We repeated 24 recordings by randomly varying starting hue across trials, and the opposite direction of hue change was also measured to remove any artifact by progressive adaptation. Three saturation levels (full, half, and quarter) were presented to dissociate the hue-selective response from mere responses to flicker. 18 color-normal adults participated in the experiment.

The result showed that the SSVEP amplitude modulation with hue changes, sensitive to chromatic saturation. The hue selectivity profile was much less asymmetric than fMRI results, but was still non-uniform across the hue. It also showed remarkable individual differences in at least two aspects. One is the sensitivity to saturation level differences. Some participants were strongly sensitive to hue changes and some other participants were only slightly sensitive. Another is the shape of SSVEP amplitude profile across the hue circle. We applied factor analysis to derive the common factors and the variability of its loading among participants. Also, by taking advantage of faster temporal resolution of SSVEP, we measured the SSVEP responses of hue-selective masking, by using one of the intermediate hues (45, 135, 225, or 315 deg) as the mask. The masking effect was significant and was maximal at the mask hue. The tuning bandwidth of hue-selective SSVEP will be discussed together with the result of factor analysis.

**DIAGNOSTIC COLOR ELICITS SELECTIVE NEURAL RESPONSES TO GRAYSCALE OBJECTS****Talia Retter<sup>1,2</sup>, Yi Gao<sup>1</sup>, Bruno Rossion<sup>1,2</sup>, Fang Jiang<sup>1</sup> and Michael A Webster<sup>1</sup>**<sup>1</sup> University of Nevada, Reno, United States<sup>2</sup> Université de Lorraine, Nancy, France*Corresponding author: talia.retter@uclouvain.be*

Some objects are strongly associated with a specific color, e.g., red strawberries or yellow Pikachu. For such objects, color may be diagnostic, leading to faster and/or more accurate recognition, and grayscale images may automatically evoke the associated colors (Hansen et al., 2006). Here, we investigated the automatic association of color and shape in the neural representation of visual objects. Specifically, we asked whether visual objects automatically elicit a color association even when color is absent from the physical stimuli. We tested 16 observers with a frequency-tagging paradigm investigating categorical responses with high-density electroencephalogram (EEG; e.g., Jacques et al., 2016). Objects were presented in 50 s sequences at a rate of 4 Hz, with a characteristically yellow object appearing as every fourth stimulus, i.e., at a rate of 1 Hz. In this paradigm, general visual responses are expected at the stimulus-presentation rate of 4 Hz, while only responses categorizing yellow are expected at 1 Hz. Stimuli were presented in two conditions: 1) naturally colored objects, and 2) grayscale versions of these objects. The object stimuli consisted of twenty-four images, distributed across four color categories (yellow, red, green, and blue) and internally matched for type (e.g., fruits/vegetables and cartoon characters). Colored stimuli were defined by mean hue angle, and both color and grayscale stimuli were equated for size, luminance, and luminance contrast. The results showed a significant yellow-categorization response for grayscale objects at 1 Hz and its specific harmonics (2 Hz, etc.), as characterized by a fast Fourier transform of the temporal EEG signals. While about 60% weaker than the response for actual colored objects, the grayscale color response was reliable at the individual participant level, and had a similar but more lateralized occipito-parietal scalp topography. This evidence suggests that visual shapes automatically elicit responses to their diagnostic colors, suggesting that color is mandatorily associated to the neural representations of objects in the visual cortex.

**FORM AND FUNCTION IN PARALLEL PATHWAYS FOR COLOUR VISION****Paul Martin**

Save Sight Institute and ARC Centre of Excellence for Integrative Brain Function, University of Sydney, Australia

Paul's abiding research interest is the structure and function of the visual system with emphasis on relation of parallel nerve pathways to color, form, and motion modalities of visual perception. His presentation will summarize evidence for distinct pathways in the retina and sub-cortical visual system that carry visual signals supporting blue-yellow and red-green axes of colour vision. These pathways emerge at the first level of visual processing in the retina, where cone photoreceptors contact bipolar cells and horizontal cells, and are carried to the brain as trains of action potentials in axons of multiple classes of retinal output neurones (ganglion cells). At the first point of interaction with brain pathways, in the dorsal lateral geniculate nucleus in the thalamus, there is anatomical and functional segregation of blue-yellow and red-green colour vision pathways. The consequences of this segregation will be discussed.

**A NEW GENETIC MECHANISM FOR TRITAN COLOR VISION DEFICIENCY****Maureen Neitz<sup>1</sup>, Elise Kjekling<sup>2</sup>, Lene A. Hagen<sup>2</sup>, Hilde R Pedersen<sup>2</sup>, Jay Neitz<sup>1</sup> and Rigmor C Baraas<sup>2</sup>**<sup>1</sup>University of Washington, United States<sup>2</sup>University of South-Eastern Norway, Kongsberg*Corresponding author: mneitz@uw.edu*

**Purpose:** In a cohort of 57 individuals who participated in color vision testing, one was considered to be a “tritan suspect” because her performance on several color vision tests was consistent with early manifestation of a tritan color vision deficiency. The purpose of this study was to investigate the possible role of short-wavelength sensitive cone opsin gene (OPN1SW) mutations as a cause of her color vision phenotype.

**Methods:** Sequencing of the OPN1SW genes of the 57 subjects revealed that the subject was heterozygous for a single G nucleotide deletion in intron 3. None of the other subjects were found to have OPN1SW gene mutations. The intron 3 G deletion is predicted to disrupt splicing. The subject’s mother and sister were examined and found to also have the intron 3 deletion, and their color vision was tested. To directly examine the effect of the mutation on splicing, we cloned the OPN1SW gene with the intron 3 G deletion and performed an in vitro splicing assay. We also performed the splicing assay on mutant OPN1SW genes for six missense mutations previously reported to cause tritanopia, and a normal control.

**Results:** The splicing products for the normal control and the six mutant OPN1SW genes previously reported to cause tritanopia were identical. The OPN1SW gene with the intron 3 G deletion gave a single splicing product that was smaller in size, consistent with disrupted splicing. We sequenced the splicing product and found that the normal control and six missense mutations gave rise to full-length messenger RNA (mRNA), but the intron 3 deletion did not. Instead, the intron 3 deletion gave rise to mRNA lacking both exons 2 and 3 consistent with a splicing defect.

**Conclusion:** The intron 3 G deletion disrupts splicing and the resulting OPN1SW mRNA is likely not translated. Thus, subjects heterozygous for the mutation are predicted to have S cones with half the normal amount of photopigment. These results suggest that haploinsufficiency causes tritan color vision defects. None of the other OPN1SW mutations known to cause tritan defects appear to disrupt splicing.

Historically, inherited protan, deutan and tritan color vision deficiencies were considered to be parallel defects mechanistically, but affecting different subsets of photoreceptors. Surprisingly, the primary cause of inherited tritan defects has been shown to be amino acid substitutions in the S opsin that inactivate the photopigment, whereas having spectrally shifted photopigments relative to normal is the primary cause of protan and deutan defects. Recently, mutation in the L and M opsin genes that disrupt splicing have been identified as the cause of a variety of vision disorders including color vision defects, cone dystrophy, and high myopia. Here we report the first example of a splicing defect as the cause of an inherited tritan color vision deficiency.

**FUNCTIONAL MAPPING OF HUMAN RETINA USING HETEROCHROMATIC MODULATION  
MULTIFOCAL ELECTRORETINOGRAMS****Avinash Aher and Jan Kremers**

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**Purpose:** To obtain a functional image of the retina using a multifocal electroretinography (mfERG) elicited by red-green heterochromatic stimulation.

**Methods:** The red-green heterochromatic stimulus was generated using red (with contrast  $C_R$ ) and green (with contrast  $C_G$ ) light, modulated in counter-phase around a mean luminance of 45 cd/m<sup>2</sup>. The red modulation fraction ( $F_R$ ), defined as the red modulation contrast over total modulation contrast [ $F_R=C_R/(C_R+C_G)$ ], was varied ( $F_R=0$ ,  $F_R=0.5$ , and  $F_R=1$ ). The measurements were repeated at 10 and 30 Hz modulation frequencies. Multifocal ERG measurements were performed using 7 hexagons. The maximal and minimal radiuses of the field of view were 19.4° and 14.4° respectively. The responses were measured from 3 normal subjects using the m-sequence technique. Fourier analysis was performed on the ERG responses at all locations. The amplitudes and phases of the fundamental components were used to describe the responses.

**Results:** The multifocal ERG responses were significantly above noise (signal-to-noise ratio >2) for all conditions and hexagons. For both 10 and 30 Hz, the response amplitudes were largest for the central stimulus. At 30 Hz, the response amplitudes were minimal for  $F_R=0.5$  condition as compared to  $F_R=0$  and  $F_R=1$ . The response phases at  $F_R=0$  and  $F_R=1$  differed by about 180°. Responses at  $F_R=0$  and  $F_R=0.5$  had similar phases. At 10 Hz, the response amplitudes decreased consistently with increasing value of  $F_R$ . The phases at  $F_R=0.5$  and  $F_R=0$  were very similar whereas those at  $F_R=1$  were about 90° shifted.

**Conclusions:** The results indicate that reliable mfERG responses can be obtained using red-green heterochromatic stimulation. We propose that the mfERGs measured at 10 Hz reflect the activity of cone opponent (putatively parvocellular) processing. An intrusion of rod and possibly S-cone driven signals cannot be excluded. At 30 Hz, the mfERGs reflect the activity of luminance (putatively magnocellular) processing. The heterochromatic stimulation mfERG may be useful for generating a functional image of the retinal post-receptoral visual processing.

**ARE ANOMALOUS PUPILLARY RESPONSES TO M-CONE ONSETS LINKED TO L:M RATIO?****Neil RA Parry<sup>1</sup>, Ian J Murray<sup>2</sup>, Xian Li<sup>2</sup> and Elena Rodrigo-Diaz<sup>2</sup>**<sup>1</sup> Manchester Royal Eye Hospital, United Kingdom<sup>2</sup> The University of Manchester, United Kingdom*Corresponding author: neil.parry@manchester.ac.uk*

Isolated M-cone onset stimulation produces a paradoxical pupillary response, whereas L-cone isolating onset induces a conventional pupil response. The phenomenon is analogous to the fact that M-cone onsets generate an offset ERG and that M-cone onsets appear dimmer than their background. Here we test the possibility that this effect may be linked to L:M ratio.

A four-primary ganzfeld (Diagnosys Colordome) was used to generate selective M- and L-cone stimulation using triple silent substitutions. Luminance-modulated stimuli (equally stimulating all 4 photoreceptor classes, contrast = 0.26) acted as controls. Cone contrast was 0.26 and mean luminance was 20cd/m<sup>2</sup>. Onset duration was 1s with a 3s offset. With full-field stimulation, the central 7° was occluded to minimise macular pigment effects. Changes in pupil diameter were measured with an Espion E3 system (Diagnosys) using the inbuilt ganzfeld camera and a LiveTrack interface (CRS). Positive and negative luminance bias was introduced using a series of 23 stimuli with luminance bias values ranging from 1.45 (brighter than cone isolation) to 0.55 (dimmer than pure cone isolation) in steps of 0.05. The value of 1.0 represented 'pure' cone isolation. 15 colour-normal subjects with no family history of colour vision deficiency participated. They had a wide range of L:M ratio from 1.0 to 6.

With most subjects, pupils responded conventionally to L-cone modulation, producing an unambiguous constriction to stimulus onset; this was also seen with luminance modulation. As previously reported, most subjects exhibited a conspicuous paradoxical constriction to a decrease in M-cone stimulation. However, those with an L:M ratio close to unity did not. For all subjects, the luminance bias sequences showed a particular point at which the (paradoxical or non-paradoxical) cone-isolated response was counteracted by the luminance increment/decrement. At this neutral point, the pupil responds equally to both onset and offset of the stimulus. For the M-cone stimulus, the neutral point for subjects with low L:M ratio occurred close to or at, the pure isolation point, so that their paradoxical pupil response for M-cone stimulation was virtually absent. Hence the neutral point varies systematically with L:M ratio, compelling evidence that the predominance of L-cones in the typical human retina is implicated in the paradoxical M-cone response.

**L- AND M-CONE DRIVEN ERG SIGNALS IN MACAQUES****Jan Kremers<sup>1</sup>, Avinash Aher<sup>2</sup>, Neil RA Parry<sup>3</sup>, Nimesh Patel<sup>4</sup> and Laura Frishman<sup>4</sup>**<sup>1</sup> University of Erlangen-Nürnberg, Germany<sup>2</sup> Dept. of Ophthalmology, University Hospital Erlangen, Germany<sup>3</sup> Manchester Royal Eye Hospital, United Kingdom<sup>4</sup> University of Houston, United States*Corresponding author: jan.kremers@uk-erlangen.de*

Purpose: To study L- and M-cone driven ERGs of macaques for comparison with those obtained in human subjects.

Methods: ERGs were recorded from the right eyes of five anesthetized macaques (*Macaca mulatta*; three females, two males). The 4-colour Ganzfeld stimuli were sinusoidal modulation of luminance (22% contrast), L-cone excitation and M-cone excitation (both 22% cone contrast). Cone isolating stimuli were generated using triple silent substitution. For each condition, the responses were recorded at 14 different temporal frequencies (4-56 Hz in 4 Hz steps).

Results: The responses were dominated by the first (fundamental) and more consistent second harmonic components than in humans. The first harmonic components showed multiple maxima and minima. The average ERG L:M ratio (using first harmonic or the addition of first and second harmonics) was about unity at low temporal frequencies and about 2 at frequencies above 30 Hz. At all temporal frequencies, the response phase of the first harmonic component to luminance and to L-cone isolating stimuli was very similar. Above 32 Hz, M phase was similar to L and luminance phase. As temporal frequency decreased, the difference between L and M response phase increased so that, below 12 Hz, there was an L:M phase shift of about 180°.

Conclusions: The responses measured in macaques contained more substantial second harmonic components than those measured in human subjects. Similar to the ERGs in humans, the responses at low temporal frequencies reflect L-M cone opponency. Above 30 Hz, the phase differences were very small, indicating that the response reflects luminance activity. An L:M ratio of 2 indicates that the luminance signal is L-cone dominated, but less strongly than in humans, for whom higher L:M ratios are often found. Macaque and human ERGs reflect activity of cone opponent and luminance pathways at low and high temporal frequencies respectively.

**RESPONSES OF MACAQUE GANGLION CELLS TO NATURAL SCENES: SPATIAL, TEMPORAL AND CHROMATIC PARAMETERS****Barry Lee<sup>1</sup> and Manuel Schottdorf<sup>2</sup>**<sup>1</sup>MPI for Biophysical Chemistry<sup>2</sup>MPI for Dynamics and Self-organization*Corresponding author: blee@sunyopt.edu*

The temporal responses of macaque ganglion cells to natural scenes was described previously (van Hateren et al., J. Neuroscience, 2002); spatial components were also summarized (Lee et al., ICVS, 2017). We here describe the spatial and temporal components of cell responses in more detail. Based on reverse correlation techniques, spatiotemporal response maps (resembling receptive fields) were generated. These were compared to known receptive field characteristics. Generally, most parameters (e.g., center size) were consistent with literature values for both MC and PC cells. Some features were of note; PC-cells |L-M| response fields were 2-3 times larger than their luminance fields. Also, indications of center-surround structure were present but weak; Gaussian fits indicated surround-center weights of ca. 0.1 for both MC and PC cells. The signal-to-noise of luminance and |L-M| signals for PC-cells had a ratio of about 3:1, despite their high responsivity to |L-M| contrast. This is due to the weak |L-M| contrast in natural scenes. Finally, by comparing cell response power spectra with that of the stimulus, we assessed whitening in the response. This was substantial, and mainly related to the temporal properties of scene movement and cells, rather than spatial structure within the video.

SATURDAY 6<sup>th</sup> JULY

**THE RELATIONSHIP OF BROWN AND BRIGHTNESS INDUCTIONS****Steven Buck<sup>1</sup> and Tanner DeLawyer<sup>2</sup>**<sup>1</sup> University of Washington, United States<sup>2</sup> Kochi University of Technology, Japan*Corresponding author: sbuck@uw.edu*

When an achromatic background is made brighter, an imbedded yellow target appears both darker and browner. The relationship between these two inductions has been uncertain. Adelson's Snake background is famous for producing dramatic brightness-induction effects. To explore the relation of brown induction to brightness induction, we measured both brown boundaries (the luminance at which brown completely replaces yellow) and brightness matches on Snake and Anti-Snake backgrounds. Effects of the backgrounds were quantified by the ratio of luminances (modulation) of brightness matches or brown boundaries on the two bands of each background.

The results show that brightness matches and brown boundaries were equally modulated by the simultaneous luminance contrasts present in the Anti-Snake and shared by the Snake. In addition, both brightness matches and brown boundaries were further modulated in equal measure by the constellation of stimulus features unique to the Snake, over and above the effects of simultaneous contrast.

The perceptual processes by which the Snake produces its modulations have long been debated but the present results show that they influence both brightness and brown inductions equally. Furthermore, the equal influence on both brightness and brown induction produced by both the simultaneous contrast of the Anti-Snake and the additional contextual cues of the Snake hints at wider generality of this close relationship between brown and brightness inductions.

**THE COLOR APPEARANCE OF THREE-DIMENSIONAL, CURVED, TRANSPARENT OBJECTS****Robert Ennis and Katja Doerschner**

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Studies of perceptual transparency have mostly focused on the generation of the percept, with thin filters floating above a Lambertian patterned background. However, in the natural world transparent objects are not just thin and see-through: they have a 3D shape, often possess specular highlights, generate caustics, refractions and shadows and - if they absorb parts of the light spectrum - a tinted image of the background. Little is known about how the color of such objects - which is a mixture of the object's material color, the illumination and colors of objects in the background - is perceived. Here, we investigated the color appearance of tinted, 3-D glass objects in a complex scene under a blue and a yellow illuminant. We conducted three asymmetric matching experiments in which observers either (1) changed the color of a patch until it had the same color as the object; (2) changed the color of a patch until it looked like the dye that was used to tint the object; or (3) changed the color of a transparent 2-D filter on an achromatic Voronoi background until its color matched the object. Overall, observers' color matches correlated significantly with the mean chromaticity and luminance of the object. However, in the first two experiments, the mean luminance of matches was offset by about +40 L\* units in the CIELAB space on average and corresponded best to the mean color of caustics seen through the object, according to the CIEDE2000 metric. The mean luminance in experiment 3 showed a reduced luminance offset from the mean luminance of the transparent object and matches corresponded better to a distributed region of patches of mostly mid-luminance across the surface of the object. These results suggest that the color of a 3-D transparent object is not determined by a single region. Rather, an integration process might take place, which could help reduce a potentially systematic influence of the multicolored background seen through the transparency.

**THE NEURAL BASIS FOR ENCODING BLACK, WHITE AND HUE SENSATIONS****Sara Patterson, Maureen Neitz and Jay Neitz**

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The question of how color vision information is encoded and analyzed in the visual system remains unanswered. Perhaps the simplest and most fundamental questions about color vision are how the basic parameters of color sensation (hue, saturation, brightness) are encoded in the visual pathway. Here, we combine psychophysics and computational models to investigate the role of parasol and midget retinal ganglion cells (RGCs) in the perception of saturation.

Our perception of test spots of light against a black background can have red, green, blue and yellow hue components as well as a white component. Saturation measures the strength of the hue components, relative to white, or in other words, the perceived distance from white. Trichromats agree that, of the four fundamental hues, monochromatic yellow is the least saturated (i.e. contains the most white) while monochromatic blue is the most saturated. This phenomenon is quantified in classic saturation discrimination experiments in which the intensity of a monochromatic light added to white is increased until the hue is just noticeably different from a white light. The resulting saturation discrimination function has been interpreted as a measurement of the ratio of hue and achromatic channel activity across the visible spectrum.

However, saturation cannot be accounted for by models assuming black and white percepts are mediated by achromatic non-opponent parasol RGCs with spectral sensitivities matching the psychophysical luminosity function. Perceived saturation is not correlated with luminosity; lights can vary greatly in luminosity without an associated difference in saturation and lights with the same luminosity can vary greatly in perceived whiteness. To investigate this further, we had subjects judge the amount of black and white in equiluminant monochromatic lights across the spectrum presented against a gray background. Contrary to the prediction that achromatic neurons with the spectral sensitivity of the luminosity function underlie saturation, the perceived amounts of black and white varied widely as a function of wavelength, even though luminance was held constant.

These results seemed more consistent with spectrally opponent RGCs mediating percepts of black and white. Although counterintuitive, L/M opponent midget RGCs do respond well to black and white edges and thus might reasonably mediate black and white percepts. To test this hypothesis, we used the spectral signatures of spectrally opponent and non-opponent neurons to link black-white percepts to their underlying neural substrates. We created a model "channel" that represents black and white sensations as the combined activity of OFF and ON cone-opponent midget RGCs, respectively. Perceived saturation, as a function of wavelength, was calculated as the OFF midget activity subtracted from the ON-midget activity. This model provided excellent fits to the saturation discrimination function.

In a classic study on saturation, Purdy, 1931 remarked "No theory of colour vision, however, can be regarded as adequate if it does not account for the laws of saturation as well as those of hue". We demonstrate that black and white percepts mediated by spectrally opponent midget RGCs provides the most accurate account to date of the physiological mechanisms underlying saturation.

**HOW TO MAKE A #theDress****Christoph Witzel and Matteo Toscani**

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If we completely understand how a phenomenon works, we should be able to produce it ourselves. The malleability of colour appearance has been brought to the spotlight by the striking individual differences in the perception of #theDress (some see it white-gold, others blue-black). However, those effects on colour appearance seem to be a peculiarity of that particular photo, and it remains unclear how the proposed mechanisms underlying #theDress can be generalized to other images.

In a series of experiments, we identified the precise chromatic characteristics of #theDress that make observers see the dress on that photo differently. In one experiment ( $n = 30$ ), we rotated the chromatic distribution of the whole photo by 90, 180, and 270deg in CIELUV. In another experiment ( $n = 30$ ), we rotated the distribution of only the dress (without background) in one and of only the background (without dress) in another condition. In a third experiment ( $n = 30$ ), we rotated the distribution in four steps of only 20deg. We also simplified the overall shape of the distribution of the dress. To assess individual differences in perception, observers matched the colour of a disk to the colour of the body and the lace of #theDress. Results showed that individual differences in perception continuously decreased with increasing hue distance to the daylight axis. They also indicated that only the colours of the dress, but not those of the background matter for the individual differences, and that the distribution of the dress can be projected onto a straight line with little effect on perception.

Based on those insights, we created a simple algorithm which transforms any image with bicolored objects into an image with the properties of #theDress. We measured the colours perceived in such images and compared them to those perceived in #theDress ( $n = 30$ ). Colour adjustments confirmed that observers strongly differ in how they perceive the colours of the new images in a similar way as for #theDress. Most importantly, these differences were not unsystematic, but correlated with how observers perceive #theDress. We reproduced all of these findings through online studies using colour naming data mapped to a metrical scale according to our previous approach.

The findings of this study show that our algorithm produces images that have similar properties as #theDress, and that the chromatic characteristics are causing the striking individual differences in colour appearance. They imply that the individual differences discovered with #theDress reflect general mechanisms underlying colour appearance beyond that particular photo.

**WHAT IS WHITE UNDER COLOURED LIGHTS?****Anya Hurlbert, Naomi Gross, Ruben Pastilha and Gaurav Gupta**

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With the increasing use of novel lighting technologies, people are exposed to a broader range of illumination spectra and chromaticities than are typical of natural daylight. Is colour constancy – the tendency of objects to remain the same colour under changes in illumination spectra – compromised under atypical illuminations? An individual's achromatic point - the surface chromaticity perceived as neutral - serves as a measure of both adaptation to the ambient illumination and colour constancy. Larger deviations of the achromatic point from the chromaticity of the adapting illumination indicate worse colour constancy and less complete adaptation. Reported deviations differ between studies, as do experimental methods, with reports of a "blue bias" for illumination chromaticities relatively near neutral ( $\approx 40\text{-}60$  dEuV distant) (Weiss et al., 2017) and no bias for moderately extreme illumination chromaticities ( $\approx 100$  dEuV from neutral) (Brainard, 1998). Here we aim to determine achromatic points as well as perceived illumination colour for a range of illumination chromaticities near and far from neutral, in an immersive illumination setting.

Participants sat in an ( $2\text{ m}^3$ ) enclosure with white walls, illuminated by four tuneable twelve-channel LED lamps, viewing a smartphone OLED display (visible size approx. 8 degrees) embedded in a neutral cardboard frame and recessed to minimise incident illumination. Participants adjusted the display to appear neutral using four joystick button inputs, corresponding to the four cardinal colour directions in CIELAB (roughly blue, yellow, red, and green). Test illumination illuminance and display luminance were held at a constant mean level. An interstimulus mask of 30 seconds of equal-energy-white light preceded each 120 second test illumination adaptation period; during the following 3 trials, lasting approximately 180 seconds, the test illumination remained unchanged. At the start of each trial, the display was set to a random chromaticity within its gamut. Test lights were generated as smooth spectra, matching 21 chromaticities, in three sets: (i) 6 samples from the hue circle at distances of  $42 \pm 22$  dEuV from D65; (ii) 9 daylight locus values ranging from 2000K to 10000K; (iii) 6 extreme chromaticities. After the final trial for each test light, participants named the illumination colour (from one of 5 choices).

Results: Mean colour constancy indices were measured in two ways, relative to the actual chromaticity of the reference neutral (D56) ("fixed"), or to the individual achromatic match to D56 ("subjective"). Both sets ranged from  $\approx 0.3$  to  $\approx 0.9$  depending on test illumination chromaticity and individual participant. Illuminations were named "white" only if their chromaticities fell on or near to the daylight locus (within approximately 45 dEuV of D56), with illuminations bluer than D56 no more likely to be named "white" than illuminations yellower than D56. Colour constancy indices, both "subjective" and "fixed", were higher for illuminations on the daylight locus, but not significantly better for illuminations named "white".

**A NEW LAMP FOR COLOR VISION TESTING : THE TRUE COLOR LED LAMP****Jean Leid and Géraldine Kraft**

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Lamps that were the standard sources of light for pigmentary color vision testing are now discontinued ( MacBeth lamp), or are too imperfect (fluorescent lamps).

Until now, LED lamps were inefficient as a light source for color vision testing, due to a totally inappropriate spectrum.

Currently, new technology for LED chips allows us to purchase a limited number of LEDs with an emission spectrum compatible with the requirements of color vision testing, provided that undesirable short wavelength spikes are eliminated.

With such a concept in mind, we propose a new lamp, equipped with a spectrum very close to that of sunlight and with a color rendering index superior to the already excellent index of the MacBeth lamp.

Its advanced ergonomic features make it practical, reliable, and durable. It is energy efficient, is maintenance free, and can be used immediately thanks to its folding tray, tinted a specific shade of gray, avoiding undesirable contrasts. Once folded, the device occupies very little space.

**LIGHTING FOR COLOUR VISION EXAMINATION IN THE ERA OF LEDS****Stephen Dain<sup>1</sup>, David Atchison<sup>2</sup>, Jeffery Hovis<sup>3</sup> and Mei Ying Boon<sup>1</sup>**<sup>1</sup>School of Optometry and Vision Science, University of New South Wales, Australia<sup>2</sup>Queensland University of Technology, Australia<sup>3</sup>School of Optometry and Vision Science, University of Waterloo, Canada*Corresponding author: s.dain@unsw.edu.au*

**Purpose:** The appropriate lighting for colour vision examination, quality and quantity, is rarely well defined. In this study we look at the quality not quantity. The requirements vary from “daylight” through to a correlated colour temperature (CCT) of “around 6500 K and a CIE General Colour Rendering Index (CRI) greater than 90”. In the time that colour vision lighting was provided by an incandescent source and a glass colour correcting filter, this was quite easy to achieve. It was also relatively easy to achieve with fluorescent tubes using halophosphates, which have very broad spectral distribution phosphors. However, halophosphate tubes are more costly and less efficient than the triphosphor technology that superseded halophosphates. In a parallel development, the demand for daylight tubes in the material and garment retail trade has diminished and the need driven only by colour matching quality control and colour vision examination applications. Early white LEDs comprised a blue pumping LED with a single yellow phosphor. The consequence was a white source with a CRI only in the middle 70s that was quite unsuitable for critical colour work. This has been improved, firstly with the warmer LED colours and, more recently, with the daylight LEDs, by including extra phosphors so that LED sources around 6500 K with a CRI well above 90. As a consequence, LEDs that comply with the CCT  $\approx$  6500 K CRI  $>$  90 are now available. Given that manufacture of fluorescent tube sources is coming to an end, it has become vital to evaluate LED sources

**Methods:** The spectral irradiances of a selection of sources were measured with a number of spectroradiometers at 3 locations. The CCTs, CRIs and CIE Daylight category were calculated using the source data and spectral reflectances of the FM 100 Hue, FM D-15 and Ishihara tests, the sources were evaluated using previously published metrics.

**Results:** There was a wide variation in the performance of sources, as has been reported previously. While it has been widely nominated and used for colour vision examination, the Macbeth lamp is one of the poorer performers consistent with CCT being a more significant measure than previously thought. While the CIE Daylight category may be a better metric than CCT and CRI, it is rarely reported by manufacturers. It is possible that CRI assessed against a single “gold standard” source, rather than against a daylight source of the same CCT, is a better metric, as is done with the Cyanosis Observation Index (AS/NZS 1680.2.5). This effectively places a limit on CCT while only using one metric. An LED high CRI daylight source is as acceptable as the better fluorescent tube sources.

**PAEDIATRIC COLOUR VISION SCREENING****Manca T Pompe**

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The purpose was to compare four available colour vision tests for screening pre-school and early school-age children. Thirty-seven children (19 girls and 18 boys, 3-9 years of age, grouped into three age groups: 3-5y, 5-7y and 7-9y) participated in the study. The first test used was an alphabetic Ishihara test (AI) (Handaya Co. Ltd., Tokyo). The second test used was "Color vision testing made easy" (CVTME) (T.L.Waggoner), which is also based on pseudoisochromatic plates with child-friendly symbols. The third test used was "Neitz test of color vision" (Western Psychological Services, WPS). The fourth test used was "Mollon-Reffin Minimalist test" (MRM) (version 0.7). In the first three tests, the child had to tell what he or she saw in the picture, whereas in the fourth test the child had to pick the coloured button among distractors. The number of errors in each of the first three tests was registered, whereas in the MRM test the least saturated button distinguished among distractors was registered. Specificity was calculated for each test. Every child was also asked to pick his or her favourite test. 21/37 (57%) of the children performed the AI test without errors. 29/37 (87%) of the children performed the CVTME test without errors. None of the children performed the Neitz test without errors. 27/37 (73%) of the children performed the MRM test without errors. 28/37 (75%) of the children chose the MRM test as their favourite one. The AI has turned out to be too difficult and therefore unreliable in the youngest children (age 3-5y). The CVTME was much more reliable in evaluating colour vision in youngest children. For children of all age groups the MRM test was easiest to perform. The MRM test was also the favourite test of most children who participated in the present study. From the clinicians' point of view a child-friendly pseudoisochromatic test such as CVTME and a MRM test are needed in paediatric ophthalmologists.

**THE CAMBRIDGE COLOUR TEST: REPRODUCIBILITY IN NORMAL TRICHROMATS****Thiago MP Fernandes, Natanael A Santos and Galina V Paramei**

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The present study aimed at evaluation of reproducibility – intrarater repeatability and reliability – of the Trivector subtest of the Cambridge Colour Test, i.e. estimates of Protan, Deutan and Tritan discrimination thresholds. To assess repeatability (test-retest agreement), for each test-retest pair the coefficient of repeatability (COR) was calculated and the Bland–Altman plots generated, indicating limits of agreement of the test measures (LoAs; Bland & Altman, 1986). To assess reliability of the Trivector measures, intraclass correlation coefficient (ICC) was estimated, which takes into account both repeatability of the test and its sensitivity to differences between subjects (Rubin, 1988). Data for healthy normal trichromats were obtained in Brazil and the UK. In both samples, exclusion criteria were congenital colour abnormality, eye diseases, diabetes, substance abuse, neurological or psychiatric disorders. Observers were dark adapted and tested binocularly. Brazilian observers (N=111; 59 males) were aged 20–49 years; the Trivector measures were estimated three times: baseline (T0), six months later (T1) and one year later (T2). UK observers (N=79; 40 males) were aged 10–69 years; the Trivector test was followed immediately by retest. The repeatability analysis showed that the COR was moderate, varying between 0.29–0.55 for the Brazil data and 0.33–0.45 for the UK data. The Bland-Altman LoAs revealed that for all Trivector paired measures, mean test-retest difference only slightly deviated from zero. Across all test-retest pairs, 88%÷98.3% (Brazil) and 89%÷94% (UK) of differences appeared to lie between the upper and lower LoAs (i.e. within 1.96 standard deviation from the mean difference). These values are close to 95% adopted by the British Standards Institution (1974). The reliability analysis revealed relatively low ICC magnitudes for the Brazil sample: they varied between 0.02–0.30; for the UK sample, the ICC magnitudes were moderate varying between 0.54–0.65. The obtained modest ICC values for the samples of normal trichromats can be explained by taking into consideration that reliability parameters are highly dependent on the heterogeneity of the study sample (de Vet et al., 2006). Indeed, in the Brazil study, the sample was highly homogeneous, with subjects representing three life decades with the best chromatic discrimination and comparable thresholds. The UK sample, in comparison, had wider age range, was more heterogeneous: it included many adolescent and mature subjects, whose chromatic sensitivity is both lower and more variable (Paramei & Oakley, 2014). Our results provide converging evidence, from two research locations, of good Trivector repeatability, the test evaluative measure. The outcomes relating to Trivector reliability – the test discriminative measure – prompt replication of the study with a sample that, along with normal trichromats, would include subjects with varying types and degrees of colour vision abnormalities.

**MEASURING HUE DISCRIMINATION THRESHOLDS IN INFANTS USING INTER-OBSERVER STAIRCASES****John Maule<sup>1</sup>, Alice Skelton<sup>1</sup>, Lydia Day<sup>1</sup>, Katie Barnes<sup>2</sup>, Anna Franklin<sup>1</sup> and Jenny Bosten<sup>2</sup>**<sup>1</sup>The Sussex Colour Group & Baby Lab, University of Sussex, United Kingdom<sup>2</sup>Sussex Vision Lab, University of Sussex, United Kingdom*Corresponding author: J.Maule@sussex.ac.uk*

Human infant color vision in the first year of life has been well-characterized in terms of the maturation of the cones and retina, the presence of signals from the L/(L+M) and S/(L+M) pathways at the cortex, sensitivity along the protan, deutan and tritan axes, and the categorical encoding of hues. Recently it has been shown that the cone-opponent L/(L+M) and S/(L+M) mechanisms form the basis of infant category boundaries (Skelton et al., 2017), suggesting that infants' behavior may be tuned in to the cone-opponent mechanisms. We investigated whether this is also reflected in discrimination – are infants better at discriminating color across the cardinal axes of cone-opponent colour space, compared to across oblique axes?

Infants aged 4-6 months ( $n = 74$ ) were shown pairs of stimuli – a uniform hue on one side and a dynamic target composed of two hues on the other, while an eye-tracker recorded where they looked and for how long. The CIELUV (1976) hue difference in the target was titrated to estimate the hue threshold around the poles of the cardinal L/(L+M) axis, S/(L+M) axis (calculated in CIELUV space), cerulean line and the reflection of the cerulean line. Given the difficulties in obtaining enough trials to derive psychometric functions for individual infants, we developed a novel method for combining information from successive participants to inform an inter-observer estimate of the threshold from ZEST (King-Smith et al., 1994). Since infant looking time from a single trial is likely to be influenced by significant noise, we applied a filtering criterion to the data passed to ZEST. For a given hue difference we gathered trials until the Bayes Factor indicated strong evidence for infant looking at the target for longer than the non-target, or for strong evidence of no preference in looking between the target and non-target. This summary information – the hue difference and whether the infants were able to detect the difference – was passed to ZEST which provides an updated threshold estimate. We have called our method the Robust Inter-Observer Threshold (RIOT) Procedure. Using this method, information from every trial is used to inform a threshold estimate across a group of observers.

Staircases successfully converged for all eight test points. Initial data indicates that the poles of the cardinal axes are not consistently associated with reduced hue discrimination in infants, compared to the poles of the cerulean line and its reflection. Infant hue thresholds are elevated by a factor of about 6, compared to a group of adults who completed the same task. There is also no clear general relationship between adult hue thresholds and infant hue thresholds around the same points. If this finding is repeatable this would suggest there are as-yet uncharted changes in hue sensitivity during development – the origins of which would merit further investigation.

**IMPLICATIONS OF MELANOPSIN PHOTORECEPTOR DYSFUNCTION IN EYE DISEASE****Beatrix Feigl**

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Melanopsin expressing intrinsically photosensitive Retinal Ganglion Cells (ipRGCs) constitute the third class of photoreceptors in the eye and have roles in image and non-image forming behaviours. Since their discovery in human and non-human primate retina in 2005 (after their initial identification in mice), researchers have extensively used animal models to study their physiological functions. My research focusses on clinical investigations of melanopsin function in humans using techniques developed in our laboratory. We have demonstrated that melanopsin photoreceptors are dysfunctional in many retinal and optic nerve diseases including age-related macular degeneration, diabetic retinopathy and glaucoma. Using chromatic pupillometry, we have established the ipRGC-mediated pupil light response as an effective early biomarker of disease, even at pre-clinical and pre-perimetric stages. This presentation will summarize our findings of ipRGC function in common blinding eye diseases and neurological disorders (i.e. Parkinson's disease). The link between ipRGC dysfunction and its implications on chronobiological behaviours (i.e. sleep) in patients will be highlighted.

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**RHODOPSIN AND MELANOPSIN CONTRIBUTIONS TO HUMAN BRIGHTNESS ESTIMATION****Andrew J Zele<sup>1</sup>, Ashim Dey<sup>2</sup>, Prakash Adhikari<sup>2</sup> and Beatrix Feigl<sup>3</sup>**<sup>1</sup>Visual Science Laboratories, Institute of Health & Biomedical Innovation, Queensland University of Technology, Australia<sup>2</sup>Visual Science & Medical Retina Laboratories, Queensland University of Technology, Australia<sup>3</sup>Medical Retina Laboratories, School of Biomedical Sciences, Queensland University of Technology, Australia*Corresponding author: andrew.zele@qut.edu.au*

In photopic illumination, human brightness estimation is determined by the combined interaction of additive (L+M) cone inputs to photopic luminosity and the photon counting properties of melanopsin expressing intrinsically photosensitive Retinal Ganglion Cells (ipRGCs) (Zele et al., 2018). Photoreception under scotopic illumination is initiated by rhodopsin; evidence suggests that dark-adapted ipRGCs, like rods, also show an intrinsic scotopic response (Sonada et al., 2018) including to a single photon (Do et al., 2009), and extrinsically mediate rod signals (Dacey et al., 2005). Here we investigated the contribution of melanopsin and rhodopsin signaling to human brightness estimation under dim illumination (-5.67 to -0.81 log cd/m<sup>2</sup>). Using a method of absolute magnitude estimation (Barlow & Verrillo, 1975), participants (n=6) judged the brightness of narrow-band, coloured primaries (Blue: 462 nm; Cyan: 499 nm; Green: 525 nm) presented in a Ganzfeld (10 ms and 1000 ms durations). Retinal illumination (0.0002 to 3.01 scotopic Troland) was estimated based on measured pupil diameters. The scotopic-mesopic transition was defined by the disappearance of the foveal scotoma for each coloured primary light. The brightness of the primary lights were estimated in two conditions spanning -4.20 to -0.95 log  $\alpha$ -opic lux, either melanopsin-equated conditions with different rod excitations (7.32 – 10.77 log quanta/cm<sup>2</sup>·s) or rhodopsin-equated conditions with different melanopsin excitations (7.38 – 10.80 log quanta/cm<sup>2</sup>·s) We show that brightness estimates increase approximately linearly with increasing melanopsin or rhodopsin  $\alpha$ -opic lux (in log units) and are always higher with longer duration stimuli. In scotopic illumination, brightness estimates with rhodopsin-equated lights are independent of the corresponding melanopsin excitations, whereas brightness estimates with melanopsin-equated lights increase with the corresponding rhodopsin excitations. In mesopic illumination, brightness estimates with rhodopsin- or melanopsin-equated lights increase with increasing melanopsin or rod excitations > -2.45  $\alpha$ -opic lux. Further analysis showed that rods mediate the baseline brightness detection in scotopic illumination and melanopsin scales the brightness estimations with increasing irradiance in mesopic lighting. We infer that rod signaling is entirely responsible for scotopic brightness detection, with rod signals mediated via ipRGCs independent of their intrinsic melanopsin response. Melanopsin contributions to the scaling of brightness perception become evident in mesopic illumination, where rod contributions are limited, thereby demarcating a transition to the combined cone and melanopsin processing of brightness sensations.

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**ADAPTATION TO MELANOPIC STIMULATION DOES NOT ALTER SENSITIVITY TO CONE-DIRECTED FLICKER****Joris Vincent, Geoffrey K Aguirre and David H Brainard**

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A subset of retinal ganglion cells contain the photopigment melanopsin, and as a result are intrinsically photosensitive (ipRGCs). These cells are known to contribute to visual reflex functions, e.g., pupil constriction. In rodents, they also can modulate signals originating in the cones via recurrent axon collaterals. Through this mechanism, stimulation of melanopsin could affect visual perception. In the current study, we investigate whether adaptation to melanopsin stimulation alters sensitivity to flicker directed at the cone photoreceptors.

Sensitivity to cone-directed stimulation was measured as the threshold Michelson contrast of cone-directed sinusoidal (5 Hz) flicker. Three participants performed a two-interval forced-choice task, where one interval contained 500 ms of the target sinusoidal flicker, and the other, reference, interval contained only the background for the same duration — intervals were separated by 500 ms of just the steady background. The target flicker contrast was controlled by interleaved adaptive staircases. Thresholds were calculated from offline psychometric function fits.

Participants performed this task under 4 different adaptation conditions, each condition tested separately. The conditions varied in the spectral power distribution of the background on which the flicker was presented. Two pairs of backgrounds were used; one pair differed by a 350% isochromatic contrast step in melanopic content, the other pair differed by a 350% isochromatic contrast step in LMS cone stimulation. Flicker sensitivity on each background was tested separately, following a period of 5 minutes of adaptation to the background for the 120 trials in that condition. All stimuli were generated using a digital light synthesis engine with 56 effective primaries. Participants viewed the 27.5 degree field (of which the central 5 degrees were occluded) through a pharmacologically dilated pupil.

Expressing the flicker threshold as the differences in LMS cone excitation of the flicker stimulus at threshold, no difference in sensitivity was found between the low melanopic and high melanopic backgrounds for any of the three participants; thresholds on the high melanopic background were 0.89x, 1.02x and 1.03x the thresholds on the low melanopic background. The thresholds on the high LMS background were 3.81x, 4.14x and 4.50x higher than on the low LMS background, which serves as a positive control generally consistent with a 4.5x increase expected from Weber's law.

In the experiment presented here, sensitivity to flicker directed at the cones was not altered by adaptation to a steady field of substantially higher melanopic content. This suggests cone sensitivity is not regulated by the signals from tonic melanopsin stimulation. Follow-up experiments are being conducted investigating the effect of transient melanopsin stimulation on cone sensitivity, as well as on suprathreshold cone function. Thus, AOSLO-based eye tracking provides new opportunities to relate visual performance of the dynamic retina to irregularities of the trichromatic photoreceptor array.

**OPPONENT MODULATION OF mRGCs AND RODS IN UNIQUE-HUE COLOR CHANNELS****Katsunori Okajima<sup>1</sup>, Yoshika Takahashi<sup>1</sup>, Graham Fielder<sup>2</sup> and Alan Robertson<sup>2</sup>**<sup>1</sup>Yokohama National University, Japan<sup>2</sup> National Research Council, Canada*Corresponding author: okajima@ynu.ac.jp*

We measured the color appearance of 78 colored lights using a Trichromator (Stiles type) and both an elemental color scaling and a categorical color naming methods. The primary colors were 645.2 nm (red), 526.3 nm (green) and 444.4 nm (blue). The intensity was 100 Td and the visual angle was 2-degree. As a result, we proposed a network model for categorical color perception (Okajima et al., 2002).

In addition, we tried the quantification of unique-hue color (red, green, yellow, blue) mechanisms (Okajima et al., 1997) but could not explain the yellow and blue channels only by using L, M and S-cone responses.

Recently, some studies have indicated the association of melanopsin-expressing retinal ganglion cells (mRGCs) with the image-forming pathway (e.g. Yamakawa et al., 2016). Therefore, we re-analyzed the data of the elemental color scaling by considering responses of mRGCs (G) and rods (R) in addition to those of cones (L, M, S). As a result, we found that linear formulae of  $\log(L)$ ,  $\log(M)$ ,  $\log(S)$ , G and R well fitted the elemental color scaling data quantitatively and that the G and the R are opponent in all the formulae, suggesting that the contributions of mRGCs and rods of broad-band compound lights to color mechanisms are almost cancelled out because the spectral sensitivity functions of melanopsin and rods are quite similar.

**CHROMATIC PROPERTIES OF JAPANESE PAINTINGS ARE SIMILAR TO THAT OF EUROPEAN PAINTINGS**

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**Background:**

The chromatic diversity in paintings is a very important property which is traditionally evaluated qualitatively by visual observation. Unlike an ordinary digital RGB camera, modern hyperspectral imaging techniques record spectral information at each pixel of paintings, and, therefore, it enables to accurately represent color information of the entire painting in different color spaces. According to the previous research that compared the color characteristics of natural environment and European paintings, the chromatic properties of European paintings generally follow the statistical features of natural environment (Cristina et al., 2016). By comparing the color features of paintings between different cultures, it may be a clue to clarify the characteristics of each culture. However, the cultural difference in the color property of paintings is not yet fully explored. In this study, we addressed this question by using Japanese paintings and European paintings, and natural landscapes which includes country side and urban environment scenery.

**Method:**

We analyzed hyperspectral images of three categories, 19 Japanese paintings, 62 European paintings and 50 natural scenes. The analysis of the chromatic properties of the paintings and natural scenes was carried out in the CIELAB color space. From the estimated spectral radiance derived for each pixel assuming the standard illuminant CIE D65, the corresponding color was computed by converting radiance into tristimulus values for the CIE 1931 standard colorimetric observer and then converting into the CIELAB color space. The chromatic properties of each category were characterized by the histograms of three parameters of the ellipse fitted to the data based on a least squares criterion: (a) the axis ratio between minor axis and major axis, (b) the angle of major axis relative to a\* axis, and (c) the area ( $a^*b^*$ ) of a polygon that encompasses all plot points.

**Results and Discussions:**

The analysis of variance revealed that there is no significant difference for the ellipses axis ratio but a significant difference was found for the angle and the area when Japanese paintings and European paintings are compared to natural scenes. Importantly, we found no significant difference between Japanese painting and European painting. These results suggest that the color properties of Japanese and European paintings are different from the ones found in natural scenes, but Japanese paintings and European paintings have similar color features. Furthermore, the analysis the ellipsis angle with respect to the a\* axis showed that the angle of the major axis Japanese and European paintings were about 25 degrees smaller than natural images. In other words, Japanese paintings and European paintings are more reddish than natural images.

These findings need to be validated against a larger number of images, but the present study seems to suggest that Japanese paintings and European paintings might have similar color features. This research may greatly contribute to the elucidation of color characteristics of paintings between cultures.

**A COMPUTATIONAL MODEL DESCRIBING THE LOCATION OF DISCERNIBLE CATEGORICAL COLOR PATTERNS IN PAINTINGS****Juan Luis Nieves, Yu-Jung Chen, Luis Gomez-Robledo and Javier Romero**

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Millions of colors are usually accepted as the order of magnitude of the number of discernible colors in natural images (c.f. Linhares et al., 2008, *J.Opt.Soc.Am.* A25, 12, 2918-2924). Nevertheless, it is obvious that an observer will not be able to differentiate such number of colors when he/she is looking at either a natural or an artificial scene. Although several color naming approaches have been early introduced to collect color names and their corresponding color ranges, the link between the number of discernible colors and a more realistic estimation of those colors simultaneously perceived in a scene has not been fully studied and is still a conundrum. In a previous work, we first heuristically analyzed this issue by introducing the term remarkable salient colors (c.f. Nieves et al., 2018, *Color Research and Applications*, 43, 713-725). Being salient colors a plausible set of locations describing how observers tend to perceive a scene, it was not clearly connected with the presumably small fraction of that big number of potential discernible colors. In this work we have developed a computational model that aims at locating those relevant colors that describe a painting without the need for a predefined color categorization and/or color naming paradigm. We collected the 4,267 paintings included in the Painting-91 dataset (c.f. Khan et al., 2014, *Machine Vision and Application*, 25(6), 1385-1397). The rationale about the computation of the number of relevant colors is as follows. We first reduced the color distribution (color diversity) of each painting by sampling the corresponding CIE L\*a\*b\* color distributions with different cube based grids. Next, a threshold value was applied to count all colors in each cubic box below that threshold; the threshold value was computed as some percentage of the total amount of pixels of the image. Values of 3% and 20 for the threshold and the grid size, respectively, were selected in the upcoming computations. Finally, we subsampled every color by selecting those ones with both high chroma and lightness values, and then replaced every color in the original image with the average color of each selected cube. After this refinement of the set of selected colors the algorithm obtained an average number of 18 relevant colors (with an SD of  $\pm 7$ ). This means a huge percentage of reduction in the number of colors in comparison with the initial average number of 17,444 discernible colors (with an SD of  $\pm 9600$ ) or the 43 colors (with an SD of  $\pm 20$ ) selected after the first threshold constraint. That number of only 18 relevant colors partially agreed with the total 11 basic color names usually found on other categorical color studies (c.f. Párraga et al., 2009, *J. Imag.Sc. Tech.*, 53(3), 31106-1-31106). The method can derive different representative colors for each image, being better adapted to the color content of every image. The comparison between the set of relevant colors and the colors obtained after applying a computational color name approach reflects significant chromatic differences between our relevant set of colors and the classical categorical color names.

**INSIGHTS INTO THE COLOURS OF ART – GRAFFITI AND PAINTINGS****Claudia Feitosa-Santana<sup>1</sup>, Carlo M Gaddi<sup>2</sup> and Sérgio MC Nascimento<sup>3</sup>**<sup>1</sup> Neuroscience for Human Development, Brazil<sup>2</sup> University of São Paulo, Brazil<sup>3</sup> University of Minho, Braga, Portugal*Corresponding author: claudia@feitosa-santana.com*

The colours of traditional paintings have a specific structure that in general mimic the chromatic structure of natural scenes (Montagner et al, 2016). In particular, their colours are distributed along an axis close to the yellow-blue axis of CIELAB. Urban artists make extensive use of colours, especially when expressing in the form of graffiti. Their colours have not been quantitatively characterized and it is unknown whether they follow the same structural trends as more traditional paintings. The goal of this work was to characterize the colours of graffiti and to compare their chromatic structure to that of traditional paintings.

Photos of 228 graffiti of the city of Sao Paulo, Brazil, were taken in five different zones of the city with a Nikon d7000 DSLR camera with a CMOS sensor of 16MB resolution (3264 × 4928 pixels). A X-Rite Macbeth ColorChecker Classic with 24 samples was included in the field of view of each photo for calibration purposes. The illumination on the colour chart was measured immediately before taking the photo with a portable spectro-colorimeter Everfine SPIC-200. The spectral reflectance of the samples of the colour checker were measured with a Minolta CM 2600d and used to obtain the chromaticities of the patches of the colour checker under each local illumination. These data were then used to correct the sRGB data from the camera for each photo using the Moore-Penrose pseudo-inverse transformation. CIELAB for each pixel were then computed from the corrected set of tristimulus values. The colours of each graffiti were characterized by the properties of an ellipse fitted to the CIELAB data based on a least squares criterion. The distributions of these parameters were then compared with those obtained from spectral imaging data from traditional paintings (Montagner et al, J. Opt. Soc. of Am. A, 2016).

It was found that graffiti have chromatic structures similar to those of traditional paintings. The distribution of orientations of the fitted ellipses for graffiti and paintings have maxima that are within 20 degrees of each other and their orientation is, on average, close to the yellow-blue axis of CIELAB. The distributions of the ellipses' axis ratios have maxima close to 0.6, expressing the same degree of gamut stretching. The distributions for the graffiti are, however, broader than for more traditional paintings, suggesting more freedom in the use of colours and a wider range of aesthetic preferences.

SUNDAY 7<sup>th</sup> JULY

**LUMINANCE AND CHROMATIC SENSITIVITY AT HIGH LIGHT LEVELS****Sophie Wuerger**

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Contrast sensitivity functions (CSF) are commonly used to characterise the sensitivity of the human visual system at different spatial scales, but little is known how the CSF changes from the mesopic range to a highly photopic range reflecting outdoor illumination levels.

The purpose of our study was to further characterise the CSF by measuring the luminance and the chromatic sensitivity for background luminance levels from 0.2 cd/m<sup>2</sup> to 7000 cd/m<sup>2</sup>. Stimuli consisted of Gabor patches of different spatial frequencies, generated using MatLab, varying from 0.5 cpd to 6 cpd and were displayed on an HDR display luminance levels of up to 15000 cd/m<sup>2</sup>. Contrast sensitivity functions were measured in three directions in colour space, reflecting early post-receptor processing stages: an achromatic (L+M) direction, a 'red-green' (L/(L-M)) direction, and a 'lime-violet' direction (S/(L+M)). Thresholds are defined as the distance in cone contrast space at which 84% correct performance was achieved.

Within each session, observers were fully adapted to the fixed background luminance (0.2, 2, 20, 200, 2000 or 7000 cd/m<sup>2</sup>) and on each trial a stimulus of a different frequency (0.5, 1, 2, 4, 6 cpd) and colour (achromatic, red/green, lime/violet) was presented.

Our main finding is that the background luminance has a differential effect on luminance compared to chromatic contrast sensitivity. Contrast sensitivity is increasing with background luminance up to around 200 cd/m<sup>2</sup>, in particular for medium and high frequencies. Higher luminance levels yield a decrease in luminance contrast sensitivity which is not observed in the chromatic sensitivity curves.

The differential effect of background luminance on luminance and chromatic contrast sensitivity implies that a local cone contrast adaptation model is not sufficient to account for the observed sensitivity changes. 2<sup>nd</sup> order adaptation (occurring beyond the receptor level) and/or spatial factors are likely to play a role.

**ENSEMBLE PROCESSING OF HETEROGENEOUS LUMINANCE DISKS****Eiji Kimura and Yusuke Takano**

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The visual system can summarize complex scenes by rapidly forming statistical summary descriptions of sets of similar items. Considering the statistical regularity and redundancy of the natural world, this ensemble processing can be critical for efficiently representing natural scenes. In our first study on ensemble brightness perception (Kimura et al., ECV2018), we showed that, when asked to compare mean brightness of heterogeneous luminance arrays, observers' judgments were efficient and precise, but biased. The analysis of the bias indicated that observers used a flexible weighted-averaging strategy to rely more on a few items in the arrays such as the highest or lowest luminance disks depending on task requirement. That is, when asked to choose the brighter array the observers relied more on the highest luminances, whereas when asked to choose the darker array they relied more on the lowest luminances. This finding of task-dependent processing suggested top-down influence on ensemble coding. In the second study, we investigated variability discrimination for luminance ensembles. The standard and comparison stimuli were heterogeneous luminance arrays composed of 24 disks (each disk subtended 1.5 degrees). The two stimulus arrays were presented side by side simultaneously for 47 msec and followed by a dynamic pattern mask. Observers' task was to indicate the more variable array of the two. Mean luminances of the standard and comparison stimuli were the same on each trial, but varied across different trials. The standard deviation (SD) of luminance distribution of the standard stimulus was set to one of 4 levels (4.0, 8.0, 12.0, or 16.0) and that of the comparison stimulus was varied from 0 to 20.5. Results showed that observers could efficiently and accurately discriminate luminance variability of the stimulus arrays. However, unlike in the case of the mean brightness judgments, no clear evidence for smart subsampling strategy was found. The percentage of correct responses in variability discrimination could be described fairly well as a function of the difference in SD between the standard and comparison stimuli. Thus, even though the stimulus was very brief and composed of many disks, observers did not rely on proxies such as the luminance range or the highest (or lowest) luminance of the arrays. This is remarkable because accurate estimation of variability requires more samples than that of mean. Our simulation of random sampling strategy on the variability discrimination task indicated that 5-6 samples for each array were required to accomplish the present variability discrimination performance; the number of samples is well beyond the capacity limit of working memory. Another interesting finding was that the discrimination performance depended solely on the difference in SD regardless of the level of the standard SD. Thus, Weber's law did not hold. Overall, these results suggested that the variability of luminance ensembles is coded in a qualitatively different fashion from the mean. The variability discrimination seems to reflect mainly the processing in earlier, bottom-up stages.

**IMPACT OF PATTERN COLOUR AND LUMINANCE CONTRAST AND FREQUENCY ON ONSET OF PERIPHERAL ILLUSORY MOVEMENT PERCEPTION****Maris Ozolinsh<sup>1,2</sup> and Anna Pastare<sup>2</sup>**<sup>1</sup>Institute of Solid State Physics, University of Latvia<sup>2</sup>Faculty of Physics, Mathematics and Optometry, University of Latvia*Corresponding author: ozoma@latnet.lv*

Grouping of elementary stimuli according to Gestalt principles and studies of perception dominance are studied on the base of Shapiro-Meilstrup "Rotating Reversal Illusion" (Shapiro et al., 2011). Stimuli contain two layers. The front stimuli layer contains concentrically allocated six circular apertures in a neutral (or coloured) background. Apertures rotate counter-clockwise and motion is assumed as perceived outer movement. Back layer that is seen through apertures consists of concentrically allocated sinusoidally luminance modulated pattern that rotates with the same speed as apertures, however clockwise. The latter motion is assumed as perceived inner movement. Apertures and back layer pattern lie concentrically with symmetry centre collocated with the hidden centre of the internal back layer motion. At certain viewing conditions and stimuli luminance, colour, spatial and temporal frequency characteristics the movement of apertures is perceived illusory - moving clockwise.

Experimentally observers made following judgements ( $T_{\text{observ}} = 2$  sec) at different viewing eccentricity ( $3^\circ - 7^\circ$ ): 1) movement of apertures seemed jumbled; otherwise - spinning was perceived continuous either: 2) counter-, or 3) clockwise. Illusory perception - clockwise perception of movement sets on when viewing peripherally. A "typical" observers' response is as follows: for low values of front layer luminance  $L$  (total range  $0 - 250$  cd/m<sup>2</sup>) there is no illusion that at increased luminance is followed by rotation reversal (onset of illusion) - observers perceive the patches to begin moving clockwise. Subsequently, at more higher luminance of front layer observers experience an opposite reversal to non-illusory perception. Thus, for neutral stimuli colour and rotation speed  $0.17$  rps and frequency  $1.8$  cpd interval of inducing of illusory motion  $\log(L[\text{cd/m}^2]) = 0.7 - 2.2$  at mean modulation pattern luminance  $\log(L_{\text{mean}}[\text{cd/m}^2]) = 1.6$  and pattern contrast  $0.9$ , eccentricity  $7^\circ$ . Corresponding 2AFC psychometric curves were plotted. Points of perception subjective equality were determined at conditions where probability of counter-clockwise perceived movement equalized to probability of clockwise perception. Favourable conditions for inducing the illusion include equality of the frontal stimuli layer luminance and the mean luminance of modulations, increased contrast of modulations, and increased viewing eccentricity; however, increase in the modulation spatial frequency reduces the illusion onset probability.

Spatial and temporal frequency content and the onset of illusion were examined by Fourier analyse and tried to use in analyse the contrast sensitivity function frequency course modifications for peripheral perceived, moving and particularly suprathreshold stimuli (Venkataraman et al., 2019; Robson, 1966; Georgeson, 1991). Variations in colour content of stimuli change the minimum modulation colour contrast and minimal differences between front layer luminance and back layer mean luminance of modulations at which illusion sets on. However not colour content but both layers luminance difference serves as dominant factor in onset of illusory perception in our experimental conditions. Supported by CAMART2.

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**DISCRIMINATING PURITY AND DISCRIMINATING HUE****Marina V Danilova<sup>1</sup> and John D Mollon<sup>2</sup>**<sup>1</sup> I.P.Pavlov Institute of Physiology, Russia<sup>2</sup> University of Cambridge, United Kingdom*Corresponding author: mar.danilova@gmail.com*

The discrimination of colorimetric purity – the correlate of perceived saturation - has often been reported to be poorer than the discrimination of hue, even when a common metric is used. It is not immediately obvious why this should be so, since purity could be considered the most fundamental form of chromatic signal. Consider a type of retinal ganglion cell that is chromatically opponent, e.g. a cell that extracts the ratio of long- and middle-wave excitation. Such cells behave as if they are designed to signal departures from the current level of adaptation. The cells are quiescent in the presence of a steady neutral field. Their responses vary with the size of the departure from the neutral point. In a sense, therefore, the one-dimensional response of an individual ganglion cell is a signal of chromatic purity. And the discrimination of chromatic purity might depend simply on comparing the size of the signals from two cells of the same type in adjacent regions of the visual field. In contrast, the perception of hue requires the observer to use information from more than one class of opponent signals.

In the present study, we considered discrimination along horizontal lines in the MacLeod-Boynton diagram, i.e. lines along which only the ratio of excitation in the long- and middle-wave cones ( $L/(L+M)$ ) is varied, while the excitation of the short-wave cones (S) is held constant. When such a line passes through the white point, it represents a variation in purity. However, a line above or below the former line corresponds to variation in hue. Do differential thresholds differ in these two cases even though they nominally depend on the same retinal signal – a signal that could in both cases be taken as representing the size of the excursion from the neutral point?

Our stimuli were brief (180 ms) increments on a steady neutral field that had a chromaticity equivalent to the Daylight Illuminant, D65; and the observer was asked to identify which of four quadrants of a foveal disc differed from the other three. Thresholds for this four-alternative forced choice were measured by an adaptive staircase procedure. For  $L/(L+M)$  values below D65, purity discrimination was always better than hue discrimination at chromaticities very near the  $L/(L+M)$  value of the white point; but as the reference chromaticity was further removed from D65 – as the excursion in  $L/(L+M)$  became larger - a doubling of the S excitation yielded systematically lower thresholds for hue discrimination.

**ADVENTURES IN BLUE AND YELLOW****Michael A Webster**

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Conventional models of color vision assume that blue and yellow (along with red and green) are the fundamental building blocks of color appearance, yet how these hues are represented in the brain and whether and why they might be special are questions that remain shrouded in mystery. This talk will explore the visual encoding of blue and yellow, from the statistics of the environment to neural processing to perceptual experience. Blue and yellow are tied to salient features of the natural color world, and these features have likely shaped several important aspects of color vision. However, it remains less certain that these dimensions are encoded as primary or “unique” in the visual representation of color. There are also striking differences between blue and yellow percepts that may reflect high-level inferences about the world, and specifically about the colors of light and surfaces. Moreover, while the stimuli labeled as blue or yellow or other basic categories show a remarkable degree of constancy within the observer, they all vary independently of each other across observers. This pattern of variation again suggests that blue and yellow are not a primary or unitary dimension of color appearance, and instead suggest a representation in which different hues reflect qualitatively different categories rather than quantitative differences within an underlying low-dimensional “color space.”

MONDAY 8<sup>th</sup> JULY

**VERIFICATION OF THE COLOR APPEARANCE MODEL FOR ANOMALOUS TRICHROMATS BASED ON THE SHIFT OF CONE SPECTRAL SENSITIVITIES****Keiko Sato<sup>1</sup>, Kazumasa Nishitani<sup>2</sup> and Hironori Takimoto<sup>2</sup>**<sup>1</sup>Kagawa University, Japan<sup>2</sup>Okayama Prefectural University, Japan*Corresponding author: satokei@eng.kagawa-u.ac.jp*

The most common inherited color vision deficiency (CVD) defects are the protan and deutan types, such individuals are referred to as individuals with red-green CVD. Red-green CVD are classified into the four types: protanope, deuteranope (red-green dichromat), protanomalous, or deuteranomalous (red-green anomalous trichromats). The incidence of deuteranomaly is the highest of four types, and deuteranomalous individuals have varying degrees of trichromatic color vision with great variation. Some studies showed a model that red-green anomalous trichromats possess red- or green- shifted photopigments instead of normal L- or M- photopigments. Machado et al. (2009) have developed the technique for simulating the color appearance for anomalous trichromats. This technique is based on a LMS-cone stage and an opponent-color stage. They modeled anomalous trichromacy by shifting the LMS sensitivity function of the anomalous cone according to the degree of severity of the anomaly. A shift of 20[nm] represents the most severe case, i.e., dichromacy, causing the sensitivity functions of the anomalous L- or M-cones to almost completely overlap with the normal M- or L-cones. They suggested that this model can handle all color vision types including normal color vision, anomalous trichromats, and dichromacy. However, since a verification of the model was not enough, the accuracy of color appearance for anomalous trichromats based on the shift of cone spectral sensitivities is unclear. The purpose of this study is to verify the color appearance model by Machado et al. (2009) and to investigate a relationship between a shifted value of the LMS sensitivities and the degree of severity based on Rayleigh matching. For this purpose, we performed the experimental verification using the 15 different images of "flower", "painting", and "food". The participants included 16 men with red-green CVD diagnosed with the type (protan or deutan) and severity (dichromat or anomalous trichromat) according to their Rayleigh matching. We prepared the simulation images using a total of 30 steps representing spectral shifted values with the range from 0[nm] (original image) to 20[nm] for protan and deutan separately. In the experiment, an original image and a simulation image were presented side by side. We asked the observers to control the shifted value of the simulation image, and instructed them to alter it until the simulation image is the same as the original image. As the results, we found the positive correlation relationship between the results of the observer's Rayleigh matching and the obtained shifted value. The larger the shifted value is, the more severe the degree of color deficiency the observer has.

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**HUE SCALING IN ANOMALOUS TRICHROMATS****Ivana Ilic, Kara J Emery and Michael A Webster**

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Anomalous trichromacy is characterized by a shift in the spectral peak of one of the longer-wave cones toward the normal M (protanomaly) or L cone (deuteranomaly). The reduced spectral separation results in reduced cone contrasts along the L vs. M chromatic dimension. Despite this, previous our work suggests that some anomalous observers exhibit greater sensitivity for the LM dimension than their cone spectra predict, potentially by compensating the deficiency by means of post-receptoral gain. We evaluated possible compensatory adjustments in color appearance by measuring hue scaling functions in anomalous trichromats and comparing these to the strength of chromatic signals predicted by their contrast thresholds. Measurements were made for 6 anomalous observers (4 deutan and 2 protan, as assessed by the Cambridge Colour Test and anomaloscope settings). In hue scaling, hues are described in terms of the perceived proportion of red vs. green and blue vs. yellow. The chromatic angles and contrast of each stimulus were defined by the LM and S axes of a scaled version of the MacLeod-Boynton color space. The stimulus angle varied in 10-deg steps around the plane to define 36 test chromaticities, and contrast was fixed at a nominal value of 60. Each was shown in a 2-deg field on a larger equiluminant gray background for 500 ms, and interleaved with 1 s of the background gray. Observers judged the hue of each test stimulus by indicating the percentage of red, green, blue, or yellow via a keypad. In the chromatic contrast threshold (4AFC) task, the test stimulus was either an increment or decrement along the LM or S axis. The stimuli were presented for 500 ms in one of four quadrants, and observers were asked to indicate in which of the four quadrants a color was presented. To determine the sensitivity ratios (LM/S) implied by the hue scaling function, we rescaled the sensitivity to the LM axis in the average color-normal settings collected under the same conditions (Emery et al. 2017) to find the best fit to the function for each anomalous observer. Notably, this rescaling provided a poor fit to many of the observers, since the degree of predicted loss differed for different regions of the color plane. Thus, their functions could not be described as a simple reduced form of the color-normal function. The best scaling also varied widely across the observers, but on average required a 2.4 times reduction in LM sensitivity. In contrast, the average threshold ratios were 6.2 times higher for the anomalous group, a difference that was significantly higher than the scaling ratio ( $t(5) = 2.02$ ,  $p = 0.04$ ). These results are consistent with other reports (e.g. Boehm et al. 2014) suggesting that subjective color experience in anomalous observers is more similar to normal than predicted by their threshold sensitivity losses.

**THE EFFECTIVENESS OF ENCHROMA'S NOTCH FILTERS IN ENHANCING DEUTERANOMALOUS COLOUR VISION****Lucy Somers, Anna Franklin and Jenny Bosten**

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EnChroma Ltd. has developed glasses they claim enhance the colour vision of anomalous trichromats, however the limited evidence available indicates the glasses have no significant effect on CVD performance in diagnostic tests (Gomez-Robledo et al., 2018). To clarify this discrepancy we modelled the effect of the glasses on a broader range of stimuli by creating a physiologically accurate model of deuteranomalous vision. Using this model we established predictions for the signal strength from L/(L+L') and S/(L+L') cone-opponent subsystems for a selection of different EnChroma products, illumination types, and reflectances. The model showed that all EnChroma filters are predicted to be roughly ineffective when viewing narrowband reflectances from a variety of display monitors, with some monitors showing a minor enhancement in a portion of the spectrum, and other monitors reducing the signal. However, an overall positive effect was found for broadband reflectances. The signal enhancement was highly dependent on illuminant type. The greater radiance at short wavelengths of LED illuminants enhanced the signal of both the L/(L+L') and S/(L+L') subsystems, but for long-wavelength-dominated halogen illuminants there was enhancement mainly for the L/(L+L') subsystem. We conducted psychophysical tests in order to validate the model, testing colour discrimination at threshold, judgments of colour differences suprathreshold, and colour appearance using a matching paradigm. Our findings support the model's predictions for colour appearance, with the enhancement conferred by the filters in some instances even exceeding the enhancement predicted by the model. Predictions were not upheld at threshold. Judgments of colour differences, assessed using multidimensional scaling, show no significant effect. The positive finding in the colour-matching data and the negative finding in the MDS suggest that, though there is evidence the filters can be effective, these increases in signal may be adapted out by the visual system with prolonged viewing.

Gomez-Robledo, L., Valero, EM., Huertas, R., Martinez-Domingo, MA., & Hernandez-Andres, J. (2018). Do EnChroma glasses improve color vision for colorblind subjects? *Optics Express*, 26(22), 28682-28692.

**DIFFERENCES IN SUPRATHRESHOLD CONTRAST RESPONSE BETWEEN NORMAL AND ANOMALOUS TRICHROMATS****Kenneth Knoblauch<sup>1</sup>, Brennan Marsh-Armstrong<sup>2</sup> and John S Werner<sup>2</sup>**<sup>1</sup>Univ Lyon, Université Claude Bernard Lyon 1, Inserm, Stem Cell and Brain Research Institute U1208, France<sup>2</sup>University of California, Davis, Department of Ophthalmology & Vision Science, USA*Corresponding author: ken.knoblauch@inserm.fr*

The reduction in peak separation of the spectral sensitivities of the two long-wavelength sensitive cone classes of anomalous trichromats with respect to that of normal M- and L-cone sensitivities results in a reduction of the difference in chromatic signal from these two photoreceptor classes. This is evidenced by poorer chromatic discrimination at threshold. Nevertheless, suprathreshold studies suggest that there exists an adaptive adjustment of post-receptoral gain that compensates for the sensory loss. To investigate this phenomenon, we used Maximum Likelihood Difference Scaling (MLDS) to estimate contrast response functions for Gabor patterns (1 c/deg, 4 deg diameter envelope) modulated along luminance and L-M color directions in normal (n=9), protanomalous (n=7), and deuteranomalous (n=10) observers. On each trial, 3 Gabor patterns ordered in contrast were presented (0.5 sec, 2.8 deg eccentricity). The middle value contrast was presented above the central fixation cross with the other two straddled to the left and right below. A forced-choice response indicated whether the pattern in the upper visual field was more similar in contrast to the lower field pattern on the left or the right. Based on a signal-detection model, perceptual scale values, parameterized as  $d'$ , were estimated by maximum likelihood to best predict the ensemble of observer choices over the 84 triples obtained from 9 pre-selected suprathreshold contrast values. The two color axes were tested separately. Observers completed 12 runs for each axis distributed over 4 sessions. The scaling functions were well fit by a Michaelis-Menten model, permitting us to estimate response and contrast gain parameters for each subject. All anomalous observers showed reduced response gain along the L-M axis but there were no differences from normal along the luminance axis. The reductions in response gain were, on average, consistent with the reduction in the chromatic signal due to anomalous cone separation. Contrast gain, also on average, was significantly higher along both the L-M and luminance axes in anomalous trichromats compared to normal, suggesting a compensation mechanism that acts at a site that influences the output of both long-wavelength sensitive cone classes.

**CHANGES IN SUPRATHRESHOLD CONTRAST RESPONSE OF ANOMALOUS TRICHROMATS AFTER WEARING COLOR FILTERS****John S Werner<sup>1</sup>, Brennan Marsh-Armstrong<sup>1</sup> and Kenneth Knoblauch<sup>2</sup>**<sup>1</sup>University California-Davis Medical Center, USA<sup>2</sup>Univ Lyon, Université Claude Bernard Lyon 1, Inserm, Stem Cell and Brain Research Institute U1208, France*Corresponding author: jswerner@ucdavis.edu*

Spectrally selective filters have been used for at least 150 years to modify the spectral distribution of illuminants and surface reflectances in attempts to improve color discrimination of observers with color vision deficiencies. Broad-band filters modify the illuminant, but to create separation in stimulation of M- and L-cone signals among anomalous trichromats, a notch filter is needed. We tested a commercial filter (Enchroma) designed for this purpose. Maximum Likelihood Difference Scaling (MLDS) was used to estimate suprathreshold contrast response functions for Gabor patterns (1 c/deg, 4 deg diameter envelope) modulated along luminance or L-M color directions. Baseline data from normal, protanomalous, and deuteranomalous observers using this technique are described elsewhere (Knoblauch et al. ICVS, 2019). Based on a signal detection model, perceptual scale values (parameterized as  $d'$ ) were fitted by a Michaelis-Menten function so that response maxima and contrast gain parameters could be estimated for each subject. Among these observers, 3 protanomalous and 5 deuteranomalous observers were tested following at least 60 prior tests conducted over three two-hour sessions that established a stable baseline that was confirmed on day one of this experiment. Subjects then wore the Enchroma glasses for approximately two weeks and were tested on days 3, 5 and 12. Subjects were asked to keep a diary to estimate the number of hours that the glasses were worn, which ranged from ~35 to 115 hours over the 12 days. All subject testing took place without the glasses. For testing along the L-M axis, 6 subjects showed an increased response gain by day 5, one by day 12, and one showed no change. For all subjects there was no change in response gain along the luminance axis. Increases in response gain along the L-M axis were correlated to the amount of time and number of days the glasses were worn. We quantified performance in terms of the ratio of L-M to luminance response gain and found that the ratio for anomalous observers after wearing the Enchroma glasses was more similar to normal trichromats. On average, the difference in this ratio between anomalous and normal trichromats was decreased by 10% on day 3, 28% on day 5, and 44% on day 12. Another deuteranomalous observer wore neutral density filters and was tested on the same schedule as the test group. He showed no change in response gain at any time point for either axis of stimulus modulation. In addition, two normal trichromats were tested with Enchroma glasses but showed no changes in response gain over the same time course. Taken together, these findings indicate that increases in L-M response over time with the Enchroma glasses must be attributed to something other than practice effects.

**COLOUR ASSESSMENT OUTCOMES – IMPLICATIONS FOR EMPLOYMENT****John L Barbur, Benjamin EW Evans and Marisa Rodriguez-Carmona**

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**Introduction.** Colour assessment protocols usually employ several tests to maximise overall sensitivity and specificity. The results are often inconsistent and difficult to interpret, even for experienced colour vision examiners, with subjects preferring the least severe outcome. Assessing the severity of red / green (RG) and yellow / blue (YB) loss is an even greater challenge. Although a single test is preferred, no existing, conventional colour-screening test passes all normal trichromats and identifies correctly all subjects with congenital colour deficiency.

**Purpose.** Advances in visual displays and improved understanding of colour vision mechanisms make it possible to overcome the limitations of conventional colour screening tests. Our aim was to produce a rapid, sensitive and inexpensive colour vision screener that can be administered quickly. Most importantly, the screener should separate normal trichromats from subjects with congenital or/and acquired colour deficiency with close to 100% sensitivity and specificity. It is expected that if such a screener was available for use within schools and visually demanding occupations, only  $\approx 10\%$  of male subjects would require full colour assessment to establish accurately the class of deficiency and severity of loss.

**Methods.** The screener is based on the effective use of dynamic luminance contrast noise to isolate the use of colour signals, originally developed for the CAD test (Barbur & Rodriguez-Carmona, 2017). The 'CAD-Screener' employs age-matched thresholds that describe the upper normal, healthy limits for RG and YB colour vision. It also makes use of data measured in 336 normal trichromats, 881 deuterans and 393 protans, ranging from least affected to complete loss of RG colour vision. The difference in thresholds between the least-sensitive normals and the least-affected, age-matched deuterans and protans enables accurate screening for congenital deficiency. The CAD-Screener employs a statistical approach to establish the presence of colour deficiency. The eight stimulus colours employed are randomly interleaved and the subject cannot make use of any other cues. The screener can also run on visual displays that support the sRGB colour mode in the absence of full calibration.

**Results.** The CAD-Screener detects all normal trichromats and all protans with 100% sensitivity and specificity. Preliminary results in deuterans show that subjects with thresholds above 1.2 times the upper normal age limit fail the CAD-Screener. Only 3.8% of deuterans have RG thresholds that fall below this limit. These subjects are close to normal trichromats in terms of RG chromatic sensitivity, but do not accept normal colour matches. It remains to be established how many of these least affected deuterans pass.

**Conclusions.** The outcome of conventional colour assessment tests in many protocols is often unexpected in that normal trichromats can fail and some subjects with congenital deficiency can pass. Many who pass can have severe loss of colour vision. The use of the CAD-Screener eliminates these unwanted problems and makes colour assessment available, inexpensive and efficient. The same approach is applied to screen for abnormal YB thresholds to detect the presence of acquired deficiency. Further work is needed to make the CAD-Screener available on the web.

**GENETIC TESTING FOR COLOUR VISION DEFICIENCIES AND THE LIMITATION OF STANDARD PSEUDO-ISOCROMATIC PLATES****Rigmor C Baraas<sup>1</sup>, Solveig Arnegard<sup>1</sup>, Lene A Hagen<sup>1</sup>, Jay Neitz<sup>2</sup> and Maureen Neitz<sup>2</sup>**<sup>1</sup> University of South-Eastern Norway, Kongsberg<sup>2</sup> University of Washington, United States*Corresponding author: Rigmor.Baraas@usn.no*

**Purpose:** Genetic testing has been proposed as the new standard for diagnosis of colour vision deficiencies with MassArray analysis reported to give reliable classification of red-green (R-G) deficiencies (Davidoff, Neitz & Neitz, 2016). The aim here was two-fold: firstly, to compare results from MassArray analysis with that of two standard pseudo-isochromatic (PIC) tests commonly used for screening for R-G colour vision deficiencies, and secondly, to elucidate who is making typical and/or misreading errors on the PIC tests.

**Methods:** Male and female participants with normal habitual visual acuity (n=452, 16–24 yrs; 191 males; 436 Caucasians) were included. Colour vision testing was performed with the Hardy-Rand-Rittler (4th ed. 2002) and the Ishihara (24-plate ed., 1964) PIC plates under 781 (±67) lux ("True Daylight Illuminator with Easel", Richmond Products, Albuquerque, NM). A subset (n=52; 28 males) were measured with Rayleigh anomaloscopy and luminance matching (HMC Oculus Anomaloscope MR, Typ 47700, Oculus Optikgeräte GmbH, Germany). L- and M-opsin genes were sequenced, and analysis of opsin array composition was carried out by MassArray and used to categorize colour vision deficiencies as described by Davidoff, Neitz & Neitz (2016).

**Results:** MassArray identified 11 males who had opsin genes associated with R-G CVD, of whom 10 performed as such on PIC tests and Rayleigh anomaloscopy. Eight were deuteranomalous, one protanope and one with a promoter mutation performing as a deuteranomal. One made no errors on the PIC tests but had match midpoint and range associated with deuteranomaly. Two males performed as deuteranomalous on the PIC tests but appeared to have normal opsin genes. Ten males had opsin genes associated with suspected deutan deficiency, eight performed as if they had normal colour vision. The other two with suspected deutan deficiency and four males with normal opsin genes made 2–4 typical and/or misreading errors on one of the PIC tests.

MassArray identified 3 females who had opsin genes associated with R-G CVD, of whom two performed as deuteranomalous on the PIC tests. Five females were identified as being protan carriers, 29 as deutan carriers and an additional 9 being suspected deutan. Twenty-two females made 2–4 typical and/or misreading errors on one of the PIC tests, of whom 17 were deutan carriers. None of the protan carriers made errors on PIC tests.

**Conclusion:** MassArray identified 11% of males and 1.2% of females to be red-green colour deficient with only 6.3% of males and 0.8% of females being identified from PIC tests alone. A total of 16.5% of females were identified as carriers from MassArray, 1.9% protan and 14.6% deutan. Nearly 40% of carriers and 2% each of males and females with normal opsin genes made 3–4 typical or misreading errors on PIC test.

**References:**

Davidoff C, Neitz M, Neitz J. Genetic testing as a new standard for clinical diagnosis of color vision deficiencies. *Trans Vis Sci Tech.* 2016; 5(5):2, doi:10.1167/tvst.5.5.2

**AN IPAD APP TO MEASURE COLOUR DISCRIMINATION IN THE FIELD****Alice Skelton, Miranda Longworth-Krafft, James Alvarez, John Maule, Anna Franklin and Jenny Bosten**

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To understand how colour perception varies across different perceptual environments (e.g urban city vs rural rainforest), psychophysical methods are needed to acquire reliable and valid measures in the field. As well as the methodological challenge of creating tasks that work well across different cultures, equipment to be used in remote locations needs to be portable, robust and make modest energy demands.

As has been well documented, colour discrimination thresholds are higher along the blue-yellow axis in colour space than along any other colour axis. One hypothesis is that this occurs as a result of calibration to the visual environment (Bosten, Beer, & MacLeod, 2015). Here we present a method to measure colour discrimination thresholds using an iPad app to enable testing of this hypothesis in the field, at remote sites where colour environments differ. Critically for colour perception experiments, iPad models can be calibrated with consistent and predictable results. iPads are also ideal practically for testing in the field as they are very portable, their touch screens promote the design of intuitive tasks.

To verify the reliability and validity of the app, we measured colour discrimination thresholds for 30 participants, each along 8 axes in the MacLeod Boynton chromaticity diagram. We pilot tested two methods: a 4AFC task, and a single target detection task where a chromatic target is presented at a random location along with 8 achromatic distractors with variable luminance. Participants completed these tasks twice, in sessions approximately one week apart.

In accordance with the existing literature, discrimination thresholds resulting from both methods are greatest for the blue-yellow direction of colour space. The extent of the blue-yellow bias in discrimination ellipses can be quantified with an 'axis ratio' (the ratio of the length of the negative diagonal of the ellipse to the length of the positive diagonal). Axis ratios are comparable to those found in existing literature, ranging from 1.6 to 2

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**ESTABLISHING THE EQUIVALENCY BETWEEN COMPUTER COLOR VISION TESTS, HOLMES-WRIGHT LANTERN AND FARNSWORTH-MUNSELL D15 FOR CANADIAN AVIATION****Jeffery Hovis<sup>1</sup>, Ali Almustanyir<sup>1</sup> and Mackenzie Glaholt<sup>2</sup>**<sup>1</sup> School of Optometry and Vision Science, University of Waterloo, ON Canada<sup>2</sup> Human Effectiveness Section, Defence Research and Development Canada*Corresponding author: jhovis@uwaterloo.ca*

**INTRODUCTION:** In Canada, civilian pilots who have a color vision defect must pass either the Farnsworth-Munsell D15 (D15) or the Holmes-Wright Lantern Type A (HWA) to qualify for an unrestricted pilot's license. The Canadian military also uses the D15 to determine whether a color-defective candidate qualifies for aircrew positions. They do not use the HWA. Because computer-based color vision tests are becoming more popular, we compared newer computer tests with the D15 and HWA to determine the pass/fail scores that would be equivalent to the current color vision standard.

**METHODS:** The computer-based tests were the Color Assessment and Diagnosis (CAD) Rabin Cone Contrast Test (RCCT), a prototype of the ColorDx-CCT-HD (CCT-HD) and Cambridge Color Vision tests (CCVT). There were 68 individuals with a red-green color vision defect (CDV) and 60 individuals with normal color vision (CVN). The Rayleigh match was used to classify color vision. The CAD threshold, HWA, and D15 were performed binocularly, the CCVT and RCCT were performed monocularly, and the CCT-HD was performed both monocularly and binocularly. Cut-off scores for the computer tests were determined using ROC curves. The University of Waterloo Research Ethics Committee approved the testing protocol.

**RESULTS:** The AC1 level of agreement between the computer tests and the HWA was at least 0.95. The predictive values of the computer tests for failing and passing the HWA approached 1.0 except for the CCT where the predictive value for passing was 0.67. The AC1 agreement values with the D15 were lower, with most tests having values less than 0.50. The exception was the CAD, which had an AC1 value of 0.70. If the cut-off score was based on maximizing the sum of the computer tests' sensitivity and specificity, then the predictive values for passing the D15 were near 0.70 for most tests and the predictive values for failing were near 0.80. If the cut-off criterion was based on maximizing the sensitivity of the computer tests, then the predictive value for passing improved to values greater than 0.80, but the predictive values for failing decreased to values near 0.70.

**CONCLUSIONS:** The high level of agreement between the computer tests and HWA was because nearly all of the color-defectives failed the HWA and only those individuals who had results near CVN normal range on the computer tests passed the HWA. The lower agreement values for the D15 were due to the number of subjects who passed D15, but had relatively poor results on the computer tests. Although the CAD had better predictive values for the D15, there were still discrepancies between the test results for approximately 30% of the subjects.

**THE RETINAL MOSAIC, EYE MOVEMENTS AND COLOUR VISION****Sarah E Regan, Allie C Hexley, Anna-Katharina Hauperich, Laura K Young, Hannah E Smithson**

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Under conditions in which visual performance is limited by sampling, small eye movements that influence the way the optic array is sampled have the potential to change visual thresholds. We use high-resolution in vivo retinal imaging to measure fixational eye movements whilst assessing psychophysical thresholds on a sampling-limited spatio-chromatic task, with the aim of testing the functional role of eye movements made during fixation.

The long- (L), middle- (M) and short-wavelength (S) cone photoreceptors tile the retinal mosaic in different relative numbers. Among observers who pass standard colour vision tests, the average ratio of L:M cones is 2:1; however, it can range from 1:1 to 16:1. This leads to the strong prediction, for which Danilova and Mollon (2013) have provided evidence, that in some circumstances, chromatic spatial thresholds are limited by the sampling density of a given cone class.

We first present data that (i) replicates the finding of Danilova and Mollon (2013) that L:M ratio, as estimated by heterochromatic flicker photometry, predicts the ratio of spatial thresholds for L- and M-isolating Landolt Cs presented to the parafovea and (ii) extends the finding to the fovea in observers with particularly good (better than 20/20) monocular acuity whose foveal spatial resolution was therefore not strongly optically limited.

We then present data on the relationship between L:M ratio, spatial resolution for L- and M-isolating targets, and eye movements as measured by an adaptive optics scanning laser ophthalmoscope (AOSLO). The use of an AOSLO provides unparalleled spatial and temporal resolution, an advantage that is both significant and necessary given that the smallest fixational eye movements, drift and tremor, displace the retinal image by a distance of the order of units to tens of photoreceptors, and are often below the resolution limit of traditional eye-trackers.

The data will be analysed to test the following predictions: (i) if eye movements help us to overcome the relative scarcity of M cones by resampling the image, M-isolating trials will be more likely to be correct in the presence of more eye movements; (ii) if eye movements are particularly useful for individuals with highly skewed L:M ratios, the performance advantage will be greater in individuals with skewed ratios compared to those with more even ratios; (iii) if eye movement is responsive to the demands of the visual task, for those with high L:M ratios, more eye movements will occur on M-isolating trials; (iv) if eye movement adapts to L:M ratio over a lifetime, those with skewed L:M ratios will move their eyes more than those with more even L:M ratios; and (v) if eye movement adapts over a lifetime and responds to the demands of the visual task, those with skewed L:M ratios will have a bigger difference between the number of eye movements during L- and M-isolating trials than those with more even L:M ratios.

Thus, AOSLO-based eye tracking provides new opportunities to relate visual performance of the dynamic retina to irregularities of the trichromatic photoreceptor array.

**LIGHT AND COLOUR IN THE WILD****Sylvia Pont**

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Light in natural scenes can be described as a light field. Light fields capture all there is to see in scenes. We developed methods and tools for the measurement and visualization of the first order properties of optical (physical, objective) and visual (perceptual, subjective) light fields, including their spatial and angular distributions. These methods are generic and can be used for any type of scene ("in the wild"). We found that perceptual light field structures are simplified with respect to the optical ones. They can be described by a framework, which, at a phenomenological level, agrees with Richard Kelly's popular (in practice) lighting design approach: a weighted combination of ambient, focus and texture or brilliance light layers. Currently we are extending our research to the color domain via theoretical modeling and simulation of basic color effects in 3D spaces, empirical testing and visualization. Preliminary results show the occurrence of systematic hue, saturation and brightness effects in light fields, which are relevant for, for instance, perception research, architecture and computer graphics.

**THE TEMPORAL DYNAMICS OF DAYLIGHT: SPEED LIMITS ON PERCEPTION****Ruben Pastilha, Gaurav Gupta and Anya Hurlbert**

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Natural illumination changes smoothly in chromaticity and illuminance through the day, yet we are largely unaware of all but the most rapid changes, at dawn and dusk. Previously, we have shown that discrimination of abrupt temporal changes in illumination chromaticity depends on the chromaticity of the reference (adapting) illumination; for more extreme chromaticities, changes towards neutral chromaticities are less easily discriminated than changes away from neutral (Aston et al., 2019). Here we examined discrimination of smooth temporal changes in illumination chromaticity along the daylight locus.

We aimed to determine the minimum detectable velocity of chromaticity change in daylight metamers in an immersive illumination setting. Participants sat in a 2 m<sup>3</sup> enclosure with matte white walls, illuminated by spectrally tunable LED lamps (Ledmotive; www.hi-led.eu). In each session, the participant first adapted for 2 minutes to the reference chromaticity (with correlated colour temperature (CCT) of 4160 K, 6500 K or 13000 K). Each trial began with 2 seconds of chromatic noise illumination, followed by 5 s of reference illumination and a smooth change in illumination chromaticity away from the reference point along the daylight locus towards higher or lower CCTs; the amount of change varied across trials while the duration was held fixed, or vice versa.

Participants (n=4 participants) were able to detect smooth temporal changes in global illumination, in the absence of explicit objects or spatial features. Highest sensitivity was found for yellowish changes from the most yellow reference light (speed  $\approx 0.3 \Delta E/s$ ); lowest was for yellowish changes from the most blue reference light (speed  $\approx 1 \Delta E/s$ ). Changes in illumination chromaticity towards a neutral reference were hardest to detect, for non-neutral reference lights (4160 K and 13000 K). Results support the notion that the brain encodes a neutral-daylight illumination prior.

**HYPERSPECTRAL ENVIRONMENTAL ILLUMINATION: DIRECTIONAL SPECTRAL VARIATION AND A REVISIT OF METAMERISM IN THE REAL WORLD****Takuma Morimoto<sup>1</sup>, Sho Kishigami<sup>2</sup>, João MM Linhares<sup>3</sup>, Sérgio MC Nascimento<sup>3</sup> and Hannah E Smithson<sup>1</sup>**<sup>1</sup> University of Oxford, United Kingdom<sup>2</sup> Toyohashi University of Technology, Japan<sup>3</sup> Centre of Physics, Campus de Gualtar, University of Minho, Braga, Portugal*Corresponding author: takuma.morimoto@psy.ox.ac.uk*

Objects in real world scenes receive incident light from every direction, and the spectral content of this light may vary from one direction to another. Such a situation can be simulated in computer graphics using environmental illumination maps, which at each pixel store the intensity of incident light from a particular direction towards a single point in the scene. However, to-date, environmental illumination databases include only three-channel (RGB) data. Consequently, the effect of environmental illumination on human colour vision has been studied little.

We have recorded a novel set of hyperspectral environmental illumination maps to (a) measure and characterize natural variation in directional illumination, (b) allow more precise optical simulation in computer-generated scenes, and (c) understand more about surface colour perception in natural environments. We imaged a mirror sphere using a hyperspectral imaging system (Hamamatsu, model C4742-95-12ER) that has 1344×1024 spatial resolution and 12-bit intensity resolution. The image of the mirror sphere was taken from 4 different angles, separated by 90 degrees, while keeping the distance between the camera and the sphere constant. The resultant images of the sphere were processed, unwrapped and stitched together, to create a full panorama illumination map of 7 outdoor and 6 indoor scenes in Braga, Portugal.

First, we found that the chromatic distribution of all illuminations in the map extended along and around the daylight locus for all acquired scenes. More importantly, it was revealed that there is significant directional spectral variation within an environment. For outdoor scenes, lights from above tend to have high intensity of a few thousand cd/m<sup>2</sup> and high energy around the short-wavelength region. In contrast, lights reflected back from the ground and other objects tend to have one log unit lower luminance and lower correlated colour temperature. For indoor scenes, spectra tend to be much more uniform across angle of incidence.

The prevalence of metamerism for natural reflectance spectra has typically been evaluated by considering surfaces that are uniformly illuminated with single-spectrum illumination. The measured spectral variation with direction might allow the visual system to break some metamers using spectral variation in the lighting environment. There are two scenarios for this. Firstly, for a pair of spatially extended three-dimensional surfaces, directional variation in incident illumination means that complete surface metamerism is unlikely because different parts of the surface will sample different illuminants. Secondly, changes in viewing geometry, either a change in viewpoint or a change in the angle of the surface within the scene, will change the set of lights that are reflected to the observer from the objects' surfaces and this might also disambiguate the metameric matches. An analysis of the number of metameric pairs drawn from a large database of 114,120 reflectances revealed that more than half of the metameric pairs calculated under a traditional single-spectrum environment are disambiguated in real illumination, either by spatial variation across an extended surface or changes in viewing geometry. Combining novel light-measurement data with computer-graphics rendering techniques has provided a new insight into metamerism under real-world illumination.

**MATERIAL QUALITIES, IMAGE STATISTICS, AND VISUAL FEATURES OF COATED METAL SURFACES****Joshua Harvey and Hannah E Smithson**

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Unlike other visual features, such as the reddening of ripening fruit, or the gloss of wettened surfaces, the human visual system did not evolve in an ecosystem of metallic stimuli. Nonetheless, we are highly accurate in our assessment of metal objects from vision alone. We present experimental data and modelling that sheds light on what drives the percept of metallicity—the quality of appearance that suggests an object is made from metal. With computer-graphics stimuli, hyperspectrally rendered in a physically plausible manner, and presented on a calibrated CRT display, we use a conjoint-measurement experimental paradigm to unpick the contributions made by qualities both of a metal object and its transparent coating to the perception of metallicity. First, we performed a maximum likelihood difference scaling (MLDS) experiment to obtain perceptually even gradations for the parameters of metal roughness and coating bumpiness ( $N = 5$ ). Then, we ran a maximum likelihood conjoint measurement (MLCM) experiment, with observers comparing objects across five roughness levels, five coating bumpiness levels, and eight possible viewing angles, deciding which object was more likely to be made of metal ( $N = 5$ ). With all possible non-overlapping pair comparisons, repeated four times, each observer responded to 1300 trials. We find that observers' judgements of metallicity are affected by metal roughness, in keeping with previous studies (Todd and Norman, 2018), but that coating bumpiness also has a statistically significant effect. Fourier and steerable pyramid analyses show that both physical parameters of the stimulus space have predictable effects on image statistics, most notably on higher-order statistics not represented in the Fourier power spectrum. For coating bumpiness, the linear filter activations at certain spatial scales correlate well for objects of the same viewing angle (for level 1,  $R$ -squared = 0.968) but poorly across all viewing angles (for level 1,  $R$ -squared = 0.336). However, linear combinations of activations at different spatial scales correlate well with the parameter level across all viewing angles ( $R$ -squared = 0.837). This suggests a level of viewing angle invariance, or material constancy, is attained. Decision-making models that incorporate these statistics exhibit results conforming to those of the observers, as do estimates of global contrast including RMS and a nonlinear gain control measure (Meese et al., 2017). We conclude that metallicity is not a simple case of estimating surface roughness, which is well-represented in Fourier power spectra, but is more akin to estimations of global contrast.

**MAPPING COLOUR NAMES IN CONE EXCITATION SPACE****Dimitris Mylonas, Lewis D Griffin and Andrew Stockman**

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The recent establishment of the physiologically-based colour matching functions (CIE 170-1:2006) provides a good determination of the cone excitation space but its relationship to higher-order mechanisms of colour appearance remains elusive.

In this study, we determined the location of colour names within LMS space (Stockman & Sharpe, 2000) through an unconstrained colour naming experiment of 600 simulated samples of the Munsell system on a calibrated CRT monitor. Test stimuli were 2 degrees of visual diameter uniformly coloured discs with a black outline presented against a neutral grey background (CIE 1931,  $x=0.3126$ ,  $y=0.3296$ ). The task of the observers was to name out loud the colour of each stimulus. Ten English speakers offered in total 7,400 naming responses. Four of the observers repeated the experiment and 62% of their responses were consistent between the first and second presentation.

In the naming responses, 52% of the data included single terms, 40% two-word and 8% three-word descriptions. The Basic Colour Terms (BCTs) black, grey, white, red, orange, yellow, green, blue, purple, pink and brown (Berlin & Kay, 1969) occurred in 35% of the responses. We compared location of centroids for the BCTs estimated in this study with the centroids obtained in an uncalibrated online experiment (Mylonas & MacDonald, 2010) and earlier laboratory-based studies (Boynton & Olson, 1987; Sturges & Whitfield, 1995). There was a good correspondence between the four datasets with the smallest differences observed against the online data (mean  $\Delta E_{00}=4.58$  /  $\Delta E_{ab}=7.30$ ). A comparison ( $\Delta E_{ab}=14.61$ ) of BCTs loci against a set of imaginary colour naming systems simulated with a k-means routine showed that perceptual structure embedded in the stimuli set alone cannot explain the agreement with the online data.

We identified the best examples, called focal colours, of lexical colour categories for three levels of consensus. Only black, white and orange were used with 100% consensus. In the second level of  $\geq 75\%$ , we found all eleven BCTs plus cream. In the lowest level ( $\geq 50\%$ ), we found eight additional names: turquoise, lilac, magenta, aubergine, lime green, and the dark modifiers of blue, green and brown. Overall focal colours were more saturated than centroids. The landmark colour names usually associated with unique hues, red and green were not colinear with white in the cone chromaticity diagram but yellow was colinear through white with blue. Red was colinear with turquoise and green with magenta. Except for blue, there was a good correspondence of the landmark colour names with the location of unique hue settings in CIE ( $u',v'$ ) space (Xiao et al., 2011).

To generalize our observations from the 600 stimuli used in the experiment to the entire 3D gamut of the CRT monitor in cone excitation space, we employed a Maximum a Posteriori estimator (Mylonas et al., 2010). The regions with the highest purity of L, M and S cone excitations were assigned to red, green and blue colour names respectively. The curvature of name borders raises questions about the form of cognitive categories in cone excitation space (Cao et al., 2005).

**WHAT DO BRIGHT, LIGHT AND DARK MEAN? THE MEANINGS OF COMMON COLOR MODIFIERS IN A CROSS-LINGUISTIC PERSPECTIVE****David Bimler<sup>1</sup> and Mari Uusküla<sup>2</sup>**<sup>1</sup> Massey University, New Zealand<sup>2</sup> Tallinn University, Estonia*Corresponding author: d.bimler@massey.ac.nz*

There is a long tradition in color research of collecting unconstrained descriptions of standardized color stimuli, to determine the denotata of a given color term: what members of a language community collectively mean when they use it. When participants modify terms with words like (English) 'bright', 'pale', 'dark', 'light' (or equivalents in other languages), to narrow their scope and increase their precision, it is unclear what they mean by these qualifiers, or how well they translate between languages. Thus many studies ignore the qualifiers and pool extended descriptions with uses of the unqualified form. Here we extend the empirical approach (Davies & Corbett, 1995) by examining denotative ranges: treating the uses of a modified term as a distribution across stimulus-points in a metric color space, for comparison with the distribution of the unmodified term. We draw on a multi-language corpus of color-naming data for 65 ColorAid-Corporation tiles. A previous study estimated the focals for each color category (Uusküla & Bimler, 2016); here we concentrate on modified versions of basic color terms. Circum-Baltic languages are of special interest, though Hungarian, Czech, and the Romance languages Spanish and Italian also provide examples. Significant numbers of Estonian, Finnish, Latvian and Lithuanian responses took the forms 'ere-X' or 'erk-X'; 'kirrkaan- / kirkas-X'; 'spilgti-X'; and 'ryški- / ryškiai-X' respectively, often glossed as 'bright-X'. Some modifiers narrow the focus of the distribution but the centroid is the same, suggesting a meaning of 'true- / prototypal-X'. In other cases, the modifier shifts the centroid to focus on greater saturation, or simply to shift the luminance ('light- / dark-X'). The context-specificity of modifiers (which includes incompatibility with some terms) underscores the need to analyse modified and unmodified terms separately when the basic term inventory of a language is at issue.

**COLOUR CATEGORIES IN SHORT WAVELENGTH SPECTRUM AMONG LATVIAN AND RUSSIAN MONO AND BILINGUALS****Renārs Trukša, Samanta Gabrāne, Katrīna Lazdāne, Sergejs Fomins and Gunta Krūmiņa**

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There are eleven Basic Colour Terms introduced by Kay & Berlin which divide colour gamut into eleven categories. This is also true for Latvian speaking people.

However, in some languages like Russian and Italian, 12 colour categories could be distinguished, devoted for the part of short wavelength spectrum.

One of the arguments in favour of legitimacy of additional colour category, is that both colour categories are used when referring to different objects. It seems that main differences between colour categories *sinij* (dark blue) and *goluboj* (light blue) are within lightness axis.

The situation resembles two other colour categories brown and yellow, which mainly differ by their lightness. This could be a case in reference to *sinij* and *goluboj* colour categories.

In scope of this study we estimate the language background on colour categorization in short wavelength spectrum. The computerized method if developed to identify borders of colour categories in short wave part of spectra. To research language effects on colour categorization in short wavelength spectrum, colour category boundaries among Latvian and Russian monolinguals, and Latvian-Russian bilinguals where measured.

The questionnaire was applied to identify the proficiency and group identity of mono- and bilinguals. All participants were female students of University of Latvia. In current design stimuli correspond to Munsell hue values of 2.5 BG, 5BG, 7.5 BG, 10BG, 2.5B, 5B, 7.5B, 10B and chroma values of 8, 12, and 16.

Preliminary results indicate vastly different and variable responses for hues under revision. However, all subjects have clear distinction of *sinij* and *goluboj* colour categories within the brightness axis, as also clear bottom and top limits. 53% of colour deficient subjects, some with severe RG loss, pass the D15 test when up to two adjacent transpositions are accepted as a pass. Whilst the D15 test is normally used to test for severe colour deficiency, subjects with severe loss can still use combined, residual RG and YB signals to pass the D15 test.

**RELATIONSHIP BETWEEN SEMANTIC WORDS AND COLOUR IMPRESSIONS FOR NORMAL AND COLOUR DEFICIENT OBSERVERS****Keizo Shinomori<sup>1</sup>, Honami Komatsu<sup>2</sup> and Ipppei Negishi<sup>3</sup>**<sup>1</sup> School of Information, Kochi University of Technology, Japan<sup>2</sup> Graduate School of Engineering, Kochi University of Technology, Japan<sup>3</sup> Department of Media Informatics, Kanazawa Institute of Technology, Japan*Corresponding author: shinomori.keizo@kochi-tech.ac.jp*

We showed (Shinomori, & Komatsu, 2018) that impressions of nine semantic words expressing abstract meanings (like "tranquil") can be expressed by twelve hues (vivid colours in PCCS) in a paired comparison method (Exp.1). Colour impressions were also estimated by a set of 35 semantic words by a semantic differential (SD) method (Exp.2). The word impressions expressed by hue were described by selection rates of colours and analysed by principal component analysis (PCA); a 2D distribution of the first and second principal component (PC) loadings revealed how the set of hues was structured to express all word impressions; a 2D distribution of the first and second PC values showed the structural relationship between words when evaluated by hues. From the SD method data, a 2D word distribution as loadings and a 2D colour distribution as values were obtained. Since the relationship between words and colours were measured twice in reverse directions, differences between the two distributions of the words or colours indicate the stability and appropriateness of the word-colour relationship.

In this study white, grey and black were added to the previous colour set. Ten colour-normal and six colour-deficient observers participated (one protanope, three deuteranopes, one protanomalous-, and two deuteranomalous-observers). Results of Exp.1 on colour-normals are similar to the data from our previous study. In results for deuteranopes, the positions of reddish or greenish hues in colour distribution either converged, or were not on the ellipse. For anomalous observers, all colours were on the ellipse and reddish-purple and green were in antagonistic position; however, three reddish or greenish warm colours converged to yellow, and two greenish cold colours almost converged to blue. Results of the word distribution in Exp.1 on colour-normals showed that nine words were categorized in four groups; the most selected colour for one word in one category was the same or close, as expected from PCA. In the word distribution of colour-deficients, since second PC values tended to be smaller, the categorization of the words was not necessarily clear, corresponding to the tendency that the same colour (yellow) was mostly selected for different words. In the word distribution of Exp.2 on colour-deficients, words converged to one half of the word circle, and "deserted" was only the word on the other half, meaning that, except for "deserted", the structure of the words for colour evaluation can be sufficiently expressed in one-dimension; this caused the colour distributions to not be the same shape as the hue circle.

Overall, for colour-deficients the difficulty of red- and green-chromatic perception influenced the word impression expressed by hue. Although it was expected that colour-deficients would use blue, yellow and neutral colours more frequently, the results suggest that they tend not to use a variety of colours to express semantic meanings (as the win-loss ratios were not very different between colours). This means that the number of perceived hues was not sufficient to express abstract meanings for colour-deficients; brightness and saturation may have more important roles for that purpose than it does for colour-normal observers.

TUESDAY 9<sup>th</sup> JULY

**GROUPING AMBIGUOUS NEURAL REPRESENTATIONS: ARE THEY DRIVEN BY CHROMATICITY (THE STIMULUS) OR BY COLOR (THE PERCEPT)?****Emily Slezak and Steven K Shevell**

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Several separate stimulus areas, each with the same ambiguous chromatic neural representation, are all resolved to the identical perceived color far more often than chance (Kovács, Papathomas, Yang, & Fehér, 1996; Slezak & Shevell, 2018). This reveals that the areas are linked (or “grouped”), but it is unclear whether they are linked because each one has the identical competing representations of the same stimuli (that is, same chromaticities) or, alternatively, identical competing representations of the same colors one sees. Chromaticity and color in each area have been completely confounded in previous work. The current study uses strong chromatic induction (as in Monnier & Shevell, 2003) to disentangle whether grouping depends on identical (though ambiguous) stimulus chromaticities or perceived hues by [1] inducing one chromaticity to appear two different colors or [2] inducing two different chromaticities to appear the same color. **METHODS** All stimuli were gratings with chromatic inducing and test fields at 3.3 cycles/degree. The inducing chromaticities were [L/(L+M),S/(L+M)] of [0.665,2.0], called “violet,” and [0.665,0.16], called “lime.” The test fields were [0.62,1.0], called “green,” and [0.71,1.0], called “red.” Three observers were tested. First, each observer completed color matches to measure induced color-appearance shifts. Second, the observer completed grouping measurements using interocular-switch rivalry, a method with rivalrous dichoptic images swapped between the eyes at 3.75 Hz (Christiansen, D’Antona, & Shevell, 2017). Each of two separate areas, one above and one below fixation, had dichoptic rivalry between “green” and “red”, but with various S/(L+M) values determined by the condition and individual observer color matches. Four conditions were tested: top and bottom areas with [1] the same (confounded) color appearance and chromaticities (a control), [2] the same color appearance but different chromaticities (same-color condition), [3] different color appearances but the same chromaticities (same-chromaticity condition), or [4] different color appearances and different chromaticities (both-different condition). Observers reported via gamepad buttons “grouped” percepts when both areas above and below fixation appeared the same color (conditions [1] and [2]); the colors associated with the same chromaticity (but different in appearance; condition [3]); or different colors derived from color matches made to identical chromaticities with opposite induction (different in both color appearance and chromaticity; condition [4]). Grouping of the areas above and below fixation would be supported if these percepts were reported reliably more often than chance (calculated from probability theory using measurements of percepts for the top or bottom area presented alone). **RESULTS/CONCLUSIONS** All conditions showed significant grouping for every observer, meaning that both areas were perceptually linked (“grouped”) regardless of color appearance and/or chromaticity differences. Moreover, there was no significant effect of same chromaticity versus same color for any observer. This is consistent with only L contributing to grouping as the relative L- to M-cone excitation ratio always was matched in the areas above and below fixation.

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**GROUPING FROM RIVALROUS COLOR AND FORM****Andrew Coia and Steven K Shevell**

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Our ability to accurately parse elements of a visual scene and group together fragments of a single but partially occluded object is critical for visual perception. Here, color vision is used as a model system to better understand how fragments are grouped. The current study tests how the visual system simultaneously uses color and form to create an integrated percept. Common color and form collectively are thought to enhance perceptual grouping of multiple binocularly rivalrous regions compared to either one of these features alone (Papathomas, Kovacs, & Conway, 2005; Kim and Blake, 2007). The current study re-examines this question with a paradigm that eliminates monocular perceptual dominance during rivalry. The results reveal an alternative to enhanced grouping with a conjunction of features (color and form).

**STIMULI:** Four separate equiluminant patterns were presented, one above and one below fixation to the left eye and right eye. Stimuli were presented using chromatic interocular-switch rivalry (CISR), in which the stimuli in each eye were swapped with each other several times each second. CISR generates percepts similar to those of standard binocular rivalry with a sustained percept often persisting for two seconds or longer (Christiansen et al., JOV, 2017). Dichoptic gratings always were presented orthogonally (so were rivalrous in orientation) and also were rivalrous in spatial frequency (2 or 5 cpd gratings) and chromaticity (appearing as red/gray or green/gray gratings). In one condition the rivalrous stimuli above and below fixation shared the same chromaticity, orientation and spatial frequency feature conjunctions. In other conditions, chromaticity was 'mismatched' above and below fixation, so grouping by common chromaticity would result in seeing gratings above and below fixation of the same color but different frequencies and orientations. Similarly, grouping by common spatial frequency and orientation would result in perceiving different colors in the top and bottom gratings.

**PROCEDURE:** In separate trials, observers pressed buttons to report when the two patterns above and below fixation appeared the same color (both red or both green, regardless of spatial frequency) or the same spatial frequency regardless of color. The proportion of presentation time when the two gratings met the above criteria was compared to expected values if the features above and below fixation were perceptually resolved independently (determined from measurements of top and bottom dichoptic stimuli presented alone). Grouping would be supported if the total dominance time for seeing two regions as the same was greater than expected from independence. Importantly, results for each observer were analyzed separately.

**RESULTS & CONCLUSION:** As expected, perceptual grouping was most frequent with a conjunction of common feature values. Surprisingly, however, grouping in the mismatched conditions (mismatched color or mismatched spatial frequency) often was reduced for only one of the two features. One common feature alone, therefore, often was sufficient to drive grouping to the same level as both features in common. This questions the general view that color and form synergistically enhance common perceptual resolution of separate parts of the visual field.

**NOT ALL AMBIGUITIES ARE CREATED EQUALLY: DIFFERENTIAL GROUPING BY TYPE OF VISUAL AMBIGUITY****Sunny MS Lee, Emily Slezak and Steven K Shevell**

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When multiple visually ambiguous objects are presented, the ambiguity itself can act as a stimulus-level feature to group them together and form stable percepts. Even when ambiguous and unambiguous objects are presented together, the two types do not group; instead the ambiguous objects resolve independently as if the unambiguous objects were not present (Lee, Slezak, & Shevell, VSS 2018). Ambiguity can have different neural representations based on how it is induced, and it is unknown how groups will form when multiples of different types of representations are present. The present study investigated how multiple objects with different forms of ambiguity group based on their separate competing neural representations. Stimuli: Up to 8 chromatic discs were presented along a circular contour around fixation. The chromaticity of each disc was  $[L/(L+M), S/(L+M)]$  of  $[0.72, 0.3]$  (called "red"),  $[0.61, 0.3]$  (called "green"), or identical to the background which averaged the two chromaticities at  $[0.665, 0.3]$ .

Methods: Observers were presented multiple chromatic discs through a haploscope and reported whenever all discs in view were perceived as the same color. The discs could be unambiguous (same chromatic discs presented to each eye changed in chromaticity every 4 seconds to prevent adaptation), in interocular switch rivalry (ISR, dichoptic discs swapping between eyes at 3.75 Hz), or in standard binocular rivalry (BR, dichoptic discs changed in chromaticity every 4 seconds). Most stimulus displays of eight discs were of two types, with the ratio of the two types either equal or 7:1. Discs were presented in a "patchwork" format, such that the measured percepts were never presented monocularly. Five conditions were tested for each ratio: [#1] All discs in ISR, [#2] ISR discs + Unambiguous discs, [#3] ISR discs + BR discs, [#4] BR discs + Unambiguous discs, and [#5] ISR discs + Unambiguous discs where all discs alternated between "red", "green", or the background color at 3.75 Hz. [#5] controlled for concerns that ISR discs and unambiguous discs could be grouped separately due by the presence of flicker rather than their ambiguity.

Results/Conclusion: ISR discs did not group with unambiguous discs, even when flicker was introduced to the unambiguous discs in the control condition [#5]. ISR discs and BR discs also did not group. Each ambiguity type resolved as a separate group. This held true regardless of whether there was a single BR disc among 7 ISR discs or 4 of each type, with no significant difference between the two ratios. This is notable as the neural representation of BR discs likely has a greater eye-of-origin representation, but due to the "patchwork" presentations, they had to be resolved at the binocular level like the ISR discs. Individual variability was observed when BR discs were presented with unambiguous discs. Overall, different ambiguity types indeed form separate competing neural representations, and further do not interact with unambiguous color percepts.

**HELIX ROTATION: A NEW TWIST ON PULFRICH AND HESS FOR INVESTIGATING COLOR AND DEPTH PERCEPTION IN VIRTUAL REALITY****Arthur G Shapiro, Anthony Loprete and Lily Donaldson**

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Since Virtual Reality (VR) and Augmented Reality (AR) displays have become increasingly common methods for image presentation, it is important to understand the effects of color and contrast in these environments and to understand whether the new technology can be exploited to reveal new aspects of how we perceive color. In both AR and VR, the perception of a third dimension is typically created by binocularly fusing images that simulate the perspective of each eye; depth is conveyed primarily through a combination of binocular disparity and monocular pictorial cues. However, the visual system can also create depth from differences in monocular adaptation (Pulfrich, 1922) and local contrast (Hess, 1904). To better investigate how monocular adaptation and local contrast affect the perception of depth in VR and AR environments, we have created a stimulus consisting of 20 dots equally spaced along the central Y axis; the dots move sinusoidally back and forth in time along the x-axis and are offset from each other in temporal phase (see <https://bit.ly/2O5cTrr>). We demonstrate that differences in monocular adaptation levels and differences in local contrast can make the dots appear to be a three-dimensional helix rotating around the central Y axis. We present a series of demonstrations and experiments that illustrate the utility of this stimulus for investigating depth cues in VR environments.

1. Basic Pulfrich effect: the perceived direction of 3-dimensional spin depends upon differences in monocular adaptation.
2. Depth depends on the relative speed: background elements recede into the virtual depth plane based on their speed in relation to the elements of the helix.
3. Separation of low spatial frequency and high frequency motion: we show that blurring the helical image creates the perception of vertical motion that was present in the unblurred image; thus we show that even though low spatial frequency motion energy is always present, it is often not perceptually salient in the presence of other high spatial frequency content.
4. The perceived longitudinal vs transverse wave motion depends on the spacing of the elements; i.e., when the elements of the helix are close together, the perception of the third dimension (and the transverse) motion disappears; so, even though the elements maintain the same motion paths, these motion signals do not always register this motion as a shift in virtual depth.
5. Changes in local luminance contrast can create the appearance of the 3D rotation; i.e., Hess (1920) showed that contrast can affect the perceived speed. This change in speed can lead to directional shifts in the helices, similar to the Pulfrich effect.
6. In general, rotational changes from unequal eye luminance (Pulfrich) override the rotational changes produced from local contrast (Hess). The results show that the effects of local adaptation and local contrast, as well as the interaction of high and low spatial frequency motion, are important for the creation of depth in VR displays.

**INVERTED HELMHOLTZ-KOHLRAUSCH EFFECT IN FACIAL IMAGES****Katsuaki Sakata<sup>1</sup> and Hitomi Shimakura<sup>2</sup>**<sup>1</sup>Joshi University of Art and Design, Japan<sup>2</sup>Shiseido Global Innovation Center, Japan*Corresponding author: sakata00031@venus.joshi.jp*

Some studies have suggested that our perception of facial images exhibits unique characteristics. For example, the visual sensitivities for redness and yellowness of facial tones are greater than those for colour patches (Tan & Stephen, 2013), and emotion can be efficiently transmitted by the perception of facial colour (Benitez-Quiro, Srinivasan, & Martinez, 2018). Other studies have reported that facial lightness can often be confused with facial brightness; we confirmed the uniqueness of facial colour perception in this study.

We measured the saturation effect on brightness, also known as the Helmholtz-Kohlrausch effect, of facial and uniform stimuli. Twenty one participants observed a pair of stimuli for 500 ms, followed by 500 ms of a random pattern mask; these stimuli were measured for brightness via the 2AFC method. For the face stimuli, the hue was  $h_{ab} = 60$  and the saturation was  $C^*_{ab} = 20$  in a CIE  $L^*a^*b^*$  colour space, which were determined to be the levels of the average Japanese female face (Kikuchi et al., 2018). Two variations of the saturation stimuli, higher ( $C^*_{ab} = 22$ ) and lower ( $C^*_{ab} = 18$ ), were also adopted for the same hue. The uniform colour patches had five variations in hue ( $h_{ab} = 0, 60, 90, 180, 270$ ), and the saturations were the same as those used for the face stimuli. The choice ratio was calculated from the observers' responses, and the psychological distance was calculated using the Thurstone's Case V scaling technique. We observed an increase of brightness with the increase of saturation expressly in uniform colour patches for all hues, i.e., the H-K effect. On the other hand, however, for the face stimuli, we observed the inverted H-K effect, i.e., the brightness of facial images increased with decreasing saturation at any saturation of three steps.

The results of this study allow us to make mechanistic hypotheses, and one of which was that our colour brightness perception was affected differently from uniform colour patches in facial images involving contrasts and gradations of colour. However, this idea was found to be questionable in previous findings regarding the H-K effect in images of natural scenery (Shizume, Ohashi, Takamatsu, & Shimodaira, 2014). The other explanation of this phenomenon is that we see brightness diversely depending on the stimuli and that face colour perception illustrates one of the unique characteristics of our visual mechanisms. In addition, this idea also involves the suggestion that the H-K effect is affected by the recognition of stimuli, i.e., the result of our higher order processing.

**SATURATED COLOURS FOUND IN NATURAL SCENES CAN DEGRADE COLOUR CONSTANCY****David Foster<sup>1</sup> and Adam Reeves<sup>2</sup>**<sup>1</sup>The University of Manchester, United Kingdom<sup>2</sup>Northeastern University, United States*Corresponding author: d.h.foster@manchester.ac.uk*

Surfaces with saturated colours offer ambiguous support for colour constancy. Although their reflected spectra remain largely invariant under changes in illuminant, the spectra reflected from non-saturated surfaces do vary. Potentially inconsistent changes in colour appearance can therefore occur across scenes. But are saturated colours sufficiently common in the natural environment for inconsistency to be a problem? In computational simulations, reflected spectra were calculated from a set of 50 hyperspectral reflectance images of natural scenes under two successive daylight illuminants corresponding to skylight and sunlight with correlated colour temperatures of 25000 K and 4000 K respectively. Changes in colour appearance of individual surfaces were calculated after application of chromatic adaptation transforms based on von Kries scaling. The sizes of residual colour and lightness differences correlated with the CIE chroma of surfaces and CIE saturation ( $r = 0.5-0.7$ ). Knowing the chroma almost halved both residual color and lightness differences. Whether human observers can use chroma to better judge constancy is unknown.

**SPATIAL COLOR CHANNELS AND THEIR ROLE IN COLOR CONSTANCY****Laysa Hedjar<sup>1</sup>, Wenyan Bi<sup>1</sup> and Arthur G Shapiro<sup>2</sup>**<sup>1</sup> Behavior, Cognition, and Neuroscience Program, American University, United States<sup>2</sup> Departments of Psychology and Computer Science, American University, United States*Corresponding author: lh1976a@american.edu*

The human visual system is capable of perceiving an object's intrinsic color as constant across various illuminations. Many recent color constancy theories invoke higher-order processing to explain this phenomenon, while less weight is given to low-level processes. However, we know that at least two types of color cells in V1 respond at different spatial scales and seem to subserve different visual functions (Conway et al., 2010; Johnson, Hawken, & Shapley, 2008). Here, following up on previous work, we investigated the extent to which separate color systems based on spatial information can account for some color constancy phenomena. We hypothesized that information about object color is carried in a relatively high spatial frequency (SF) channel, while information about illumination color is carried in a relatively low SF channel. Images of paintings were separated into high and low SF color components (S, L-M and Lum). The gamut of either the high or low SF component was then rotated multiple points around the achromatic axis in LUV space (altering the chromaticity) and recombined with the remaining original low or high SF component. Observers were asked to rank the images based on the amount of red, green, yellow, or blue they judged to be contained in either a preselected object in the scene or the overall illumination in the scene for all rotated images. The images were ranked based on the amount of, for example, 'redness' within the object/illumination. Both high and low SF-rotated images were ranked for each color and object/illumination. Observations of the transformed images show that object color judgments spanned a greater range (e.g., various degrees of 'redness' across the images) when observers made them for the high SF-rotated images than the low SF-rotated images. Appearance of object colors across hues also varied much more for the high SF-rotated images. Comparisons of illumination judgments between high and low SF-rotated images were more similar. A series of experiments will examine the variation and range of object/illumination colors observers perceived between the low and high SF-rotated images, and whether we could optimize the separation of object and illumination color by varying our filtering parameters.

**DIFFERENTIAL IPRGC STIMULATION OF COLORED STIMULI INFLUENCES PERCEPTION OF BRIGHTNESS IN A SPATIAL 2AFC TASK****Tanner DeLawyer<sup>1</sup>, Sei-Ichi Tsujimura<sup>2</sup> and Keizo Shinomori<sup>2</sup>**<sup>1</sup> School of Information, Kochi University of Technology, Japan<sup>2</sup> School of Design and Architecture, Nagoya City University, Japan*Corresponding author: delawyer.tanner@kochi-tech.ac.jp*

We measured the perceived brightness of chromatic stimuli viewed through an artificial pupil with controlled levels of intrinsically-photosensitive Retinal Ganglion Cell (ipRGC) stimulation using a spatial two-alternative forced choice (2AFC) task in which observers selected which of two simultaneously presented stimuli was perceptually brighter. These stimuli were varied in regards to their chromaticity, luminance, and ipRGC stimulation level. By combining the effects of hue with ipRGC activity we can develop insight into the potential visual pathways ipRGC information is integrated with.

The stimuli were created using a series of 3 projectors capable of producing very high luminance stimuli (over 1000 cd/m<sup>2</sup>) that had filters applied in order to reduce the wavelength spectrum of each projector. This allowed us to create a set of stimuli with identical CIE chromaticity coordinates and luminance, but differing levels of ipRGC stimulation. Stimuli were viewed through a 2-mm artificial pupil and had a presentation duration of .25 or 2 s with a 2 s black screen intertrial interval. The stimuli were randomly presented on either the left or right side of a small black gap with a 2.5° diameter black-circle occupying the central position. The stimuli also had their luminance modulated by up to 20% in order to compare the relative contributions of ipRGC stimulation on brightness perception.

We found a main effect for ipRGC stimulation, such that higher ipRGC stimulation predicts greater perceived brightness. This is in concordance with previous findings using different methodology that suggest a role for ipRGC activity in perceived brightness (Brown et al., 2012). We have also found evidence for an interaction between ipRGC stimulation and chromaticity on brightness such that the chromaticity of a stimulus can act as a moderating variable on the degree to which the amount of ipRGC stimulation influences brightness perception. This follows previous data showing brightness perception is moderated by chromaticity (Lotto & Purves, 1999). Interestingly, we did not see a significant effect of duration (.25 versus 2 s presentation), despite the relatively long time-course of most ipRGC cells in terms of physiology (Barrionuevo et al., 2014). This suggests the possibility that the effect observed here is processed in either shorter time-course ipRGC cells, or is due to a confounding process such as penumbral cone activation.

The presence of an ipRGC stimulation effect on brightness for stimuli of all tested hues suggests it is a global effect and not limited to a subset of chromatic channels. However, the degree to which the ipRGC contribution to brightness perception is independent from hue and saturation contributions to brightness is currently being investigated (as ipRGC stimulation could also contribute to changes in perceived hue and saturation which in turn would change the perceived brightness of a stimulus).

**ASSESSING THE EFFECTIVENESS OF A MELANOPSIN-BASED SIGNAL FOR COLOUR CONSTANCY****Daniel Garside and Lindsay MacDonald**

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Melanopsin is expressed by ipRGCs, which are known to play a role in the entrainment of the circadian rhythm (Berson, Dunn, & Takao 2002) and in control of pupil diameter (Lucas, Douglas, and Foster 2001). Whilst their influence is traditionally thought to be limited to non-image-forming pathways, there is increasing evidence for a role in image-forming-, and specifically colour-, vision (Spitschan, Bock, Ryan, Frazzetta, Brainard, & Aguirre et al., 2017; Cao, Chang, & Gai 2018; Zele, Feigl, Adhikari, Maynard, & Cao, 2018). The spatial and temporal qualities of ipRGCs are broader and slower than other retinal cell types; both desirable qualities for a signal involved in recovering the illuminant upon a scene.

Additionally, the distinct spectral profile and spatial configuration (providing a secondary mesh across the retina) might provide a signal which would allow for point-wise colour constancy transformation, without relying on scene-level properties such as those employed in algorithms based on a 'grey-world' assumption.

To explore this problem, spectral reflectance data of natural objects from the Vrhel+ dataset (Vrhel, Gershon, and Iwan, 1994), spectral power distributions from the Hernández-Andrés+ dataset (Hernández-Andrés, Romero, Nieves, & Lee, 2001), and the CIE 2006 10-deg cone fundamentals (CIE 2006), were used to compute chromaticity co-ordinates for a large number of feasible natural colour signals in MB space. The Lucas+ melanopsin fundamental (Lucas et al., 2014) was used to compute analogous melanopic values.

An optimally performing colour constancy algorithm was defined as one which re-mapped sparse chromaticity co-ordinates (representing multiple object reflectances under multiple illuminants) to the reduced set of chromaticity co-ordinates representing a set of intrinsic colours (term of (Shepard, 1992)) of the objects. Considering that a realistic performance would be sub-optimal (mapping points instead to a limited distribution surrounding an intrinsic colour), it becomes clear that a method for quantitatively assessing the performance of such an algorithm is required. Quantitative analysis of colour constancy algorithms is rare, with commentators instead focusing on assessing whether the assumptions/regularities required by each algorithm are present in the real world and whether they overly limit applicability (see (Hurlbert, 1998)). Forsyth (Forsyth, 1990) proposed a method whereby the clustering of points was measured by taking the median residual distance from an average chromaticity and normalising it by the Euclidean magnitude of the outputs.

Using this measurement, effectiveness of a melanopsin-based signal was compared to a basic 'grey-world' algorithm. It was found that both algorithms performed to a similar level of effectiveness, despite the fact that the grey-world algorithm requires a stable set of object reflectances, whereas the melanopsin-based algorithm can perform well even on a single unknown sample.

**MELANOPSIN ACTIVATION COULD ENHANCE COLOR CONSTANCY****Dingcai Cao, Clemente Paz-Filgueira and Michael Tan**

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Color constancy is a perceptual phenomenon in which the perceived color remains relatively invariant with changes in illumination. Color constancy requires chromatic adaptation that involves either retinal or higher order mechanisms. In retina, melanopsin-expressing intrinsically photosensitive retinal ganglion cells (ipRGCs), though rare, form an integrated network through their dendrites that may help to pool retinal neural signals. In this sense, melanopsin activation may affect chromatic adaptation through intraretinal signaling and thus help to achieve a better color constancy. To test this, we measured color constancy with illuminations that differ in melanopsin activations but have the same cone excitations.

The perceived color of a green chip ( $4.8^\circ \times 1.7^\circ$ ) in a Mondrian surface pattern ( $17.8^\circ \times 17.8^\circ$ ) was measured in a Haploscopic matching. The Mondrian was placed inside a four-primary Ganzfeld and was illuminated with a White [ $l=L/(L+M)=0.665$ ,  $s=S/(L+M)=1.0$ ], Red [ $l=L/(L+M)=0.738$ ,  $s=S/(L+M)=1.0$ ], Green [ $l=L/(L+M)=0.64$ ,  $s=S/(L+M)=1.0$ ], Blue [ $l=L/(L+M)=0.665$ ,  $s=S/(L+M)=1.5$ ] or Yellow [ $l=L/(L+M)=0.665$ ,  $s=S/(L+M)=0.5$ ] light (luminance  $\approx 1300$  cd/m<sup>2</sup>). For each illuminant color type, there were two melanopsin activation levels (Weber contrasts 9%-14%), but cone excitations were kept the same. Therefore, we had 10 total illuminant conditions (5 illumination colors  $\times$  2 melanopsin activation levels). The matching field (viewed by the left eye) was presented on a calibrated CRT. Observers were instructed to adjust the  $L/(L+M)$ ,  $S/(L+M)$ , and  $(L+M)$  to match the color of the green chip in the Mondrian (viewed by the right eye). The color constancy index was computed based on the CIE  $u' v'$  color space, with the White illuminant as the reference illuminant.

The results showed that for each illuminant color type, the higher melanopsin activation condition had lower matching  $L/(L+M)$  than the low melanopsin activation condition, and this color shift could not be predicted by the chromaticity difference in the test chip. Further, the high melanopsin activation condition had better color constancy index than the low melanopsin activation condition for the Green and Yellow illuminants but with worse constancy index for the Red illuminant. The color constancy for the Blue illuminant was very low, irrelevant to the melanopsin activation level.

Our results suggest that melanopsin activation contributes to color perception. Importantly, manipulation of melanopsin activation levels could help to achieve a better color constancy in a complex image with Green or Yellow illuminants.

## POSTERS

**VALIDITY OF VIRTUAL-REALITY-BASED SYSTEMS APPLIED TO LIGHTING AND COLOUR RENDERING RESEARCH****Pedro J Pardo, Halina C Cwierz, Francisco D Barrancas, Angel LP Rodriguez and Maria I Suero**

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In recent years, there has been a very important advance in graphic computing and technology related to the capture and representation of images in both 2 and 3 dimensions. One of these technologies is Virtual Reality (VR), whose advance is based on the great computing capacity of current graphic cards and the appearance of Head Mounted Displays (HMD) with an improved quality compared to pre-existing ones.

With this advance, opportunities arise for the use and application of these technologies to fields different from those previously established. One of these fields can be the research in colour vision. When computers appeared with different display devices: CRT first, TFT screens later and even video consoles, colour vision researchers quickly incorporated these devices into their laboratories. Something similar happens with the research in lighting and colour rendering, although in these cases in a more limited extent due to the added difficulty of the spatial 3D representation.

In order to incorporate VR devices into research tasks in colour vision, these systems must be previously validated by reproducing existing and well-known tests or techniques and by obtaining results in which there are no significant differences with the same test performed by traditional equipment.

The objective of this work is to perform the validation of these VR systems for research in colour vision and colour rendering of light sources. We made several comparative studies on the behaviour of this immersive 3D scene visualization systems. In particular, we have implemented a virtual version of a pseudoisochromatic test, a colour arrangement test and finally we have carried out a colour rendering test for several light sources.

To achieve the best results, we have included a colour management system in the virtual reality software that has allowed us to obtain a faithful reproduction of the colour when working with digital images. We have also implemented spectral computing algorithms that allow us to obtain a realistic colour visualization when changing light sources. Finally, we have created a method to capture 3D objects from the real world using a hyperspectral camera and applying photogrammetric techniques. In this way, we managed to introduce 3D objects in the virtual reality software with spectral texture that allowed us to perform psychophysical tests related to lighting and colour rendering.

The results of these three tests are diverse since they are very different in terms of complexity and standardization, but in all cases they have shown that there are not statistically significant differences between the real and virtual versions of the tests.

**NON-LINEAR COLOR ADDITIVITY IN TIME DOMAIN****Lin Shi**

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Linear color additivity laws were the foundation of colorimetry. In space domain, color additivity didn't depend on the order of additive color. It was thought that color additivity remained independently with the temporal order of additive color in time domain also. My experiment showed that identical screen frame sequences with various temporal order caused different color perception. A screen was divided into two parts by a black paper bar located at the vertical center line of the screen. Periodic frame sequences were presented synchronously at two halves of screen separately. For example, the frame sequence of left-half-screen was R, G, B, R, G, B, ..., while the frame sequence of right-half-screen was B, G, R, B, G, R, .... Observers were asked to judge whether two parts of screen were visually same or not. Both a non-FSC-LCD display and a CRT display were used in the experiment. Results showed that observers' judgement depended on the temporal order of frames. It suggested that color additivity depended on the temporal order of additive color. In other words, color additivity was non-linear in time domain.

**PROLAB: PERCEPTUALLY UNIFORM PROJECTIVE COLOUR COORDINATES SYSTEM****Ivan Konovalenko<sup>1,2</sup>, Anna Smagina<sup>1</sup>, Vladislav Kokhan<sup>1,2</sup> and Dmitry Nikolaev<sup>1,2</sup>**

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Various algorithms of technical colour vision (mostly related to colour constancy problem) operate in so called linear colour spaces which are obtained by linear mappings of the spectral power distribution space. This practice follows from the linearity of the underlying optical image formation model. In this work we appeal to redundancy of the mapping linearity requirement. Furthermore, we consider this requirement meaningless at least for the algorithms using linear regression, since, in such colour coordinate spaces as CIE XYZ, euclidean distance does not correlate well perceptual colour difference while the image noise is heteroscedastic. We propose the proLab projective mapping of the spectral power distribution space as a colour coordinate space which is more adequate for such algorithms. We show that euclidean distance in the proLab coordinate space provide even closer approximation of perceptual differences between colours rather in the CIE L\*a\*b\*. Also, the transition into proLab coordinates makes image noise more homoscedastic. In addition, we discuss how to construct colour coordinate systems balancing between preserving of submanifolds affine properties and accuracy in approximation of perceptual difference with euclidean distance.

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**PUPILLARY CHANGE DEPENDS ON STIMULUS DURATION AND LUMINANCE WHEN BLIND-SPOT IS STIMULATED WITH BLUE LIGHT****Tim Schilling<sup>1</sup>, Yeshwanth Seshadri<sup>1</sup>, Mojtaba Soltanlou<sup>2,3</sup> and Hamed Bahmani<sup>1,4</sup>**<sup>1</sup>Dopavision GmbH, Berlin, Germany<sup>2</sup>Department of Psychology, University of Tuebingen, Germany<sup>3</sup>LEAD Graduate School & Research Network, University of Tuebingen, Germany<sup>4</sup>Max Planck Institute for Biological Cybernetics, Tübingen, Germany*Corresponding author: schilling@dopavision.com*

**Introduction:** In the human visual field, there is a region known to be blind for conscious vision, called the blind-spot. The blind-spot corresponds to part of retina where retinal ganglion cells bundle through the optic disc to form the optic nerve. Since there are no cones and rods in the optic disc, no image is formed at that region and it is effectively a blind zone to the observer. Nevertheless, intrinsically photosensitive retinal ganglion cells (ipRGCs) can express melanopsin also at their axons up to the head of the optic nerve (Hattar, Liao, Takao, Berson, & Yau, 2002). It has been shown that pupil response could be modulated by duration and luminance when the retina was stimulated full-field (Park, Moura, Raza, Rhee, & Kardon, 2011). Here, we investigated whether duration and luminance of a blue light stimulus could also modulate pupil response, when applied locally on the blind-spot.

**Methods:** Pupil response was recorded in five adult participants. The right eye was covered with an eye patch and the left eye was recorded with an eye tracker (EyeLink 1000 Eye Tracking system, SR Research Ltd., Ottawa, Ontario, Canada), after the inbuilt calibration. The maximal pupil constriction, which followed the stimulus presentation, was expressed as pupillary change by dividing the amplitude by the pre-stimulus baseline, according to the standards in pupillography (Kelbsch et al., 2019). The stimulus consists of blue circular discs presented on the optic disc with varying stimulus Luminance (10, 5, and 1 cd/m<sup>2</sup>) and Duration (3000, 300, and 30 ms).

To calibrate the stimulus on the blind-spot, the participant looked at a fixation target and adjusted a disc on the screen to the position and radius of the blind-spot. The stimulus is on the blind-spot when the participant reports it as invisible.

The experiment was started with a 20 secs fixation phase. The stimulus presentation consists of 6 blue stimulus flashes, separated by 6 secs blank intertrial intervals.

**Results:** A repeated measure ANOVA revealed a significant main effect for Luminance ( $F(6,2) = 32.0, p < 0.001$ ) and Duration ( $F(6,2) = 10.8, p < 0.01$ ), but not for their interaction ( $F(12,4) = 2.1, p = 0.617$ ) for pupillary change. A Tukey corrected post-hoc test showed that pupillary change is higher in 10 and 5 cd/m<sup>2</sup> compared to 1 cd/m<sup>2</sup> ( $t(6) = -8.0, p < 0.001$ ;  $t(6) = -4.1, p = 0.020$ ) as well as in 10 compared to 5 cd/m<sup>2</sup> ( $t(6) = -3.92, p = 0.023$ ). Regarding Duration, a Tukey corrected post-hoc test showed that pupillary change is higher in 3000 ms compared to 30 ms ( $t(6) = -4.6, p = 0.011$ ). Furthermore, strong correlations between pupillary responses and both duration and luminance were observed ( $r^{(2)} > 0.83, p < 0.001$ ).

**Conclusion:** Additional to full-field (Park et al., 2011), we showed that pupillary response to blue light stimulation of the blind-spot depends on luminance and duration as well. These results suggest that excitability of melanopsin on the head of optic nerve is related to both duration and luminance.

**BLUE LIGHT-FILTERING IOLS VS NON-BLUE LIGHT-FILTERING IOLS: INFLUENCE OF DIFFERENT SPECTRAL POWER DISTRIBUTIONS (SPD)****Beatriz M Matesanz<sup>1</sup>, Eduardo G Vicente<sup>1</sup> and David Galarreta<sup>2</sup>**<sup>1</sup> Universidad de Valladolid, Spain<sup>2</sup> Hospital Clínico de Valladolid, Spain*Corresponding author: beatriz@opt.uva.es*

Cataracts surgery, with the subsequent implantation of an intraocular lens (IOL), allows old people to recover visual performance. Currently, there is a great controversy between yellow tinted and non-tinted IOLs. Most of the experiments performed compare photoreception and photoprotection after cataracts surgery between both IOLs (Mainster et al., 2010). Mesopic contrast does not show a significant influence of the yellow filter (Mayer et al., 2006). However, the influence on contrast threshold (CT) and reaction time (RT) of these two types of IOL with different spectral power distributions, has not been studied yet.

Eleven young subjects (control group) and twenty old subjects before and after cataract surgery (ten with a blue light-filtering IOL implanted and ten with a non-blue light-filtering IOLs), participated in the study. A two-channel Maxwellian view optical system was used to measure CTs and RTs with a high pressure sodium (HPS) lamp and a metal halide (MH) lamp, at 0.01 cd/m<sup>2</sup> background luminance and at 10° temporal retinal eccentricity.

Under these experimental conditions, mean CT is significantly influenced by the different transmittance conditions. Lower mean CT value is obtained for the control group and after surgery group with non-blue light-filtering IOL for MH lamp in comparison to HPS lamp. Concerning RT mean values, there is a tendency to decrease after surgery for both IOLs groups and for the two lamps. However, there is no evidence of the influence of the spectral composition in RT values for both IOLs groups.

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**FARNSWORTH D-15 MODEL PROPOSES SIGNIFICANT ROLE OF BLUE-YELLOW CHANNEL IN ANOMALOUS OBSERVERS****Sergejs Fomins, Renārs Trukša, Gunta Krūmiņa and Maris Ozolinsh**

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Recently, Schneck et al. (2014) showed that results of arrangement tests are age related and blue-yellow mechanism plays a substantial role in pass rates of D-15.

The pattern of responses could be analyzed in many ways to give one representative value. Even in case if illumination criteria is met non canonical response patterns are common. To understand the role of colour channels we propose a model to account for D-15 outcome in case of anomalous colour deficiencies. We compared the data from anomaloscope and PIC tests to Farnsworth D-15 to support our model's outcome. Performance of the virtual observer was modeled taking into account spectral data of samples under D65 illuminant and anomalous colour vision pigment curves. The procedure for sorting of caps was proposed on DKL colour space signals.

Proportions of blue-yellow, red-green and luminance signals were varied to find most compatible to assessment results.

According to our algorithm significant impact on the appearance of caps was drawn by information coming from blue-yellow channel and negligible from the luminance information. The model allows to explain over 3/4 of the response patterns for D-15.

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**MULTIPLICATIVE MODULATIONS IN HUE-SELECTIVE CELLS ENHANCE UNIQUE HUE REPRESENTATION****Paria Mehrani and John KT Robertson**

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Which region in the brain represents unique hues is a matter of debate among color vision researchers [1, 2]. Here, we introduce a hierarchical model inspired by neural mechanisms in the visual system for local hue representation and with computational simulations suggest that neurons in V4 and beyond have the capacity to encode unique hues. Our model builds a network of single-opponent color and hue-selective neurons that successfully encodes local hue. Our network differs from that of [3, 4] as it models neurons in each of LGN, V1, V2, and V4 areas and explicitly reveals how the contributions of each visual cortical area participating in the process can lead to a hue representation. Our network receives cone responses as input and achieves local hue encoding through gradually increasing nonlinearities in terms of cone inputs as observed by [5]. Specifically, single-opponent color LGN responses are obtained by linearly combining cone activation. In V1, half-wave rectification keeps tunings of these cells similar to those of LGN neurons as suggested by [6], while V1 cells become nonlinear in terms of cone inputs. In V2, in addition to single-opponent color cells, we propose employing neurons with multiplicative modulations. De Valois et al. [3] suggested that additive or subtractive modulation of cone-opponent cells with S-opponent cell responses rotates the cone-opponent axes to red-green and blue-yellow directions. Here, we achieved this rotation with multiplicative modulations of V1 L- and M-opponent cell activations with V1 S-opponent neuron responses. Multiplicative modulations of nonlinear V1 responses increase nonlinearities in cone input and allow for mixing of color channels. Furthermore, unlike additive and subtractive modulations with no notable impact on tuning bandwidths, multiplicative modulations decrease V2 tuning bandwidths. Finally, V4 responses are computed by linearly combining V2 activations with weights determined according to tuning peak distances of V2 cells to the desired V4 neuron tuning peak. Our experimental results indicate that multiplicatively modulated V2 cells play an important role in the representation of hues along intermediate directions in the MacLeod-Boynton diagram [7]. Similarly, these neurons have substantial input weights compared to single-opponent V2 cells to V4 neurons selective to unique green and blue hues. Moreover, we observed a gradual decrease in distance of tuning peaks to unique hue angles reported by [8] from our model LGN cells to V4 neurons. Our simulation results demonstrate that responses of our network neurons resemble those of biological color cells.

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**EFFECT OF CORRELATED COLOR TEMPERATURE OF ROAD LIGHTING'S LEDS ON MESOPIC VISUAL PERFORMANCE****Isabel Arranz, Eduardo G Vicente, Santiago Mar and Beatriz M Matesanz**

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Currently, streetlamps like sodium high pressure are being replaced by light emitting-diodes (LEDs). LEDs are energy-efficient, more long-lasting and lower maintenance is required. While people prefer light sources with low correlated color temperature (CCT), for walking or driving (Jin et al., 2015; Dong et al., 2017), there is not enough research on the influence of CCT on visual performance. The goal of this study is to quantify the effect of different CCTs on mesopic visual performance.

We used a two-channel four-primary photostimulator to measure contrast detection threshold (CT) and visual reaction time (RT). This device allows working with any of the XYZ coordinates of the CIE. Its versatility also allows you to select different or the same scotopic/photopic ratio (S/P-ratio) for the visual stimulus. Measurements were performed on three subjects with experience in visual psychophysics and with normal vision. The stimulus that was positioned at 10° temporal eccentricity consisted on a 2° circular center and a 10° equiluminant surround. Data were collected from different CCTs, ranging from 1870 to 6350 K at a background luminance of 0.1 cd/m<sup>2</sup>.

The preliminary results of this study will be reported in this meeting. First outcomes show that, while contrast threshold increases with higher CCTs, reaction time seems not to be influenced by changes in this parameter. These results suggest that CCT influences visual performance in varying degrees depending on the visual task.

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**SEEING FRUIT ON TREES: AMPLIFIED PERCEPTUAL DIFFERENCES FROM AMBIGUOUS NEURAL REPRESENTATIONS****Jaelyn Peiso and Steven K Shevell**

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**PURPOSE** Our visual system normally constructs a meaningful and unambiguous representation of the world. This representation gives perceivers the ability to act on the world and the objects within it. If the visual system has two or more possible interpretations of the same region of space, neural responses usually result in perceptual dominance of one interpretation. Grouping processes aid in the resolution of ambiguity caused by two or more spatially separate ambiguous representations. Can a grouping process act on competing representations when they rival on different feature dimensions (e.g., one with only ambiguous orientation and another with only ambiguous chromaticity)? **METHODS** Two separate gratings were made ambiguous by rivalry of two features, orientation (i.e., 45° or 135°) and chromaticity (i.e., one appearing green and the other red), to determine if grouping processes can act across ambiguity of different rivalrous features. Four observers viewed 1.5° dichoptic equiluminant chromatic square-wave 4-cpd gratings presented in interocular-switch rivalry, swapped at 3.75 Hz (Christiansen et al., 2017). The rivaling chromaticities were set at Macleod-Boynton chromaticity coordinates [L/(L+M), S/(L+M)] of [0.62, 1.00], referred to as “green”, and [0.71, 1.00], referred to as “red”. Each trial had two separate perceived gratings, one above and one below fixation, with one of the gratings rivaling in only orientation (e.g., green-45° and green-135°) and the other in only chromaticity (e.g., green-45° and red-45°). Observers reported four possible percepts using button presses: top and bottom gratings identical in only color (e.g., green-45° and green-135°), top and bottom gratings identical in only orientation (e.g., green-45° and red-45°), top and bottom gratings identical in both color and orientation (e.g., green-45° and green-45°), and top and bottom gratings different in both color and orientation (e.g., red-45° and green-135°).

**RESULTS** All four observers perceived the two gratings (above and below fixation) different in both color and orientation (e.g., green-45° and red-135°) more often than chance ( $p < 0.01$ ). The same was found for two gratings that differed in color but with identical orientation (e.g., green-45° and red-45°) ( $p < 0.05$ ). Chance was defined as the independent probability of perceiving the upper and lower gratings with each percept when measured in isolation. Strikingly, top and bottom gratings were perceived to be consistently different in color more often than chance, suggesting that color disambiguation may enhance perceptual differences, rather than similarities. **CONCLUSION** Overall, a disambiguating process may, in some cases, select for the maximum perceptual difference between two sets of competing representations. A difference-enhancing process, whereby the percepts of separate objects are resolved to be dissimilar in both features, is an alternative to traditional grouping processes that result in greater perceived similarity (Kovács et al., 1996; Slezak & Shevell, 2018).

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**THE IMPACT OF COLOUR IN DEEP NEURONAL NETWORKS OBJECT CLASSIFICATION****Arash Akbarinia and Karl R Gegenfurtner**

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Although our perception of the world is colourful, the importance of chromatic information in visual tasks is a matter of debate. Here, we investigated the impact of luminance and chromatic contrast in deep neuronal networks (DNNs).

We evaluated the performance of thirteen prominent networks (e.g. VGG, ResNet, Inception, etc.) trained to classify one thousand objects in static images. The experiments were conducted on the validation set of the ImageNet dataset, containing 50,000 images of size 224 by 224.

Reducing the chromatic signal (in CIE Lab or DKL colour space) did not impact the classification accuracy: 25% of chromatic contrast is enough for networks to retain 99% of their original performance. The complete elimination of the chromatic contrast had a modest effect. Networks, on average, retained 87% of their performance when inputted with grey-scale images. The impact of eliminating a single colour opponent channel was slight. When red-green was absent, networks retained 94% of their performance, for the absence of yellow-blue this number was 92%. Contrary to this, reducing the luminance contrast of input images dramatically degraded the classification accuracy of all examined networks. At 10% luminance contrast the accuracy of networks, on average, dropped to 40% and without any luminance contrast to 15% of their original performance. Inversion of the luminance channel similarly deteriorated the performance of networks. Overall, these results suggest that the representation of objects in these standard classification DNNs does not rely heavily on the colour of objects rather than on luminance information. This is in agreement with a modest contribution of colour to object recognition in psychophysical experiments and the fact that colour-deficient observers have little difficulties in daily tasks. We further trained 'dichromat' networks that during their training were exposed to images that lacked either of the colour opponent channels. The performance of these DNNs is on a par with their 'trichromat' counterparts, suggesting a deficiency in one chromatical channel barely impacts general object classification.

We observed a clear difference between natural and man-made objects. Networks faced with grey-scale images, on average, retained 84% of their original performance for natural objects and 90% for man-made objects. This is in line with the nature of man-made objects that are often not restrained to a single hue, contrary to natural objects that are often strongly associated with a diagnostic colour (e.g. yellow banana). For some man-made object classes that are typically grey (e.g., 'analog clock', 'television', or 'typewriter keyboard'), the classification accuracy of all examined networks was even increased for grey-scale images. At the absence of chromatical information, confusions mainly arose between objects of a similar nature but with a different colour, e.g. within the class of mushrooms. Although this might appear of little importance, such nuance discrimination might be a matter of survival (poisonous food).

**MECHANISMS OF COLOR VISION AND DYSCHRMATOPSIA****Justyna Niewiadomska-Kaplar**

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In the studies on the ratio of quantum parameters of light wave motion, the lengths of the four light waves were selected (768, 576, 432, 384 nm). These waves, despite being unevenly separated in terms of frequency, follow each other on the criterion of total energy.

Assumptions adopted in this scientific work originate from the attempt to understand the possible implication of these monochromatic waves to describe the mechanisms of color vision. These four monochromatic waves, far apart from each other in the spectrum, produce three mixed colours: red = magenta 768 nm + yellow 576 nm, green = yellow 576 nm + cyan 432 nm and indigo = cyan 432 nm + magenta 384 nm.

As result of these observations, I propose to estimate the sensitivity peaks of L cones ( $\approx 576$  nm) in values of red and yellow waves, as also to interpret the sensitivity peak of M cones ( $\approx 540$  nm) as the average between sensitivity to cyan 432 nm, yellow 576 nm and two magenta stimuli: 768 nm and 384 nm (at the beginning and at the end of the visible spectrum) named in my approach *magenta IR* and *magenta UV*.

This assignment of the sensitivity to *magenta IR* 768 nm, yellow 576 nm, cyan 432 nm and *magenta UV* 384 nm to cones is the basis for the method of analyzing the mechanisms of colour vision, which are additively synthesized from these monochromatic waves.

This way of composing colors is particularly suitable for the analysis of dyschromatopsia, which are generated by total or partial blindness to one or more of the four aforementioned monochromatic waves. In fact, the various types of dyschromatopsia find a precise interpretation with this method. The test is developed to probe the deficiencies of color perception in 30 color blind persons. The Italian Colourblind People Association is collaborative on the verification of the method.

**IMPROVEMENT OF REALISM SENSATION IN VIRTUAL REALITY SCENES APPLYING SPECTRAL AND COLOUR MANAGEMENT TECHNIQUES****Francisco D Barrancas, Halina C Cwierz, Pedro J Pardo, Angel LP Rodriguez and Maria I Suero**

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Previous works have shown the great improvement of visualization systems based on Head Mounted Displays (HMD) and Virtual Reality (VR). In these previous pieces of research the authors carried out a subjective evaluation study of virtual reality scenes in which it was possible to visualize artwork replicas (Pardo et al., 2018). In that study, several aspects related to the visual quality of the image were analysed, such as geometry, lighting, shading and colour. Likewise, a global assessment of the sensation of realism perceived by the observers when comparing the virtual scene with a real scene was made. The results indicated that the level of realism reached today is significant and the factor that most influenced this sense of realism is the colour.

With this background we aimed to improve this perception of realism by improving the reproduction of colour in the virtual reality environment. We introduced a Colour Management System (CMS) within the virtual reality software whose native colour space is RGB. The starting point was the chromatic characterization of two commercial HUD display devices (Oculus Rift CV1 and HTC Vive) and the definition of the colorimetric profiles associated with these devices. Then, a third part colour management library (LittleCMS) was introduced into the colorimetric transformation chain made by the VR software. With these two elements it was then possible to make a correct colour management in digital images without changing the colour of the light source used to illuminate the virtual reality scene. As a step of further improvement, mathematical functions have been implemented in the VR software to allow the calculation of tristimulus values for any light source characterized by its spectral power distribution. Subsequently, we applied a colour transformation from CIE XYZ 1964 colour space to the native RGB colour space of the VR software through the ICC profiles and the colour management system.

As for the objects represented in the virtual reality scene, we have opted for the inclusion of 3D objects captured from the real world by means of a complex system based on a hyperspectral camera that takes multiple hyperspectral images of the same object rotating on a motorized base and later, by means of a photogrammetric software, the point cloud of the object was determined together with its hyperspectral texture.

With all this, the colour visualization capabilities of virtual objects in virtual reality devices were improved.

In order to know the actual progress that suppose the introduction of this colour management system, a psychophysical test was designed and built. Using objects with hyperspectral texture, the observers could evaluate the sensation of realism of the VR scene comparing it to a real scene mounted on a light booth and real objects. The results indicated a clear improvement of the sensation of realism although there is still room for improvement in the perception of realism.

Pardo, P.J., Suero, M.I., & and Pérez, Á.L. (2018). Correlation between perception of color, shadows, and surface textures and the realism of a scene in virtual reality. *JOSA A*, 35, B130-B135.

**COLOR CONSTANT REPRESENTATIONS IN EARLY VISUAL CORTEX****Anke M Albers, Elisabeth Baumgartner, Hanna Gertz and Karl R Gegenfurtner**

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The light entering our eyes is the product of the illumination and the surface reflectance of an object. Therefore, it changes considerably when the illumination changes. Still, humans are able to reliably perceive the color of objects.

To investigate which brain regions represent color in such a color-constant fashion, we used fMRI and multi-voxel pattern analysis (MVPA). Participants (N=19) observed colored and grey patches under both a neutral and two simulated colored illumination conditions (yellowish, bluish), while we measured their brain activity (3T, 3x3x3 voxels, TR = 1.72 s). The patches were based on the cube presented by Lotto & Purves (2004, Rev. Prog. Color) and contained 9 uniformly colored central squares and a variegated surround. In the neutral illumination condition, the central squares were colorimetrically yellow or blue. In the colored illumination conditions, the central squares were colorimetrically neutral. However, the colored illuminant induced a change in the percept of these grey central patches. Under the bluish illumination, the central patches appeared yellow; under yellowish illumination, the central patches appeared to be blue. To optimally stimulate the BOLD response, the center patches (neutral illuminant) or the surrounding illuminant dynamically oscillated between grey and blue or grey and yellow.

We then trained a support vector machine classifier (SVM) to discriminate between the blue and yellow center-patches based on the BOLD activity pattern in retinotopically defined V1-V4. As expected from previous work (Brouwer & Heeger, 2009, J. Neurosci.; Vandebroucke et al., 2014, Cereb. Cortex; Kuriki et al., 2015, Cereb. Cortex), colorimetric colors could reliably be decoded from V1-V4 in the neutral illumination condition (V1: 55.38%, V2: 57.73%, V3: 54.76%, V4: 56.32%, all  $p < 0.003$  uncorr.). However, the classifier could also learn to discriminate between apparent yellow and blue (V1: 59.91%, V2: 59.95%, V3: 60/63%, V4: 59.14%, all  $p < 0.3 \cdot 10^{-5}$  uncorr.). Crucially, we then trained the classifier to discriminate between the center patches under neutral illuminants, but tested whether it could discriminate between the (colorimetrically identical) central patches under the colored illuminants. We found that in V1 there was indeed a colorimetric-like response to the apparent colors (54.30%,  $p = 7.36 \cdot 10^{-4}$ ). Color constancy could also be observed in participants' V3-V4 to varying degrees (V3: 52.57%,  $p = 0.10$ , V4: 52.46%,  $p = 0.01$ , uncorr.). Preliminary data of a grey control condition suggest that lightness constancy might contribute to this effect.

These findings suggest that not only colorimetric, but also apparent color is represented to some degree in retinotopic visual cortex, as early as in V1. Although these representations might partly depend on feedback, some of the calculations to support constancy could be performed in V1 or even earlier, with each region contributing to optimal perceived constancy.

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**HUE SELECTIVITY OF COLLINEAR FACILITATION WITH AND WITHOUT LUMINANCE NOISE****Tomoharu Sato<sup>1</sup>, Takehiro Nagai<sup>2</sup> and Ichiro Kuriki<sup>3</sup>**<sup>1</sup> National Institute of Technology, Ichinoseki College<sup>2</sup> Tokyo Institute of Technology, Japan<sup>3</sup> Tohoku University Technology, Japan*Corresponding author: tsato@g.ichinoseki.ac.jp*

Psychophysical and neurophysiological studies have shown that cortical neurons selectively respond to intermediate hues between cardinal axes of opponent color space. However, their detailed characteristics, such as hue selectivity and etc., are still unclear. In this study, we addressed this issue by psychophysically measuring colinear facilitation (CF) effects, which mainly reflect the property of V1 and/or V2 networks, for chromatic Gabor patches modulated on an isoluminant plane in the DKL space.

Three Gabor patches were presented in a row: the target (center) and two flankers. The chromaticity of Gabor patches was modulated in one of four hue directions; two cardinal axes (0-180, 90-270 deg) and two intermediate directions (45-225, 135-315 deg). The center hue of the target Gabor patch was 0, 45, 90, or 135 deg, and the hue differences between the target and flankers were defined by the difference in the center hue angle of these Gabor patches. Flankers were modulated with a contrast along the hue circle of 80% of the maximum saturation available. Detection thresholds for the target were measured by two interval forced choice procedure, in which the target contrast changed with 1-up 2-down staircase. The threshold ratios were derived as a measure by normalizing the threshold with flankers to that without flankers. To eliminate luminance artifacts, we also measured the hue selectivity of CF while masking the target by a luminance noise, defined from the property of the target, in a separate session.

The results without luminance mask showed significant CF for the 0-180 deg target condition, with the maximum effect with the 0 deg flanker. For the 90-270 deg target, clear hue selectivity was not observed; the threshold ratios had large individual differences. The CFs for the intermediate hue directions were not straightforward. For 0 and 45 deg target conditions the CF was maximum with the 0 deg flanker, which suggests a common mechanism behind these conditions. Similarly, the CF with 135 deg flanker was maximum for 135 deg target conditions, but the results were too noisy. In contrast, hue-selective CF was observed for 90-270 deg target when the luminance mask was presented. With the luminance mask, the CFs for 0 deg, 90 deg, and 135 deg target showed maximum CFs to flanker hues the same as the target hue, but 45 deg target showed maximum CF at 0 deg flanker. It is possible that the 0 deg and 45 deg targets could have been detected by a common mechanism, while the other two targets were detected by independent mechanisms. The selectivity bandwidths of CF estimated by fitting pseudocyclic gaussian functions showed that 0 deg and 45 deg target had narrower bandwidths than 90 deg and 135 deg target conditions.

Without the luminance mask, neural mechanisms with inputs from L- and M-cones seem to be dominant for the detection of the target. The CF on S-cone related mechanism worked effectively only when the luminance related mechanisms were blocked. Hue selectivity of CF may reflect a complex combination of input from the cones.

**IS RED COLOUR DAZZLING AND OUTSTANDINGLY BRIGHT FOR ANYONE?****Yasuyo G Ichihara<sup>1</sup> and Takashi Sakamoto<sup>2</sup>**

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*Corresponding author: ichihara@cc.kogakuin.ac.jp***1. Objectives**

This study examined differences in perception of brightness and aesthetic impression of various red stimuli by observers with protan, deutan and normal trichromatic vision. Perception of red by normal trichromats is well known: red looks bright, dazzling, and is judged beautiful. However, there exist hardly any studies on aesthetic impressions of red by individuals with protan and deutan vision. Generally, those with protan vision see red not only as dark but also as gloomy, and it does not appear to be their favourite colour. The present study investigated aesthetic perception of observers with protan and deutan vision, estimating the following:

- A) greyscale stimuli equivalent in their brightness to various red stimuli
- B) the “gloomy” red area of a CIELAB colour space
- C) the differences between protans, deutans and normal trichromats in their colour harmony.

**2. Methods**

Participants were 10 protans, 10 deutans, and 13 normal trichromats (the latter passed the Ishihara Test). The colour vision type and abnormality degree were estimated using in addition, each participant was examined using an anomaloscope and the D-15 test, which enabled estimating the type and degree of colour vision abnormality (protans and deutans).

Two types of experiments were conducted:

- 1) In Experiment 1, an array of red stimuli chosen from the Munsell R5 hue area was resented; to each red stimulus, participants were asked to choose a greyscale stimulus of equivalent brightness.
- 2) In Experiment 2, participants were asked to choose four colours that, in their view, would be harmonic. Further, using the four colours they had chosen, they were asked to create the patterns that they would consider beautiful.

**3. Results**

We report the following findings:

- A) In the area of the Munsell R5 hue, the greyscale stimuli of equivalent brightness chosen by protan participants, with regards to the Munsell Value were 10 percent darker than the red stimuli. In contrast, participants with deutan vision chose the equivalent-brightness greyscale stimuli that were 5 percent darker than the red stimuli. Red sensitivity of deutans was found to be intermediate between that of the protans and normal trichromats.
- B) The red area that the participants with protan vision perceived as “gloomy” was small. However, if the red stimulus judged as “gloom”, was added a blue or pink tint, the participants with protan vision judged these brighter.
- C) In Experiment 2, protan participants chose various reds for the “beautiful” patterns they created. Their chosen four colours deviated from the protan confusion line and greatly varied in brightness. This result suggests that people with protan and deutan vision have their own idiosyncratic perception of colour harmony.

**THE ROLE OF MELANOPsin ACTIVATION IN PERIPHERAL COLOR MATCHING FUNCTIONS****Pablo A Barrionuevo<sup>1</sup> and Dingcai Cao<sup>2</sup>**<sup>1</sup> Instituto de Investigación en Luz, Ambiente y Visión (ILAV), UNT-CONICET, Argentina<sup>2</sup> University of Illinois at Chicago, United States*Corresponding author: pbarrionuevo@herrera.unt.edu.ar*

Trichromatic color theory is based on the notion that only three types of cones (L, M and S) mediate foveal color vision in photopic lighting levels. Consequently, three primaries are sufficient to match any spectral colors. Cone fundamentals were obtained by linear transformations of traditional color matching functions (CMFs), for example,  $10^\circ \bar{r}, \bar{g}, \bar{b}$  from Stiles and Burch (Optica Acta, 1959). However, since the discovery of melanopsin expressing intrinsic photosensitive retinal ganglion cells (ipRGCs) in the peripheral retina, several works have demonstrated the involvement of the melanopsin photopigment in color vision. The goal of this study was to assess the intrusion of melanopsin activation in peripheral CMFs.

We obtained CMFs for a set of monochromatic test lights (470nm-630nm) in photopic levels ( $\sim 1780\text{Td}$ ), which were matched with three intensity-adjustable LED primaries [peak wavelengths: 630nm (R), 520 nm (G) and 460 nm (B)]. Both set of lights (test and matching) were presented using a Maxwellian view optical arrangement and were foveally-fixedated. The measurements were conducted in three spatial conditions: 1) "peripheral" ( $10^\circ$ - $26^\circ$  annular field); 2) "large central" ( $10^\circ$  circular field); 3) "small central" ( $1.7^\circ$  circular field). The test and matching stimuli were presented sequentially over time, with three seconds each. Observers adjusted primary lights to match the monochromatic test light color. Each observer repeated at least five matches for each test wavelength and stimulus condition. CMFs were normalized allowing for comparison with Stiles and Burch's CMFs.

Our results showed that the three spatial conditions had similar R matches. On the other hand, the small central condition had higher B matches than the large central and peripheral conditions, particularly at 480nm to 510nm. The small central condition had lower G matches than the peripheral condition at 490nm and 500nm. A control experiment aimed to rule out rod intrusion showed that bleaching did not change peripheral results for most of the test wavelengths, except at 490nm for the three matches and at 520nm for G and R matches. The peripheral CMFs were in a good agreement with Stiles and Burch's CMFs (R match:  $r_2 = 0.92$ ; Green match:  $r_2 = 0.82$ ; B match:  $r_2 = 0.97$ ). Statistical modeling indicated that the inclusion of rod and melanopsin with foveal cone fundamentals (yielded from small central CMFs) help to improve the predictions of peripheral S- and M- but not L-cone sensitivity functions (yielded from peripheral CMFs). Similar results were obtained for CIE CMFs.

CMFs for periphery are similar than CMFs for large central field but different for small central field CMFs. Since ipRGCs and rods are present in the periphery and absent in fovea, it is likely that CIE  $10^\circ$  color matching function involves both melanopsin and rod intrusions. Based on bleaching experiment, the difference between peripheral and  $2^\circ$  CMFs could be accounted mostly by melanopsin intrusion.

**ASSESSMENT OF COLOUR DISCRIMINATION IN PATIENTS WITH HYPOTHYROIDISM BEFORE DRUG TREATMENT USING FARNSWORTH MUNSELL 100 HUE TEST****Kalina Racheva<sup>1</sup>, Tsvetalin Totev<sup>1</sup>, Emil Natchev<sup>2</sup>, Raymond Beirne<sup>3</sup> and Margarita Zlatkova<sup>1,3</sup>**<sup>1</sup>Institute of Neurobiology, Bulgarian Academy of Sciences, Sofia, Bulgaria<sup>2</sup>Department of Endocrinology, Medical University Sofia, Bulgaria<sup>3</sup>School of Biomedical Sciences, University of Ulster, United Kingdom*Corresponding author: kalinair@abv.bg*

Hypothyroidism is a condition of decreased thyroid function, which results in insufficient synthesis, or lack of the thyroid hormones (TH). In acquired hypothyroidism a wide variety of health issues can arise including sensory defects such as visual changes. It has been shown that the induced TH suppression affects cone opsin expression in adult rodents, by activating S cone opsin expression, and repressing M-cone opsin expression (Glaschke et al, 2011). If the same mechanism controls the human cone opsin, hypothyroidism could affect human colour vision. There are no systematic studies of colour vision in patients with hypothyroidism and the existing studies have not been performed under strictly controlled conditions.

The purpose of this study is to compare colour discrimination of patients with hypothyroidism (30–53 Yrs of age) before treatment with synthetic thyroxine with an age-matched control group of volunteers without thyroid dysfunction, using the Farnsworth Munsell 100 hue (FM100) test. The FM 100 is a sensitive colour discrimination test often used to test for colour deficiency or colour blindness, including acquired deficiencies. An important question is if the hypothyroid patients would make more errors in one of the two main colour axes – blue-yellow (B-Y) or red-green (R-G). Based on mice and rat data, a higher error rate along R-G axis would be expected. The total error scores (TES) and partial error scores (PES) were recorded for both groups using standard testing conditions.

The experiments were conducted using a colour vision examination box, specially designed in the Institute of Neurobiology. The test illuminance, colour temperature of the light source, the procedure and data processing adhered to the original instructions (Farnsworth, 1957). Square root of the error scores was used in the analysis.

The average  $\sqrt{TES}$  and  $\sqrt{PES}$  scores for the hypothyroid group were not significantly different from the age matched normals, although the patients with hypothyroidism tended to show higher values (6.9) compared to the control group (5.8). However, hypothyroid patients showed a significantly higher  $\sqrt{PES}$  along the blue-yellow axis (5.7) compared to the red-green axis (3.8)  $p < 0.02$ . There was no statistically significant difference between the B-Y and the R-G  $\sqrt{PES}$  for the control group ( $p > 0.6$ ). This result suggests that the absence or reduction of thyroid hormone affects colour vision. The thyroid hypofunction had a greater impact on blue-yellow discrimination errors compared to the red-green discrimination errors, opposite to the expectations based on opsin expression in adult hypothyroid rats and mice. The question remains how these deficits would respond after treatment with synthetic thyroxine for an extended period of time.

Study was supported by the National Science Fund, Bulgaria, Grant № 13/11.

**SPATIAL SUMMATION AND RESOLUTION ACUITY OF COLOUR MECHANISMS IN PERIPHERAL RETINA****Margarita Zlatkova<sup>1,2</sup>, Kalina Racheva<sup>1</sup>, Tsvetalin Totev<sup>1</sup>, Milena Mihaylova<sup>1</sup>, Ivan Hristov<sup>1</sup> and Roger Anderson<sup>2</sup>**<sup>1</sup> Institute of Neurobiology, Bulgarian Academy of Sciences, Sofia, Bulgaria<sup>2</sup> School of Biomedical Sciences, University of Ulster, United Kingdom*Corresponding author: mb.vidinova@ulster.ac.uk*

Many studies have suggested that M-cones are more numerous than L-cones at peripheral locations, although there may be substantial interindividual variations (e.g. Hagstrom et al., 1998). It is a question of interest how the L- and M-cone number and arrangement peculiarities affect the post-receptoral colour mechanisms in the retinal periphery. We examined the performance at the resolution limit (resolution acuity) using chromatic gratings, which, in the periphery, is limited by the sampling density of the relevant ganglion cells. This was compared to the area of complete spatial summation (Ricco's area). Our previous study has shown that for S-cone increments, Ricco's area increases in the periphery proportionally to the dendritic field size of the S-cone ON ganglion cells (Vassilev et al, 2003).

Circular spots and sinusoidal gratings were presented at 20 deg in the temporal retina of 7 subjects with normal colour vision (37-46 yrs) using a 21" CRT monitor. For both type of stimuli, the chromaticity was determined using the silent substitution method, using modulation from an achromatic background to 90, 270, 0 and 180 deg in DKL space, loosely called here blue, yellow, red and green. The stimuli were made subjectively isoluminant using the method of minimum grating resolution, by changing the luminance ratio of the chromatic grating bars with the achromatic grating bars, the latter remaining the same as the background. The individual resolution acuity vs luminance ratio curve displayed a point where the resolution acuity was minimal, this point being taken as the isoluminant point for each individual. The spatial frequency at this point was taken as a chromatic resolution acuity and used in further considerations.

Spatial summation was studied by measuring threshold cone contrast for spots of variable size ranging from 0.68 to 4 deg in diameter. The area of complete spatial summation (Ricco's area) was estimated using a bilinear fit of the spatial summation function.

The resolution acuity differed between chromaticities, the highest being for blue, decreasing for yellow and red and showing a sharp decline for green gratings, suggesting lower density of the underlying sampling cells at this eccentricity. The average Ricco's area was significantly smaller for blue stimuli compared to all other chromaticities. There was no evidence of increase in summation for green relative to red spots. In anatomic context, this result should not be expected if dendritic field size is linked to cell density to keep the retinal coverage constant for a given cell type. The interindividual variations in either resolution acuity or spatial summation for green chromaticity did not differ from those for red or from the rest of the chromaticities tested, suggesting that if large individual variations of L- and M-cone number or arrangement existed, they did not affect the psychophysical measurements in this study.

Study was supported by the National Science Fund, Bulgaria, Grant № 13/11.

**REMOTE SIMULTANEOUS COLOR CONTRAST AND ASSIMILATION EFFECTS ACROSS THE L-M CONE AXIS****Tama Kanematsu<sup>1</sup> and Kowa Koida<sup>2</sup>**<sup>1</sup>Department of Computer Science and Engineering, Toyohashi University of Technology, Japan<sup>2</sup>Electronics-Inspired Interdisciplinary Research Institute (EIIRIS), Toyohashi University of Technology, Japan*Corresponding author: t131304@edu.tut.ac.jp*

Simultaneous color contrast and color assimilation are two opposite effects reflecting the color of surroundings. It is known that both effects depend on the spatial frequency and luminance contrast. Color contrast is evident for equiluminance between a center and surrounding area, whereas color assimilation is evident when the stimulus have a certain luminance contrast. High spatial frequency stimulus induces color assimilation, whereas low spatial frequency stimulus induces color contrast. Moreover, it was shown that color shifts occurred both the assimilation from an adjacent to a center area and the contrast from a remote area induced by the S-cone color (Monnier & Shevell, 2003, 2004).

Here we report a simultaneous color contrast effect across the L-M cone axis of which thin (typically 1 px) gray lines on a cyan background appear red when the lines are surrounded by thin (typically 1 px) white gaps, which was clearly more vivid than the lines without gaps. This strong simultaneous color contrast effect was prominent for fine lines and dots, but it was not quantitatively examined. In this study, we quantified the amount of color shift when we systematically changed the width of both the gray line and the white gap. Stimulus was varied 1~12 px (0.015 deg~0.495 deg) for gray lines and 0~8 px (0.0 deg~0.124 deg) for the white gap. There were two luminance levels of the gray line and four inducing colors (cyan, red, violet, and yellow from the cardinal axes).

Results showed that the optimal width for the cyan and red surroundings was 1 px (0.015 deg) white gap and 1 px gray line; on the other hand, the optimal width for the violet and yellow surroundings was 4~16 px (0.062 deg~0.248 deg). These differences in the optimal width would reflect spatial resolution of L-M and S-cone-determined stimuli and the distribution density of the L, M, and S cones. Observed color shift could be explained by the band-pass characteristic (Monnier & Shevell, 2004); however, the characteristic had limitations in explaining the appearance of the gap. The band-pass filter would change the color of the gap into red, but the appearance of the gap was white.

We also found a novel type of remote color-assimilation effect, which was observed for the fine gray line (1 px, 0.015 deg) with the large white gap (8 px, 0.124 deg). This was not consistent with previous reports of color assimilation from remote areas overcome with the thick white gap. This remote assimilation might be useful to elucidate the mechanism of color assimilation since it can remove a blur from the color background by inserting the thick white gap.

**THE RAYLEIGH MATCH ON THE PERIPHERAL RETINA****Alexander Belokopytov<sup>1</sup>, Egor Ershov<sup>1</sup>, Ilia Nikolaev<sup>2</sup> and Peter Nikolaev<sup>1</sup>**<sup>1</sup>Institute for Information Transmission Problems (Kharkevich Institute), Moscow, Russia<sup>2</sup>Moscow State University, Faculty of Physics, Russia*Corresponding author: abelokopytov@gmail.com*

Recently, a widespread misconception that, at the periphery of the visual field, color perception is absent or poor, attracted attention of Tyler (2015, 2016), who emphasized that peripheral color vision is foveal-like if stimuli are scaled in accordance to eccentricity. This statement is based on the results of investigations using various methods, such as wavelength discrimination (van Esch et al., 1984), sensitivity to spatiotemporal color contrast (Noorlander et al., 1983), color discrimination thresholds (Nagy, 1993), etc. In this work we tried to characterize peripheral color vision on the basis of the Rayleigh match. For this purpose we developed a prototype free view alternating stimuli device consisting of stimulus box and arduino based control box. Stimulus box contains PCB with LEDs mosaic (green, red and amber LEDs with peak intensities at 520, 620, 590 nm respectively), first diffuse acrylic plate, second orange diffuse acrylic plate and exchangeable white diaphragms with 2, 3 or 4 cm circular window. Orange plate (used to avoid S-cones stimulation) shifts the green LED emission spectrum peak to 550 nm leaving the red and amber LED peaks untouched. The first field contains a mixture of red and green lights, the second field contains amber light. Fields alternate every 1.5 sec. RG knob on the control box varies relative amounts of the red and the green lights in the mixture field from 0 (only green) to 1 (only red) at constant brightness of 50 cd per square meter, AB knob varies intensity of the amber field. For foveal vision, the subject task was to eliminate perceived flickering using RG and AB knobs. Device calibration was performed with 10 normal trichromats; the individual RG match midpoints varied from 0.417 to 0.469; the accepted ranges boundaries were less than 0.005 from midpoint. For the peripheral color vision assessment the stimulus box was moved along the horizontal arc of the Förster type perimeter. Viewing distance was 30 cm, ambient light 200 lx. The stimulus box was located at the temporal side of the test eye, other eye of the subject was occluded. The task of the subject was to achieve match midpoint using RG and AB knobs while gazing at the central fixating point (red LED). Pilot study of the peripheral color vision was conducted with 3 subjects at the eccentricities of 20°, 40° and 60°. The main results were: (1) no peripheral color vision abnormalities for eccentricities up to 60° were found in any of our subjects; (2) for constant field size, all subjects demonstrated noticeable increase of RG ranges with eccentricity increase; (3) increasing field size with increasing eccentricity resulted in much less dependence of RG ranges on the eccentricity; for example, for one subject accepted RG ranges were: 0.500-0.525 (25°; 2 cm), 0.525-0.550 (40°; 3cm), 0.525-0.570 (60°; 4cm). We believe these preliminary results are in favor of the statement that peripheral color vision is foveal-like.

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**A PILOT PERIMETRIC STUDY OF FAR PERIPHERAL COLOR VISION USING TWO SMARTPHONES****Galina Rozhkova<sup>1</sup>, Alexander Belokopytov<sup>1</sup>, Egor Ershov<sup>1</sup>, Iliia Nikolaev<sup>2</sup> and Peter Nikolaev<sup>1</sup>**<sup>1</sup>Institute for Information Transmission Problems (Kharkevich Institute), Moscow, Russia<sup>2</sup>Moscow State University, Faculty of Physics, Russia*Corresponding author: gir@iitp.ru*

Despite a significant number of investigations showing that, in conditions of a proper scaling test stimulus size and/or luminance, human peripheral retina can provide foveal-like color perception, some doubts concerning peripheral color vision are still common among visual scientists and ophthalmologists. Methodological and technical problems in creating conditions for a suitable stimulus presentation and adequate characterization of perceived images at the periphery of the visual field make it difficult to collect enough data and formulate comprehensive notion of the peripheral vision. Up to now, search for a simple technique allowing fast assessment of the peripheral vision capabilities seems to be rather pressing. In our pilot study, we tried to use identical smartphones (Samsung Galaxy S6 with AMOLED screen) both for test stimulus presentation and for quantitative evaluation of perceived images using color checker. The test stimuli (uniform color circles of 4-8° in diameter turning on/off each 1.5 s) were displayed on the smartphone attached to the platform moving along the perimetric arc to vary stimulus eccentricity. The second smartphone, displaying color checker circle, was fixed at the center of the perimeter arc. The hue and saturation of each test stimuli corresponded to one of the smartphone primaries (R, G, B). Hue, saturation, and luminance of the checker circle could be easily controlled by the subject employing mouse connected with the checker smartphone. The test stimulus and the checker circle were observed simultaneously in monocular viewing conditions. Subjects were three males and one female (30 - 75 years old) with normal color vision. The subject task was to make the appearance of the checker image as similar as possible to the appearance of the peripheral one adjusting hue, saturation, and luminance of the checker circle. Presenting color test stimuli at far periphery (temporal visual field, 60-95°), we have found that perceived peripheral images could be vivid and allowed matching in hue and saturation to the foveal checker image. The peripheral images preserved or changed their appearance with increasing eccentricity depending on the stimulus parameters and individual eye properties. For instance, in subjects IP and PN, at the maximal test stimulus intensities, the quantitative estimates of the perceived hue (according to the HSV color model) at the eccentricities of 60°, 80° and 95° were: 0→3→1; and 0→0→0 (for R); 126→76→81 and 121→30→135 (for G); 217→227→211 and 234→240→232 (for B), respectively. In the range 80-95°, perceived luminance could be very high, significantly exceeding the maximal possible level of the checker image. It was surprising that, in certain conditions, two of our subjects could perceive the red stimuli as certainly the green ones or see the two hues at once in one image. Transformation of the red image into the green one and back could be verified by means of moving the test stimuli along the perimetric arc repeatedly.

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## SPECTRAL IMAGING OF THE SKIN OF HUMAN FACES: A COMPARISON OF DIFFERENT METHODOLOGIES

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Measuring the spectral properties of the human skin is of great importance as the spectral information may provide further detailed information that RGB data alone cannot [1,2].

Traditional methods to acquire the spectral properties of the human skin are based on contact spectrometers that can only provide information of a given area at the time, making comparisons among different areas of measurements or successive measurements difficult.

The purpose of this work was to obtain spectral properties of the skin of human faces using different methodologies and to compare the differences between them.

Six patients were used and their facial skin spectral properties were obtained using three methodologies. A contact spectrophotometer (Minolta 2600D, Konica Minolta, Inc.) from 400 to 700 nm in 10 nm steps, a telespectroradiometer (PR-650 SpectraScan, Photo research, Inc) from 380 to 780 nm in 4 nm steps and a home built Hyperspectral Imaging System (HIS) from 400 to 720 nm in 10 nm steps and a spatial resolution of 1024 (V) x 1344 (H) pixels. In each case the spectral reflectance was estimated against the used illuminant. The similarity index [3] and the CIEDE colour difference formula in the CIELAB colour space assuming the CIE E illuminant and the CIE 1931 standard observer [4] were estimated. The spectral properties of the facial skin obtained with the Minolta 2600D were assumed as the ground truth.

It was found that the spectra similarity index obtained using the telespectroradiometer and the HIS are close to the one obtained using the Minolta 2600D by 85% and 80%, respectively. For each of these cases the chromatic difference in CIE(a\*,b\*) was found to be 4.4 ( $\pm$  1.8) and 4.6 ( $\pm$ 2.3). Taking into account that the different methods have different geometry measurements, these results are remarkably good.

These results seem to indicate that the methods to retrieve the facial skin spectra properties used here are capable of providing good spectral accuracy when compared with more traditional methods. The new methods, in particular the HIS with its spatial and spectral information combined, seems to be a capable tool for providing valuable spectral information of the spectral properties of human skin.

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**ADVANTAGES AND SHORTCOMINGS OF USING A CONTACT LENS WITH AN IMPLANTED OCCLUDER IN THE ASSESSMENT OF PERIPHERAL COLOR VISION****Elena Iomdina<sup>1</sup>, Olga Selina<sup>1</sup>, Galina Rozhkova<sup>2</sup>, Alexander Belokopytov<sup>2</sup>, Egor Ershov<sup>2</sup>, Iliia Nikolaev<sup>3</sup> and Peter Nikolaev<sup>2</sup>**<sup>1</sup> Moscow Helmholtz Research Institute of Eye Diseases, Russia<sup>2</sup> Institute for Information Transmission Problems (Kharkevich Institute), Moscow, Russia<sup>3</sup> Moscow State University, Faculty of Physics, Russia*Corresponding author: iomdina@gmail.com*

Retrospective overview of publications available on peripheral color perception shows that there are practically no behavioral studies demonstrating real capabilities of peripheral vision as such and its linkage/cooperation with central vision. In particular, it seems important to obtain behavioral and psychophysical data on "pure peripheral vision", i.e. to investigate visual perception "switching central vision off". For this purpose, we decided to use contact lens with an implanted occluder in the hope to overcome some of the principal deficiencies of commonly employed techniques. When peripheral vision is studied, visual attention is usually divided between the peripheral test stimulus and the fixation stimulus at the center of the visual field. Such unnatural and uncomfortable conditions inevitably cause substantial difficulties in the assessment of potential capabilities of peripheral vision. Firstly, central fixation means forced limitation of the test stimulus image drift over the retina, whereas, for optimal perception of the peripheral stimuli, the drift should be enhanced (Yarbus & Rozhkova, 1977). Secondly, voluntary stabilization of the eye position deteriorates natural oculomotor activity, preventing normal saccadic movements that usually occur several times per second. Thirdly, at the cognitive level, mental resources are divided between the two tasks thus decreasing quality of the peripheral stimulus analysis. In our pilot investigation, we used contact lens with an implanted opaque occluder overlapping the pupil area and completely excluding central vision (shading the area of 60-80° in diameter). In total, our experiments confirmed significant benefits of this technique for studying peripheral vision capabilities. The subjects with an occluder on the contact lens demonstrated a significantly decreased tendency of turning the eye to foveate the peripheral stimulus since such turns were useless. Despite perceiving a large dark area at the center, the subjects could observe the periphery of the visual field without discomfort. They could walk freely around the rooms and corridors recognizing furniture and people. In general, the perceived scenes (under illumination of about 250 lx) were similar to the normally observed ones excluding some low contrast fragments and unsaturated colors. One of the subjects reported that he perceived the surroundings almost as in normal viewing conditions but felt himself as "looking through the iris but not through the pupil". Among the shortcomings of our technique the following three seem to be the most essential. (1) The size of the shaded area depends not only on the occluder diameter but also on the individual eye optics and the ambient luminance indicating the necessity of additional measurements for proper describing viewing conditions. (2) One of the critical parameters determining the size of the shaded area is the pupil diameter that is permanently changing during observation and depends on physical parameters of the scene and the emotional content of the stimuli. The amplitude of possible "pupil pulsations" has to be taken into consideration. (3) The lens can slip over the cornea changing the position of the occluded area in the visual field; such slippage should be prevented or taken into consideration.

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**VISUAL ACUITY, COLOUR DISCRIMINATION IN PATIENT WITH CATARACT****Zane Jansone<sup>1</sup> and Maris Ozolinsh<sup>1,2</sup>**<sup>1</sup> University of Latvia, Faculty of Physics, Mathematics and Optometry, Latvia<sup>2</sup> Institute of Solid State Physics, University of LatviaCorresponding author: [jansonezane1993@gmail.com](mailto:jansonezane1993@gmail.com)

Senilis cataract is a common cause of visual impairment among the elderly. In the severe cases cataracts can progressively impair visual acuity and colour discrimination. In optometry practice colour vision tests are not used quite often to check progression of cataract but it can be a useful method to detect cataract development and help us to understand patients' complaints about colour vision differences before and after cataracts surgery. Our aim was to evaluate visual acuity and colour vision changes before and after cataract surgery.

We used saturated and unsaturated versions of Farnsworth D-15 arrangement test to assess the colour sensitivity changes along *tritan*, *protan* and *deutan* confusion lines. Results were analysed by three methods: (1) summing colour differences between adjacent caps according to Bowman's method, (2) averaging colour difference vectors according to Vingry and King – Smith, and (3) linear regression method applied for incorrect arrangements of caps. Visual acuity was measured with Landolt C vision chart, 1 day before the surgery and 2 months after. Out of 92 eyes that were investigated, just 26 eyes with cataract were deemed suitable for further investigation, as the other 66 exhibited glaucoma, macular diseases, had lower visual acuity than Visus 0.10 decimal units, or were possessed by diabetics.

Three analysis methods showed that the cataract caused lens opacities and significantly decreased the chromatic resolution along visible spectrum. Colour vision sensitivity improved to 26 eyes after the surgery. 22 eyes had normal colour vision, but two eyes showed changes to *tritan* colour deficiency. This allowed to conclude that the colour vision sensitivity changes not only due to the lenses' light absorption, but due to other pathological factors. In the near distance (40 cm) average visual acuity before surgery was  $0.50 \pm 0.05$  decimal units (using best near correction SE  $+3.50 \pm 0.25$  D). After the surgery the average visual acuity was  $0.63 \pm 0.05$  D (SE  $+2.75 \pm 0.50$  D). Colour vision tests can give information on cataract progression stages. Test results can be an indicator for optimum IOL selection as well.

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**COLOR CONTRAST ADAPTATION TO TEMPORAL VARIATIONS ON COMPLEX LUMINANCE-CHROMATICITY LOCI****Takehiro Nagai<sup>1</sup>, Kana Kakuta<sup>2</sup>, Tomonori Tashiro<sup>2</sup> and Yasuki Yamauchi<sup>2</sup>**<sup>1</sup>Tokyo Institute of Technology, Japan<sup>2</sup>Yamagata University, Japan*Corresponding author: nagai.t.aa@m.titech.ac.jp*

Our visual system seems to adjust the color sensitivity according to different types of color information in the visual scenes. Color contrast adaptation is one of the phenomenon for this sensitivity adjustment. However, in previous experiments about color contrast adaptation, stimuli with simple chromaticity-luminance modulations were typically employed. In this study, we psychophysically examined if our visual system adapts to stimuli whose colors were temporally changed on a complex loci in a luminance-chromaticity plane. Each of the adaptation and test stimuli was a uniformly colored circle with black edge on a 15 cd/m<sup>2</sup> gray background. The luminance and chromaticity of the stimuli were defined in the luminance-chromaticity(L-M) plane. In the adaptation phase, the observer fixated the adaptation stimulus for a minute, whose luminance and chromaticity were temporally changed according to the locus with a “<” or “>” shape on the plane in 2 Hz. For instance, the “<” locus was composed of high- and low-luminance with reddish (positive) L-M values and middle-luminance with greenish (negative) L-M values. In the test phase, a test stimulus with one of the five luminance values (3.75 - 60 cd/m<sup>2</sup>) was presented for 500 ms. The observer responded if the test stimulus appeared reddish or greenish after the stimulus presentation. The PSI staircase method controlled L-M values of the test stimuli and estimated achromatic points per luminance level. In the results, after adapted to the “<” locus, the achromatic L-M values for the low and high luminance values were significantly larger than that for the middle luminance values. Namely, the shifts of perceived chromaticity induced by the adaptation were different among the luminance levels, and the locus of achromatic points was similar to the adaptation stimulus locus in shape. Similarly, after adapted to the “>” locus, the achromatic locus exhibited the “>” shape. These results suggest that our visual system can adjust color sensitivities according to the relations of the luminance and chromaticity independently across ON and OFF luminance signals in the adaptation stimulus. Finally, we examined if these achromatic loci can be expected from the adaptation effects in a multi-channel color representation model in a simulation. The model consisted of eight channels tuned to 0~315 degrees at 45 degree intervals on the luminance-chromaticity plane. Each of the channels received linear combinations of cone responses. The channel sensitivities were assumed to decrease linearly according to standard deviations of channel responses during the adaptation phase. Also, the squared sum of the eight channel responses was assumed to determine the perceived colors on the test stimuli. In the simulation results, this model reproduced quite similar patterns of the achromatic loci to the real observer’s one. In contrast, a similar model but with only four channels tuned to cardinal directions cannot yield such achromatic loci at all. These results suggest that the multiple channel model is one of the candidates mechanisms underlying the complex luminance-chromaticity adaptation.

**PLAID FROM ORTHOGONAL RIVALROUS GRATINGS AND BINOCULAR RESOLUTION OF COMPETING NEURAL REPRESENTATIONS****Xiaohua Zhuang<sup>1</sup> and Steven K Shevell<sup>2</sup>**<sup>1</sup> Illinois College of Optometry, United States<sup>2</sup> University of Chicago, United States*Corresponding author: zxhelsa@gmail.com*

Monocular presentation of alternating orthogonal gratings at a frequency above critical fusion gives the percept of a plaid. Recent studies of interocular-switch rivalry (ISR) show that a plaid percept occurs also at a much lower temporal frequency with rivalrous stimuli. The question addressed here is whether the plaid perceived using ISR is caused by a binocular process resolving the competing orthogonal representations from the left and right eyes or simply by superposition of signals from orthogonal stimuli in each eye.

Methods: Orthogonally oriented ( $\pm 45$  degree) 4 cpd luminance gratings were presented to the two eyes. The gratings were presented in three conditions: (1) standard binocular rivalry (SBR) condition, in which each eye saw only one of the two gratings during an entire 10-second trial; (2) interocular-switch rivalry (ISR) condition, in which the orthogonal gratings were swapped between the two eyes every 160 msec (3.13 Hz) during the 10-second trial; and (3) binocular non-rivalrous viewing (NR) condition, in which the same grating was presented to both eyes at any given moment, with the grating alternating between the two orthogonal orientations every 160 msec. Similar conditions, but with 2 cpd gratings, added 20-second prior adaptation to 10-Hz full field luminance flicker before each 10-second trial. The aim of adaptation was to desensitize the magnocellular (MC) pathway (Zhuang, Pokorny, & Cao, 2015; Zhuang & Shevell, 2015) in order to assess the pathway's contribution to perceiving binocular plaid.

Results and conclusions: Plaid was observed most frequently in the interocular-switch rivalry condition, less often in the standard binocular rivalry condition, and seldom in the non-rivalrous condition. Thus, swapping the orthogonal stimuli between the two eyes facilitated the appearance of plaids (ISR vs. SBR conditions). This is consistent with plaids resulting from suppression of interocular inhibition for competing orthogonal stimuli at the binocular level. Further, the rare appearance of plaid in the NR condition eliminated the possibility that plaid with ISR was caused by only monocular combination of the stimulating grating's orientation with an afterimage of the most-recently-extinguished grating's orthogonal orientation. Prior adaptation to 20-second of 10-Hz luminance flicker, intended to desensitize the MC pathway, did not significantly alter the proportion of time that plaid was perceived with ISR. Overall, the results nonetheless remain consistent with the hypothesis that transients in the MC pathway inhibit interocular suppression during rivalry because (1) perception of plaids is enhanced during ISR, when the stimulus has an implicit MC temporal transient every 160 msec, and (2) of the likelihood of very rapid MC recovery from preceding flicker adaptation, which may have minimized an adapting effect.

**CONGENITAL RED-GREEN COLORBLINDNESS CONFINED TO ONE EYE****Alex Neitz, Maureen Neitz and Jay Neitz**

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The study of color blindness has been used as a guide to the nature of normal color vision and a test for theories of it. One fundamental question is what colors do colorblind people experience? One approach to this question is to study individuals in which red-green dichromacy is confined to one eye with the hope that the normal eye can be used to calibrate the perceptions with the other eye. Understanding the underlying cause of the disturbance is important for assessing the validity of one eye representing normal and the other dichromatic vision; however, none have been reported since it has been possible to assess the genetic basis of the disorder to determine the cause and nature of the unilateral condition. Thus, we have examined the opsin genes and color vision of a 64-year-old woman who self-reports having a colorblind father and having normal color vision in one eye but being colorblind in the fellow eye for as long as she can remember.

L and M opsin genes were amplified separately and sequenced. In addition, the first gene, and all downstream genes in the opsin gene array were separately and specifically amplified and sequenced. A MassArray based color vision assay that distinguishes the L and M genes and the first gene in the array from all downstream genes was used to estimate opsin gene copy number and the proportion of L vs. M genes. Standard tests of color vision were performed. The subject was also asked to make comparisons of color appearance between the two eyes.

The subject tested as a protanope when viewing with her left eye but showed a very mild red-green color vision deficiency in her right eye. The MassArray assay indicated a low proportion of L genes compared to the total number of genes consistent with either a protan defect or a protan-carrier genotype. However, sequence analysis indicated both that L and M genes were present indicating that protan carrier status is more likely. In addition, a single nucleotide substitution was detected in the promoter region of a subset of her M genes.

This is the first case of a person having protanopic color vision confined to one eye in which it has been possible to examine the genetics underlying the condition. There has been speculation that the patchiness of X-inactivation could produce a carrier of color-blindness with one normal and one colorblind eye much like the coat-color of calico cats. However, modern results indicate that the X-inactivation patches of cones are very small or non-existent making the occurrence of monocular protanopia by this mechanism unlikely. Moreover, previously, in 300 mothers of colorblind sons (Feig & Ropers, 1978) all pairs of eyes were very similar and monocular disturbances of color vision were not observed. Thus, it appears that a rare combination of genetic changes is required to produce the dramatic difference in color vision reported here, providing a rare opportunity to gain insight into the perceptions of the colorblind.

**INFLUENCE OF STIMULUS COMPLEXITY ON THE GAMUT EXPANSION EFFECT****Taiga Mikami and Yoko Mizokami**

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The gamut expansion effect is a phenomenon which the perceived saturation of an object varies with the variance of surrounding colors. A target embedded in a surround with colorful pattern looks less colorful than the same target on a uniform surround (Brown & MacLeod, 1997). This effect suggests that we have an adaptation or normalization mechanism to the color gamut of an environment. However, Ekroll et al. (2008) measured the effect by comparing uniform targets on various surrounding conditions including uniform and multiple colors and suggested that chromatic variance has no special status but is only a condition that prevents color scission. Thus, the mechanism of the gamut expansion effect is still not conclusive. Besides, the target patches used in these studies are uniform and any condition with complex target patches has not been done. In more naturalistic conditions, such as computer graphics created by synthesizing object images and surrounding images, both objects and surroundings have complex colors, but it is not clear whether the appearance of an object with multiple colors also become desaturated due to the variance of surrounding colors.

In this research, we investigate the color gamut expansion effect in complex targets and surroundings. A test target was a circular patch with a multicolored square pattern. The diameter of the test target was 10 degrees and the size of the random square was 0.06° or 0.13°. The color of the target consisted of four hues with same metric chroma and they were chosen from the a\* and b\* axis of the CIELAB color space. High chroma condition (Ct\* = 40) and low chroma (Ct\* = 20) condition were tested. For comparison, uniform targets with each of four colors were also tested. The background also consisted of a multicolored square pattern with 8 hues and same metric chroma (Cs\* = 60). We examined four different square size conditions (0.03°, 0.13°, 0.23°, and 0.45°). In the experiment, observers adjusted the saturation of matching stimulus on a uniform gray background to match that of test target on various backgrounds. Observers adjusted for a total of 48 conditions with the various combinations of the target and background.

The result shows the reduction of perceived saturation in all conditions. We found that no significant differences among conditions. The shift of perceived saturation tended to be larger when the chroma contrast of target and surround was higher (Ct\* = 40, Cs\* = 60) compared to the conditions that the contrast was lower (Ct\* = 20, Cs\* = 60). Our results suggest that the color gamut expansion effect occurs regardless of the complexity of stimulus and surround.

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**AGE-RELATED CHANGE IN PREFERENCE FOR CHROMATIC COMPOSITIONS OF ART PAINTINGS REVEALED BY 30K-SUBJECTS EXPERIMENT****Shigeki Nakauchi, Masaya Nishimoto and Hideki Tamura**

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Background: Several studies have shown that observers preferred the original art paintings rather than the hue-rotated fake paintings even for abstract paintings although they have never seen them before (Nascimento et al., *Vision Res.*, 2017; Kondo et al., *ICVS2017*; Nakauchi et al., *VSS2018*). This study aims to confirm the robustness of this "original-preferred judgement" for art paintings and to explore the individual differences of preference due to age, gender, household income by recruiting more than 30K participants with broad age groups.

Method: 4-AFC paradigm was used to measure the preference for art paintings (Kondo et al., *ICVS2017*; Nakauchi et al., *VSS2018*). Participants ( $n=30,777$ : male=16,837, female=13,940; mean age=46.6, S.D.=15.4, ranging from 15 to 97 years old; only Japanese participants) were asked to select the most preferable one among four images of original (0 deg) and three hue-rotated images (90, 180 and 270 deg) which have the same luminance and mean chromaticity as the original (Nascimento et al., 2017). Art paintings used in the experiment were collected from WikiArt (<https://www.wikiart.org>) with the genres of abstract, flower, poster, still life and symbolic. Subjects were divided into 50 groups (about 600 subjects in each group) and each group was presented the same 24 sets of paintings. This enabled us to analyse the individual differences in painting-selection patterns: originals of which paintings were preferred and not preferred in addition to the original-selection rate.

Results and Discussions: Original paintings were selected as most preferable (44.12 % among four choices) duplicating our previous findings. Original-selection rate weakly correlated with age of subjects while it did not show significant difference in gender and correlation with household incomes. Next, we analyzed the individual differences in the painting-selection patterns among subjects. It was found that (1) variation in painting-selection patterns decreased according to the age, meaning that elderly subject group tended to select similar paintings than younger subject group, (2) variation among female subjects was smaller than that of male subjects, (3) no significant change in variation correlated with household incomes was found. Furthermore, similarity analysis in the painting-selection patterns between female and male subjects revealed that (4) similarity between female and male subjects decreased according to the age, that is, female-male difference in the painting-selection patterns was bigger in young age groups than elderly subject groups. These findings strongly imply that the preference for chromatic composition of art paintings is acquired not only during school age shown in our previous study investigating children of 6-to-12 years old (Imura et al., *ECVP2018*) but it would be affected in a lifelong range. Furthermore, individual and gender differences tend to be decreased according to age, suggesting that the preference patterns would converge to a certain universal form, presumably due to cultural, educational and/or social feedbacks.

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**COLOR AND ORIENTATION RESOLUTION IN NECKER CUBES WITH CHROMATIC RIVALRY****Ryan Lange and Steven K Shevell**

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Resolving ambiguous neural representations and determining which neural representations correspond to parts of the same object (grouping) are important aspects of visual perception. Experiments using many discs, each one presented with chromatic binocular rivalry, show all discs often appear the same color, thus revealing the discs' colors are not resolved independently. Instead the discs are grouped. Resolution of the discs' color has been proposed to take place at a binocular level, following grouping of the discs (Kovacs et al, 1996). Experiments using Necker cubes have shown grouping of their perceived orientation (Babich & Standing, 1981), and experiments using colored gratings have shown grouping of color and form by binocular neurons following integration of the two features (Slezak & Shevell, 2017).

The question here is whether two different types of visual ambiguity—chromatic ambiguity from rivalry and orientation ambiguity from Necker cubes—are resolved after color-orientation feature conjunction. An initial experiment showed that a pair of Necker cubes in chromatic rivalry is perceived to be the identical color and identical orientation more frequently than expected from independent resolution of each feature in each object. The main experiment tested whether the total time for perceiving identical color and identical orientation for a pair of Necker cubes in color rivalry was greater than for a pair of achromatic Necker cubes beside color-rivalrous discs.

Rivalrous stimuli were presented in chromatic interocular-switch rivalry (CISR) and patchwork presentation. In CISR, each rivalrous element swapped color between eyes at approximately 3.75 Hz; and in patchwork presentation, one of the elements presented to one eye in a frame was a different color than the other element to the same eye. The chromaticities in MacLeod-Boynton coordinates were [0.62, 1.0] for "green" and [0.71, 1.0] for "red." Stimuli were either a pair of color-rivalrous Necker cubes or a pair of achromatic (non-rivalrous) Necker cubes with a pair of color-rivalrous discs, depending on the condition. Observers reported when stimuli were the identical color and also when they were the identical orientation using button presses. Total times that both color and orientation were identical were recorded.

Necker cube orientation and color were not found to be both identical more frequently when the two features were bound together in a pair of color-rivalrous cubes compared to when the two features were distributed across two pairs of objects (achromatic Necker cubes and color-rivalrous discs). This is the expected result if the neural representations of chromaticity and of Necker-cube orientation are grouped before conjunction of the two features. Grouping of gratings with chromatic rivalry, on the other hand, has been posited to depend on binocular neurons that represent feature conjunctions (Slezak & Shevell, 2017).

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**CAN DIFFERENCES IN CRYSTALLINE LENS THICKNESS EXPLAIN DIFFERENCES IN ESTIMATES OF L:M CONE RATIO BETWEEN YOUNG MALES AND FEMALES?****Lene A Hagen<sup>1</sup>, Solveig Arnegard<sup>1</sup>, James A Kuchenbecker<sup>2</sup>, Stuart J Gilson<sup>1</sup>, Maureen Neitz<sup>2</sup>, Jay Neitz<sup>2</sup> and Rigmor C Baraas<sup>1</sup>**<sup>1</sup> University of South-Eastern Norway, Kongsberg<sup>2</sup> University of Washington, United States*Corresponding author: lene.hagen@usn.no*

**Purpose:** Spectral sensitivity functions measured by electroretinogram (ERG) flicker photometry give a reliable estimate of L:M cone ratio when adjusted for individual differences in peak sensitivity ( $\lambda_{\max}$ ) of the L cone opsin and for the optical density of the crystalline lens [Carroll et al., 2002; Hofer et al., 2005]. The crystalline lens changes throughout life, with large between-individual differences associated with sex at a given age [Mohamed et al., 2018]. The purpose of this study was to assess whether crystalline lens thickness (LT) could explain differences in estimates of L:M cone ratio between young Caucasian males and females.

**Methods:** Spectral sensitivity functions were measured by full-field ERG flicker photometry in the dominant eye of 43 healthy 16–18 years old Norwegian Caucasian normal trichromats (23 males). L:M cone ratios were estimated from the spectral sensitivity functions after adjusting for individual differences in L and M  $\lambda_{\max}$ , determined from genetics, and for optical density of the crystalline lens by an age-dependent lens correction (Pokorny et al., 1987). LT was measured with Zeiss IOLMaster 700 (Carl Zeiss Meditec AG, Jena, Germany) 15–20 minutes after administering Cyclopentolate Hydrochloride 1%. Cyclopentolate was used to ensure a precise LT measurement not influenced by accommodation.

**Results:** Estimated %L ranged from 49.9 to 99.5%. Mean  $\pm$  SD %L was  $74.2 \pm 11.2$  in males ( $n = 23$ ) and  $83.7 \pm 10.6$  in females who had L opsins with identical L  $\lambda_{\max}$  ( $n = 9$ ). In females who had L opsins with two distinct L  $\lambda_{\max}$  ( $n = 11$ ), mean %L was  $74.4 \pm 9.7$  ranging from  $69.8 \pm 9.2$  to  $79.6 \pm 10.2$ , based on the maximal and minimal L  $\lambda_{\max}$ , respectively. Overall, mean %L in females ( $n = 20$ ) was  $78.6 \pm 10.9$ . Mean LT was  $3.4 \pm 0.2$  mm (range: 3.1–3.8 mm), with significantly thicker LT in females than males ( $3.5 \pm 0.1$  vs  $3.3 \pm 0.1$  mm;  $t = -3.58$ ,  $p = 0.001$ ). LT correlated significantly with estimated %L cones (Pearson  $r = 0.49$ ,  $p = 0.001$ ), such that estimated %L cones was significantly higher in those with thicker than thinner LT ( $n = 22$  vs  $21$ ;  $80.2 \pm 9.2$  vs  $73.0 \pm 11.6$  %L,  $t = -2.68$ ,  $p = 0.01$ ). Multiple linear regression showed a significant association between estimated %L cones and LT ( $\beta = 35.0$ ,  $p = 0.002$ ) when adjusted for sex [ $F(2, 40) = 6.26$ ,  $p = 0.005$ ,  $R^2 = 0.23$ ].

**Conclusion:** The data suggest that each 0.1 mm increase in crystalline lens thickness adds 3.5% to the estimate of %L cones, which implies that a 0.15 mm thicker mean crystalline lens in females may cause mean %L cones to be overestimated by 5.3%. The higher L:M cone ratio in females than males in this population (difference of 4.4 %L) may be explained by differences in crystalline lens thickness. An age-dependent crystalline lens correction may not be good enough for adjustment of spectral sensitivity functions.

**CONTRAST THRESHOLDS AS A FUNCTION OF STIMULUS LUMINANCE FOR TWO COMMERCIAL COMPUTERISED COLOUR VISION TESTS****Mei Ying Boon, Abdulaziz Alotaibi and Stephen Dain**

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**Purpose:** The Cambridge Colour Test (CCT) (Mollon & Rega, 2000) and the Colour and Diagnosis (CAD) (Barbur et al., 2006) test are two gold standard computerised tests that operate on different design principles. The CCT uses static stimuli whereas the CAD has dynamic stimuli and dynamic luminance noise and a higher background luminance than the CCT. These differences are expected to influence colour perception by altering the relative stimulation of different visual pathways (Magnocellular, Parvocellular, Koniocellular). Barbur et al. (2006) evaluated thresholds from the CAD as a function of luminance, but it is not known how the CCT compares. Therefore the purpose of this study is to compare the effect of stimulus luminance on measured thresholds for the CAD and CCT.

**Methods:** Young adults (aged 18-35 years) with normal vision (6/6 corrected binocular visual acuity, passing the Ishihara pseudoisochromatic plate test), pupil size difference of <0.5 mm between the two eyes and good self-reported general health were recruited. Chromatic contrast thresholds were assessed using the CCT and CAD under no room illumination. Luminance of the test stimuli were reduced through the use of neutral density filters (ND 0.3, 0.6, 0.9, 1.5 and 2.0) worn in pseudorandom order. Participant pupil size was recorded through the different neutral density filters under no room illumination using a Neuroptic pupillometer. As the CCT and CAD report data in different units, the CCT was converted to CAD units then both were z scored.

**Results:** Twenty participants (median 19 years, range 18-32 years, 5 males and 15 females) were recruited that met the inclusion criteria. The impact of pupil size and ND filters was estimated for their effect on retinal luminance then luminance of the stimuli were calculated.

CAD thresholds were more affected by low stimulus luminance levels than the CCT and blue-yellow thresholds were more affected by low stimulus luminance levels than red-green thresholds.

**Discussion and Conclusions.** The characteristics of the stimuli and the tasks for the two tests likely account for these differences, including the CAD having a more dynamic stimulus with dynamic noise and more centrally located chromatic stimulus than the CCT. Results are consistent with Knoblauch et al.'s (2001) research that noted lower tritan thresholds were associated with a larger stimulus size and longer stimulus duration, which describes the CCT stimulus. Results are also consistent with Barbur et al.'s findings (2006).

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**COLOURSPOT: TABLET BASED APP FOR SCREENING FOR COLOUR VISION DEFICIENCY IN YOUNG CHILDREN****Teresa Tang<sup>1</sup>, Leticia Álvaro<sup>2</sup>, James Alvarez<sup>1</sup>, Brenda Meyer<sup>1</sup>, John Maule<sup>1</sup>, Anna Franklin<sup>1</sup> and Jenny Bosten<sup>1</sup>**<sup>1</sup> University of Sussex, United Kingdom<sup>2</sup> CES Cardenal Cisneros, Spain*Corresponding author: teresa.tang@sussex.ac.uk*

Colour vision deficiency (CVD) is a common genetic visual abnormality affecting about 8% of males and 0.5% of females. However, CVD is often under-recognised and not detected until late childhood. In the UK, colour vision screening is not compulsory in schools and many opticians do not include colour vision screening as part of their eye examination. Existing tests of colour vision for children include the Ishihara Unlettered Persons and the Neitz Test of Colour Vision. However, both tests require an ability to report shapes which can be challenging for children who are under 5 years old.

We have developed a child friendly gamified tablet-based app to use as screening for CVD in young children. This app does not require children to use their language or reading skills. On each trial, children are shown 12 discs (spots) which contain a deutan, a protan, a tritan target and 8 distractors. Children are asked to find and tap the "coloured" spot on the screen. If a target is tapped, an animal character appears whilst making a sound. Depending on whether a target or a distractor is tapped, the saturation of the targets are altered along the three confusions lines according to an adaptive staircase procedure. There are 5 scene changes to keep the children engaged.

We have tested about 800 boys aged 4-7. Each child was tested on the Ishihara Unlettered. Any child that made an error on the Ishihara Unlettered did the ColourSpot app. A control sample of randomly selected boys (approximately N=160) also did the ColourSpot app. Any child that made three or more errors on the Ishihara Unlettered was considered CVD (6.6% of boys). Any child that made one or two errors on the Ishihara Unlettered was assigned to a third 'inconclusive' group (1.5% of boys).

Data from ColourSpot were fitted with psychometric functions in order to extract protan, deutan and tritan thresholds. For children characterised as normal, their deutan, protan and tritan thresholds performances were similar. For children characterised as CVD, deutan and protan thresholds were higher than their tritan thresholds. Our data suggest that comparing threshold ratios (protan/deutan to tritan) is a more reliable way of identifying children with CVD than using the raw deutan and protan thresholds.

ColourSpot is a sensitive test for CVD in young children and could be used as a diagnostic tool for CVD to benefit teachers, clinicians and researchers. The next steps are to determine appropriate criteria for assigning CVD in marginal cases, as well as to investigate the potential for categorising dichromats and anomalous trichromats. We plan to continue validating the ColourSpot in a larger sample of 4-7 year old children as well as test ColourSpot against the anomaloscope in older children.

**THE CHROMATIC STRUCTURE OF PAINTINGS FROM PRE-PRIMARY CHILDREN****Catarina FM Herdeiro, João MM Linhares and Sérgio MC Nascimento**

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Children use colours since very early age. Their drawings and paintings can be easily identified as done by children but are they that different from adults' colour compositions? Quantitative information about how very young children use colours is scarce and it is unclear whether their aesthetic preferences are similar to those of adults. The goal of this study was to analyse the colours of paintings of pre-primary school children and to compare their chromatic structure with traditional paintings made by adult artists. 104 paintings from 9 children in the age range 3 to 5 years old were digitalized with hyperspectral imaging from 400 nm to 720 nm, with a 10 nm interval, and a spatial resolution of 1344×1024. The paintings were selected from past children's portfolio and had no underlying formatting template. The children had normal colour vision as tested by the Ishihara colour test. The spectral reflectance for each pixel of the paintings were estimated from spectral imaging data and used to render each painting under the standard illuminant D65. Data were then converted into CIELAB colour space. The colours of each painting were characterized by the properties of an ellipse fitted to the CIELAB data based on a least squares criterion. The distributions of the ellipses parameters across paintings were then compared with those obtained from spectral imaging data for 44 paintings rendered in the same way and done by different artists from different époques (Montagner et al, 2016). It was found that the chromatic structure of the paintings done by children is very similar to that of the paintings done by artists. The distributions of the parameters of the ellipses for children's and artists' paintings were remarkably similar. In particular, the ellipses show the same tendency to have axis ratios close to 0.6, i.e., the same degree of elongation of the colour gamut in CIELAB. They also show similar tendency to be oriented along an axis close to the blue-yellow axis. These results suggest that aesthetic preferences for colour compositions of very young children are similar to those of adults.

**TOWARDS A BETTER UNDERSTANDING OF VISUAL SNOW****Simon Saryazdi and Jenny Bosten**

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Background: Variations of perceptual noise within the visual system have been detailed in the literature since the 19th century under terms such as 'augenschwarz', 'eigengrau', 'eigenlicht', 'light chaos', 'light dust' and 'idioretinal light'. While these and other similar terms have been subjected to different phenomenological descriptions since that time, they generally refer to an achromatic movement of spots or dustings of light seen in the visual field in the absence of external light. More recently, the term 'visual snow' has been used to describe a clinical symptom where individuals report experiencing a persistent presence of TV-like static or moving dots within their visual field, even during the day, which bears striking resemblance to some of the phenomena previously described. Visual snow in this population is usually accompanied by a heterogenous variety of other visual symptoms, such as palinopsias in the visual field (e.g. persistence of afterimages and visual trailing). As such, the condition has now been described as a syndrome (visual snow syndrome). Those with visual snow syndrome have reported both achromatic and chromatic experiences of visual snow. We were interested in understanding how visual snow is related to earlier descriptions of visual noise, and whether the achromatic/chromatic distinction is informative as to the cause of visual noise.

Methods: We produced a detailed questionnaire to investigate the properties of visual snow syndrome. The purpose of the questionnaire was to help us refine its diagnostic criteria, and to develop tools to measure the intensity of visual symptoms and the impact those visual symptoms have on individuals. In the context of visual noise, we asked participants about their own experiences of visual snow. Using lay language, we asked participants whether they experienced achromatic and/or chromatic visual snow. We asked if these experiences differed under photopic and scotopic conditions. We asked whether graphical animations of visual snow presented were representative of their own experiences of visual snow, and if they experienced chromatic visual snow, what colours they experienced. We additionally asked if the colours they perceived in their chromatic visual snow were uniform over the visual field or not, and whether the dots themselves were of colour, or if the colour was separate from the dots.

Results: We detail the different presentations of visual snow across individuals and how these relate to historical descriptions of perceptual noise. We assess whether the range of visual symptoms experienced by individuals with visual snow can be predicted by whether they experience achromatic or chromatic visual snow. We explore the correlation with other visual symptoms to ascertain with greater certainty that chromatic visual snow is not merely an integration of achromatic visual snow and coloured artefacts of other visual symptoms.

**COLORFULNESS ADAPTATION AND NATURALNESS IN THE COMBINATION OF SATURATION AND LIGHTNESS CONTRAST ON IMAGES****Taishi Masumitsu and Yoko Mizokami**

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It has been shown that our visual system can adapt various changes in the color environment. Mizokami et al. (2012) showed that the effect of colorfulness adaptation was stronger for natural images than for shuffled images with a collage of randomized color blocks. It suggests that the naturalness of spatial structure affects the strength of the colorfulness adaptation. However, they examined the condition that only the saturation of images was modified. On the other hand, Nakano et al. (2009) showed that the image appeared more natural when the luminance contrast of an image was increased (decreased) according to the increase (decrease) of saturation of the image than when only saturation was changed. This perceived difference in naturalness due to the combination of saturation and luminance contrast may also affect colorfulness adaptation. In this research, we investigated whether colorfulness adaptation was influenced by the naturalness of images whose saturation and lightness contrast were modulated.

In the experiment, three types of modulated images were used as adaptation stimuli: images which only their saturation changed ("Saturation-modulated stimuli"), images which their lightness contrast changed in proportion to the saturation ("Naturally modulated stimuli") and images which their lightness contrast changed in inverse proportion to the saturation ("Unnaturally modulated stimuli"). Each stimuli group included six images. A test stimulus for colorfulness judgment was an image which was not included in adaptation stimuli. We also used three types of modulated images for test stimuli: "Saturation-modulated test stimuli", "Naturally modulated test stimuli" and "Unnaturally modulated test stimuli". Following to 3-minute-dark adaptation, observers adapted to images with certain saturation level chosen from one of the adaptation stimuli groups for 2 minutes. After that, a test image was presented for 3 seconds followed by 10-second re-adaptation to the same adaptation stimuli, and observers judged whether the test image appeared "natural" or "too colorful". This judgment was repeated for seven test images during one session. Three saturation levels in three adaptation stimuli groups were examined. Five observers participated and each observer run three sessions for each condition.

Our results showed that the perception of colorfulness was influenced by adaptation to the saturation of images. When observers adapted to higher saturation, the border of "natural" and "too colorful" appearance shifted to higher saturation and vice versa. The effect was stronger when adapting to saturation-modulated stimuli and naturally modulated stimuli, and weaker when adapting to unnaturally modulated stimuli. All conditions of the test stimulus showed a similar trend. We further evaluated the subjective naturalness of adaptation images. The result showed that images in saturation-modulated stimuli group and naturally modulated stimuli group obtained high naturalness, but images in unnaturally modulated stimuli group obtained low naturalness in general. This trend was consistent with the result of the adaptation experiment.

It was shown that the combination of saturation and lightness contrast modulation affected the strength of colorfulness adaptation, suggesting that the naturalness of color combination is an important factor for colorfulness adaptation.

**EXPERIMENTAL COMPARISON BETWEEN ELDERLY COLOUR VISION AND COLOUR VISION SIMULATED WITH THE LENS AGEING MODEL: VISIBILITY OF HANDRAILS UNDER PHOTOPIC AND MESOPIC VISION ENVIRONMENT****Takashi Sakamoto<sup>1</sup>, Yuri Kajimura<sup>2</sup>, Akiko Kubo<sup>2</sup>, Masafumi Yoneda<sup>2</sup>, Hiroyuki Hagiwara<sup>1</sup>, Koji Kitamura<sup>1</sup>, Yoshifumi Nishida<sup>1</sup> and Yasuyo G Ichihara<sup>3</sup>**<sup>1</sup>AIST (National Institute of Advanced Industrial Science and Technology), Japan<sup>2</sup>YKK AP Inc., Japan<sup>3</sup>Kogakuin University, Japan*Corresponding author: takashi-sakamoto@aist.go.jp***1. Objectives**

This study focuses on the visibility of real objects by the elderly in the mesopic vision environment, where the elderly, perhaps, encounter problems in seeing and recognising objects, such as handrails. In the twilight evening and early morning, the elderly often walk in the corridor and the stairs of their houses without turning on lights; accordingly, handrails could enable the elderly evade falling accidents. In the ageing society, the visibility of handrails has become a social issue. Therefore, this study aims to investigate the visibility of various coloured handrails and backgrounds among the older adults in the photopic and mesopic vision environments. Furthermore, this study aims to investigate whether glasses simulating elderly colour vision based on the lens ageing model could be used to assess the visibility of the older adults.

**2. Methods**

We performed the experimental assessment using six handrails coloured with pale yellow (with woody texture), dark brown (with woody texture), white, red, orange, silver (with metallic texture) and two pale yellow handrails with luminous tapes and LED lights. In addition, the lighting environment was provided with two illuminance conditions and three wall colours. Illuminance conditions were photopic vision condition (501 lux under 6500 K fluorescent light) and mesopic vision condition (0.51 lux under 4000 K fluorescent light). Wall colours were white, dark brown (with woody texture) and grey (with concrete texture). In this study, 15 Japanese elderly participants (age, 75–85 years) and 15 adult participants (age, 30–49 years) passed the colour vision and visual acuity tests. All 15 adult participants wore glasses that simulated elderly colour vision based on the two-factor model (Pokorny et al., 1987). In that case, adults were expected to be equivalent to 75–80 years old. All participants were assessed on the basis of the visibility of handrails using the magnitude estimation method, scaled from 0 to 100.

**3. Results**

In the 501-lux illuminance condition, we observed no significant difference between the assessment of the elderly and adults wearing glasses. Red and orange handrails exhibited the best visibility under the photopic vision condition. Conversely, under 0.51-lux illuminance condition, almost complete assessment by the elderly was markedly better than that by adults wearing glasses. Remarkably, when participants saw a handrail with LED lights, the assessment by the elderly was markedly worse than that by adults wearing glasses; this reverse phenomenon could be attributed to 'discomfort glare' or optical scattering originating from the particles of protein in the ageing lens. Moreover, a handrail with LED lights displayed another negative result; almost all elderly participants could not recognise it as a handrail, because they only found a bright, long object on the wall, although a handrail with LED lights had the best visibility.

**COLOUR COMPARISONS OF NATURAL SCENES UNDER CHANGES IN LIGHTING GEOMETRY****Zeinab Tirandaz and David Foster**

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The lighting in natural scenes is inconstant. In the absence of cloud, the main source of variation is the sun, whose elevation leads to changes in the spectrum of the illumination and its geometry. Chromatic transformations of the reflected colour image, recorded by the eye or trichromatic camera, can compensate for changes in the spectrum, but not in the geometry, especially changes in the distribution of shadows over surfaces. The aim of this work was to determine whether geometric changes are sufficiently dense within natural scenes to impair colour comparisons across time. Data were taken from sequences of 7-9 time-lapse hyperspectral radiance images acquired from four medium-to-far-distance outdoor scenes of woodland, herbaceous vegetation, barren land and rock, and rural and urban buildings. Intervals between image acquisitions varied from 0.25 h to 6.25 h. Points in scenes were ranked for possible changes in illumination geometry according to their luminance differences and were excluded if they exceeded an empirically determined threshold percentile. To quantify the colour appearance of the remaining points, CIECAM02 Jab coordinates were calculated, representing lightness and red-green and yellow-blue chromatic components, respectively. The product moment correlation coefficient between Jab coordinates was then calculated across intervals. For some scenes, correlations were high with just 10% to 15% of scene points excluded; for other scenes, correlations were much lower, despite more points being excluded. Reliable colour comparisons are clearly possible under changes in lighting geometry, but identifying, in a principled way, which scenes and surfaces allow such comparisons remains a challenge.

**WHEN DO CHILDREN DEVELOP ADULT-LIKE COLOUR CONSTANCY?****Rebecca Wedge-Roberts, Stacey Aston, Ulrik Beierholm, Bob Kentridge, Maria Olkkonen and Marko Nardini**

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Colour constancy is the ability to perceive surfaces as having a relatively unchanging reflectance under changes in illumination despite the surface reflectance and illumination being confounded in the signal sent from the retina. Colour constancy has been studied in adults, using techniques such as achromatic setting and asymmetric matching. Some studies (e.g. Delahunt and Brainard, 2004) suggest that people are more colour constant for scenes illuminated by lights on the daylight locus, particularly blues. This implies that priors for certain illuminations can constrain the problem of colour constancy. However, little is known about how colour constancy develops throughout childhood, and traditional methods of measuring colour constancy are inappropriate for children. Here, we have developed a novel task adapted from the goal-directed task used in Radonjić et al (2015). This will provide insight into the extent to which colour constancy may be an evolved skill or one that depends on experience with surfaces and lights.

In a two-dimensional computer-based task, six- to 11-year old children, and adults, were asked to find Derek the Dragon's favourite sweet from a set of eight competitors. The reference sweet (Derek's favourite) was shown on the left side of the screen under a neutral illumination (D57). The eight competitors were shown on the right side of the screen under a test illumination – either blue or yellow (on the daylight locus) or red or green (perpendicular to the daylight locus in CIELUV space). All chromatic illuminations were 30ΔE away from D57 in CIELUV. The competitors were selected to come from a continuum containing a tristimulus match (no colour constancy) and a reflectance match (the target sweet – perfect colour constancy). From the sweets selected under the test illumination, as well as the sweet chosen under a neutral control condition, we calculated a colour constancy index (CCI).

A significant main effect of illumination colour was found on adult CCIs. They had the highest CCIs for scenes under blue illumination, consistent with previous research, but the lowest CCIs under yellow illumination, despite this being on the daylight locus. This suggests that there may be a specific benefit to blue illuminations rather than daylight illuminations in general. A comparison between children and adults suggests that, under blue and yellow illuminations, children and adults have a similar degree of colour constancy. However, preliminary results suggest that younger children may have a higher degree of colour constancy under red and green illuminations than older children and adults. This may be because younger children have not yet learned the blue-illumination priors that adults use when determining whether a colour change is due to an illumination or surface change.

Following on from these findings, we plan to test colour constancy in a three-dimensional scene, with more available information. The extent to which adults will show a greater benefit than children when additional potential cues to constancy are available will provide further insight into the degree to which using these cues is a skill which is learned through experience over the life-span.

**COLOUR-SPECIFIC RESPONSES OF THE GOLDFISH RETINAL GANGLION CELLS REVEALED BY CONE-ISOLATED VISUAL STIMULATION****Paul Maximov, Alexey Aliper and Elena Maximova**

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Three types of cones (long-wave, middle-wave and short-wave sensitive) in the goldfish retina determine its color vision observed in its behavior. However the most of retinal ganglion cells (GCs) projecting to the tectum opticum – motion detectors – seem to be colour blind. Nevertheless the connections of the ganglion cells (through the bipolar cells) with different spectral types of cones proved to be non-uniform. To examine these connections we use cone-isolated visual stimulation.

Earlier we showed that direction-selective GCs classified as ON-type cells according to the results of achromatic stimulation, respond to the movement of the stimuli selective for the long-wavelength (L) receptor as ON-type cells as well, but respond to the stimuli selective for the middle- and short-wave receptors (M, S) – as OFF-type cells. Orientation-selective GCs responding as ON-OFF cells to gray edges, respond to the coloured edges selective for L cones as ON-OFF cells as well, but respond as OFF-cells to the stimuli selective for M cones and as ON-cells to the stimuli selective for S cones. To explain this behaviour it was necessary to assume the presence of special types of bipolar cells in the retina, forming synapses of different signs with cones of different spectral types (Maximov et al., 2015).

The responses of sustained GCs to selective stimulation of color channels look even more complex. Some of the observed dark sustained GCs respond both to the stimuli exciting L cones and to the stimuli inhibiting L cones, and demonstrate complex colour interactions in the receptive field when stimulated with colours that excite (or inhibit) two spectral types of cones simultaneously. Thus the retinal circuitry underlying this interaction looks unclear and needs to be modelled.

The model is made in the form of a three-layer artificial neural network. An input layer consists of three receptors corresponding to the three spectral cone types of the goldfish. Neurons of the second layer (bipolar cells) are connected with all receptors by synaptic connections, the weights and signs of which can be arbitrarily chosen. In addition, each of the neurons of the second layer is given a certain potential corresponding to its state at the moment when no input signals come to it. The neuron of the third layer (a GC) is connected with second layer neurons by non-inverting rectifying synaptic contacts. The weights and signs of the synapses of the second layer neurons as well as their potentials are adjusted (manually or by iterative computations) to get the responses similar to those observed in the electrophysiological experiments.

The experiments with the model have shown that in most cases the responses of GCs to colour stimulation observed in the electrophysiological experiments can be explained by the model with two types of bipolar cells forming specific synaptic connections with cones of different spectral types.

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**INTERNAL WHITE POINTS MEASURED BY ACHROMATIC ADJUSTMENT****Gaurav Gupta, Anya Hurlbert, Naomi Gross and Ruben Pastilha**

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Colour constancy and adaptation to ambient light have often been characterised in terms of achromatic settings (the surface chromaticity perceived as neutral under the adaptation conditions) (see e.g. Werner & Walraven, 1982; Brainard, 1998; Bosten et al., 2015; Winkler et al. 2015; and Weiss et al., 2017). The assumption is that, under perfect adaptation, participants will produce achromatic settings that are indiscriminable from the chromaticity of the ambient illumination. Similarly, settings indicating only partial constancy would lie somewhere between the ambient illumination chromaticity and a neutral reference chromaticity. Typically, participants make matches representing varying levels of partial adaptation. Participant achromatic settings show high individual variability, in our own experiments as well as in others. For example, it has been shown that a range of daylight chromaticities are considered as acceptable white (see Winkler et al., 2015; and Weiss et al., 2017). The question we ask is whether the variability is influenced by stable differences in individual “internal” white points.

To investigate this idea, we establish and compare individuals’ internal achromatic points from two different achromatic adjustment paradigms. The first paradigm involves making neutral matches on a display under fully-immersive ambient illuminations ranging from moderate to extreme chromaticities, while the other involves making neutral matches of a patch against a black surround on a computer monitor (in the “void”). Ideally, in order to assess internal whitepoints, we would like to obtain achromatic settings in the absence of other cues to “acceptable” white, which the extreme illuminations and black surround satisfy. The moderate chromaticities of the first condition are included for further insight into the range of achromatic settings. Analysis of the two sets of results allow us to assess the following assumptions about the internal chromatic point: a) it lies on the extended vector of partial adaptation, is a memory chromaticity that is stable under visibly non-neutral ambient illuminations, and is indicated by the intersection of many partial adaptation vectors under different chromatic illuminations, b) it is also indicated by neutral matches made in the “void”, and c) it is stable whether tested by the method of extrapolation from partial adaptation vectors or by the method of adjustment in the “void”.

Our findings suggest that the internal achromatic point is indeed stable for the individual under different ambient illuminations that are clearly non-neutral, and also that the focal point of achromatic settings may shift when the light chromaticity is moderate enough to be accepted as neutral. The results from the two paradigms differ in that there is remarkable intra-participant consistency in the achromatic settings for a patch in the “void” displayed on a computer monitor, while there is larger variability in the achromatic matches under immersive illumination.

**BEST LIGHTING FOR VIEWING THE SKIN OF HUMAN FACES****Andreia E Gomes, João MM Linhares, Ricardo JF Pereira and Sérgio MC Nascimento**

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The colour of the human skin provides several types of information about the individual, e.g. health condition, emotional status and beauty. For example, dermatologists use chromatic cues to diagnose skin conditions. The cosmetic industry invests millions to develop products to optimize skin colour.

As the perception of the human skin is influenced by the colour and spectrum of the illumination it is important to estimate the light that observers prefer to visualize natural human skin. The purpose of this work was to estimate the best daylight illumination for viewing the skin of human faces.

A set of 11 human faces with eye lids and mouth closed were imaged by hyperspectral imaging, and the reflectance spectra estimated. Spectral radiance was then computed assuming daylight illuminants from 4000 K to 25000 K in 41 steps and the tristimulus values were estimated assuming CIE 1931 2<sup>o</sup> standard observer. Images obtained were then displayed in a CRT colour monitor calibrated in colour and luminance at 1m from the observer with an average luminance of 12 cd/m<sup>2</sup>. Each trial started assuming a random daylight illuminant and were presented in a circular endless loop carousel, providing the observer with no cues of the viewing limits. The observers' task was to select the images that produced the best visual impression, after circulating through all available possibilities. Twelve young observers with normal colour vision performed the experiment completely unaware of the purpose or the design of the experiment and unfamiliar with the human faces in testing. The frequency of daylight illuminant selection was pooled across observers and a gaussian function was fitted to the data. The position of its maximum was assumed to be the preferred lighting condition.

It was found that the preferred daylight illuminant had a CCT of about 5590K. If black and white skins were considered independently, the preferences were of about 5800K and 5460K, respectively.

These results seem to suggest that these observers preferred a smaller CCT when compared with the average daylight D65 and differences exist if black and white skins are considered independently.

**THE INFLUENCE OF MODIFYING COLOURS TO SIMULATE COLOUR-APPEARANCE FOR COLOUR DEFICIENT OBSERVERS ON THE RELATIONSHIP BETWEEN SEMANTIC WORDS AND COLOURS****Ipppei Negishi<sup>1</sup>, Honami Komatsu<sup>2</sup> and Keizo Shinomori<sup>3</sup>**<sup>1</sup> Dept. of Media Informatics, Kanazawa Institute of Technology, Japan<sup>2</sup> Graduate School of Engineering, Kochi University of Technology, Japan<sup>3</sup> School of Information, Kochi University of Technology, Japan*Corresponding author: negishi@neptune.kanazawa-it.ac.jp*

The purpose of this study is to investigate how the relationship between semantic words and colours would be changed when the colours are modified to simulate colour-appearance for colour deficient observers. We tested the influence of this modification on normal and colour deficient subjects. We carried out two experiments using both paired comparison (Exp. 1) and semantic differential (Exp. 2) methods (Shinomori & Komatsu, 2018) on ten normal and five colour deficient subjects. The selection rates of the colours were converted to z-scores.

In Exp. 1, subjects chose from two colour patches which colour was more appropriate for one of nine given words. The patches were selected from 15 colours (12 vivid tone colours from PCCS, as well as white, grey and black) in the colour normal condition. Each subject performed a total of 630 trials (6 times each for 105 combinations of 15 colours) for each word [this part will be presented in Shinomori et al., ICVS 2019]. In the colour-deficient simulated condition, we converted these same 15 colours to simulate colours for deuteranopic vision using the universal colour design assistance tool "UDing", which employs Brettel et al. (1997)'s model. For normal subjects, the difference of z-scores between the normal and simulated conditions had a similar tendency for all words, but for colour deficient subjects, the differences between conditions were much smaller. Unexpectedly, the results of the simulated condition were still different between normal and colour deficient subjects, suggesting that the simulated colour was not necessarily a perfect representation of deuteranopic vision. We additionally analysed the z-score data by principal component analysis (PCA). For normal subjects, PC loadings of the colours were different between the two conditions, whereas PC loadings for colour deficient subjects were almost identical between conditions. In Exp. 2, subjects evaluated 15 colours (the same to Exp. 1) for 35 paired semantic words using seven rating scales. The evaluations were performed three times for each combination of colours and words, and the means of seven-scale scores were converted to z-scores. PC values of the colours were similar between two conditions for colour deficient subjects.

As expected from the results of these two experiments, the impressions of simulated colours were still different between colour normal and colour deficient people; the influence to the relationship between semantic words and colours may not be simply explained by the missing photoreceptor pigment. For colour deficient people, the word impression evaluated by simulated colours had a simpler structure than that of the original colours, suggesting that colour appearance for some of the original colours may be slightly different than the appearance of the simulated colours.

**DO LUMINANCE AND BRIGHTNESS DIFFERENCES MEDIATE IN COLOUR ASSIMILATION?****Kim Cerda-Company, Xavier Otazu and Alejandro C Parraga**

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Colour induction is the effect of the surrounding colours (the inducers) on the perceived colour of the target region. This phenomenon is composed by two opposite effects: colour assimilation and colour contrast. The former occurs when the target region is shifted towards the first (closest) inducer, while the latter occurs when the target region is shifted away from that. In our studies we use concentric rings patterns where one is the “test” ring and the others the “inducers”.

Previously, we observed that colour assimilation depends on the luminance difference between the target region (the test ring) and the first inducer but also on the chromatic condition (Cerda-Company et al., 2018). In this study, we ask whether this luminance effect is due to luminance or brightness differences. To approach this question, we have defined both, equiluminant and equibrightness stimuli and we have varied both the luminance and the brightness of the all different elements in a patterned stimulus (the test ring, the first inducer, the second one, and both at the same time in an opposite way). At equiluminance, brightness differences might be present and, at equibrightness, luminance differences might be present. Moreover, we defined four chromatic conditions along the cardinal axes of the MacLeod-Boynton colour space (red-green, green-red, purple-lime and lime-purple).

We observed that the effect on colour assimilation is very similar in both experiments: In the equi-conditions (either equiluminance or equibrightness) no colour assimilation occurs, while in unconstrained conditions (non-equi-conditions) it may occur. This result could suggest that the differences (either luminance or brightness differences) at equi-conditions are not large enough to induce colour assimilation. The most striking differences between both experiments are observed along the *s* axis, where the colour assimilation effect is strongly reduced. In contrast, along the *l* axis, the results are identical. Similarly to previous results, the red-green (i.e., first inducer is red and second inducer is green) chromatic condition tends to induce colour assimilation whereas green-red never induces this effect.

Interestingly, the effect is almost the same when either the luminance or the brightness of the elements vary: When the test ring luminance (or brightness) is varied, in the *s* axis, the strongest colour assimilation occurs; for the first inducer case, the effect is the same, albeit weaker; the luminance (or brightness) of the second inducer does not take much into account; and when both inducers are varied, the effect is very similar to the first inducer case.

In this study we conclude that: (1) luminance (or brightness) differences are a key factor to induce colour assimilation; (2) the effect of luminance (or brightness) differences is stronger along the *s* axis than along the *l* one; (3) in agreement with previous results, green-red chromatic condition never induces colour assimilation; (4) the results along the *s* axis support the mutual-inhibition hypothesis in the koniocellular pathway; (5) the further away the varied region, the weaker its influence; (6) the strongest colour assimilation occurs when the inducers compose an equiluminant, but not equibrightness, surface.

Cerda-Company, X., Otazu, X., Sallent, N., & Parraga, CA. (2018). The effect of luminance differences on color assimilation. *Journal of Vision*, 18(11), 10.

**SPECTRAL DENSITY CURVES OF THE HUMAN LENS ARE INACCURATE DUE TO INCREASED RAYLEIGH SCATTER IN POST MORTEM EYES****James A Kuchenbecker, Maureen Neitz and Jay Neitz**

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Light energy in the environment travels through ocular media before it reaches the cone photoreceptors in the back of the retina. These ocular media are not neutral in the absorption of wavelengths across the EM spectrum, and thus alter the light energy as it is measured at the cornea. Thus, having an accurate estimate of the absorption caused by these ocular media is important for knowing the spectrum of light reaching the cones. The absorption spectrum of the human lens dominates the estimate of the transmission of the ocular media. This is because 1) even at the shortest path length through it, the lens has largest optical density of any absorptive media, and 2) the low-pass-filter (LPF) nature of the spectral cutoff serves the function of preventing harmful ultraviolet (UV) light from damaging the retina. Estimates of the human lens reported by Wyszecki & Stiles (1982 Color science) have often been used however, transmission estimates that emphasize material excised from cadavers have the disadvantage of the possibility of errors introduced by post mortem changes in the lens. The most salient artifact is increased cloudiness in proportion to time after death. If lens media contained only a single pigment absorber, it should introduce little scatter and follow Boltzman statistics, which are modeled well by a single Gaussian. However, the human lens measurements from cadaver tissue exhibit a non-Boltzman statistics curve between the main pigment cut-off and the transition into the longer wavelengths. The possibility that there are errors in the human lens density curves in common use due to time-dependent post mortem changes have not been well investigated. Here, we measured spectral transmission of lenses from three species of genus *Macaca* within a maximum 25 minutes post euthanasia (n=30). We also derived an in vivo estimate of the human lens using data of scotopic sensitivity from Crawford (1949, Proc. Phys. Soc. B, 62:321; n=50, age<30) and a theoretical rhodopsin photopigment template. Both results from the macaque and the human in vivo sensitivity show that the shape of the lens is consistent with a single pigment fit by a Gaussian. Stiles reported that cadaveric tissue with visible cloudiness was excluded from the average estimate, but evidence here suggests time post-euthanasia induces Rayleigh scatter elements that affect the measurements before they are visible by inspection with the human eye. We propose a new transmission curve for the average young human eye that is free of inaccuracies due to increased Rayleigh scatter in post mortem eyes.

**RELATIONSHIP BETWEEN PERIFOVEAL L-CONE ISOLATING SPATIAL ACUITY AND RETINAL STRUCTURE IN EARLY AND INTERMEDIATE AMD****Hilde R Pedersen, Åshild B Horjen, Stuart J Gilson and Rigmor C Baraas**

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A significant correlation has been reported between measures of L-cone acuity and cone density at 5 deg eccentricity in young healthy adults (Baraas et al., Vision Res. 2017;132:45-52). The aim here was to examine if measures of L-cone acuity at 5 deg eccentricity correlated with changes in the cone photoreceptor mosaic in individuals who have early and intermediate age-related macular degeneration (AMD).

Multimodal high-resolution imaging, including colour fundus photographs, Heidelberg Spectralis SD-OCT2 and Adaptive Optics Scanning Light Ophthalmoscopy (AOSLO), were employed to examine the outer retina in participants with early and intermediate AMD (n=10, aged 61–78 years) and healthy controls (n=15, aged 24–70 years). Colour vision was examined with the Ishihara (24 pl. ed., 2005) and the Hardy-Rand-Rittler pseudoisochromatic plates (HRR, 4th ed., 2002) under controlled illumination. Red-green (RG) and yellow-blue (YB) chromatic thresholds were measured in the best eye with the Colour Assessment and Diagnosis (CAD) Test under standard test conditions.

L-cone isolating spatial acuity was measured in the best eye with a tumbling Sloan E letter of 23% increment cone contrast. The background was 10 cd/m<sup>2</sup> with chromaticity metameric to CIE illuminant D65. Observers were corrected to best foveal achromatic acuity and viewed a fixation cross (fixation verified with an eye-tracker) from a distance of 229.2 cm while the L-cone Sloan E was presented at 5 degrees temporal eccentricity. The size of the stimulus varied on each trial using a 4AFC Bayesian adaptive method (Kontsevich & Tyler, Vision Res. 1999;39:2729–2737) to determine the discrimination threshold (as the minimum angle of resolution, MAR). Confocal and split detection AOSLO images at 5 degrees temporal eccentricity were used to identify individual cones and estimate Inter Cell Distance (ICD). Nyquist sampling limit of the cone mosaic (Nc) was calculated for each participant's ICD (Rossi & Roorda, Nat Neurosci. 2010;13:156-157).

Best corrected foveal acuity was 0.3 logMAR or better. All participants made < 3 errors on Ishihara and HRR, except one deuteranomalous male who was excluded from the CAD analysis. RG and YB SNU thresholds were similar in participants with early AMD compared with age matched normal controls only (mean ± SD RG SNU 2.41±0.36 vs. 2.89±0.97, P = 0.59 and YB SNU 3.12±1.02 vs. 2.45±0.54, P = 0.23), but those with intermediate AMD had significantly higher RG and YB SNU than age matched controls (RG SNU 8.58±5.82, P < 0.05 and YB SNU 11.04±5.93, P < 0.05).

AOSLO images of sufficient quality for analysis and L-cone logMAR measures were obtained for 7 of 10 with AMD and 14 normal controls. There was a significant correlation between L-cone logMAR and logNc for controls and participants with early AMD (n= 19, Pearson's r = 0.46, P < 0.05). Those with the most severe degrees of AMD had L-cone logMAR > 4 SD poorer even if Nc was within the normal range. This suggests that perifoveal functional changes precede changes in the cone photoreceptor mosaic in AMD.

**EARLY INFANCY DEVELOPMENT OF DISCRIMINATION IN PROTAN, DEUTAN AND TRITAN COLOR CONFUSION AXES USING 2-AFC VERSION OF THE CAMBRIDGE COLOUR TEST****Marcelo Costa, Leonardo D Henriques and Dora F Ventura**

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Color vision from birth to infancy is still an intriguing subject since norms for responses to the different color confusion axes have not been determined and the developmental course is not yet adequately established. Testing of newborn and infants is challenging, due to attentional fluctuations and to difficulty in gaining the infant's collaboration. Here we propose a 2-AFC paradigm adapted from our previous modification of the Cambridge Colour Test (Goulart et al., 2008) in which an approximately square patch is presented at either the left or the right side of a monitor screen. The patch chromaticity differs from the background along the protan, deutan and tritan color confusion axes between 1100 X 104 and 20 X 104 u'v' units in the CIE 1976 u'v' color space. We tested 98 term infants aging from 3 to 45 months (51 males, 47 females) with normal visual acuity assessed by the Teller Acuity Cards. The testing distance was 55cm. with the color target subtending about 7° of visual angle. The experimenter guessed where the target was by judging the infant's direction of gaze or other behavioral indications. Correct responses advanced the chromaticity towards the background and wrong responses moved in the opposite direction. Thresholds were based on 11 reversals. Our results for infants between 3-6 months show that the deutan axis thresholds were lower than for the other axes ( $F_2 = 3.75$ ,  $p = .033$ ), while at 16 months protan and deutan thresholds were similar. Tritan thresholds were always the highest. A development model was better adjusted to a power function with the exponents of -.95, -.84 and -.87 for the protan, deutan and tritan axes, respectively. Our results revealed better chromaticity discrimination for the deutan axis in comparison with the other two axes, suggesting an early development for the M-cone pathway. The higher exponent for the protan axis might indicate a faster L-cone pathway developmental rate. The power function modeling indicates an exponential ratio between age increase (in months) and the decrease of the chromaticity thresholds (in CIE 1976 u'v' units).

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Goulart, PR., Bandeira, ML., Tsubota, D., Oiwa, NN., Costa, MF., & Ventura, DF. (2008). A computer-controlled color vision test for children based on the Cambridge Colour Test. *Vis.Neurosci.*, 25(3), 445-450.

**A QUADRATIC MODEL OF THE FMRI BOLD RESPONSE TO CHROMATIC MODULATIONS IN V1****Michael Barnett, Geoffrey Aguirre and David H Brainard**

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**Purpose:** Color isodetection contours have successfully been modeled as ellipsoids (Poirson et al., 1990). In addition, fMRI has been used to examine the cortical responses to chromatically varying stimuli. Specifically, this method has been used to measure color tuning at the level of visual areas (V1, V2, etc.) Here we examine how well an ellipsoidal model describes cortical responses to stimuli modulated in the LM-cone plane. Successful validation of such a model would allow for model fits based on efficient sampling of the stimulus space and would enable the prediction of responses to the full set of color directions and contrasts. In addition, the model parameters provide a succinct characterization of cortical color sensitivity and how it varies within and across visual maps.

**Methods:** We performed fMRI scans on 3 subjects while they viewed full field chromatic stimuli that were temporally modulated in the LM-cone plane at 12 Hz. These stimuli were bipolar modulations around a common background shown at 5 different contrast levels in each of 8 color directions. Subjects viewed each contrast/direction pair 10 times while performing an attention task. Data were analyzed within V1 between 0- and 20-degrees eccentricity. We tested a nested set of models in which we successively reduced the number of free parameters. We started with a general linear model (GLM) in which the response to each stimulus was characterized by its own weight parameter. This GLM model provides a benchmark for subsequent model performance. Next, we fit Naka-Rushton functions to the contrast-response functions in each color direction, and varied which parameters (amplitude, exponent) were constrained to have common values across the different directions. Finally, we tested a quadratic color model (QCM) which assumes an ellipsoidal isoresponse contour in the LM plane and a single Naka-Rushton response nonlinearity common to all color directions (using a total of 6 parameters). Both the Naka-Rushton models and the QCM model produced estimates of the GLM beta weights. The time course of the V1 response can be predicted by convolving the HRF with the model predictions based on the stimulus sequence for a given run. We cross-validated the performance of the different models to test the generalizability of the predictions. This provides us with a mean cross-validated RMSE and standard error for the GLM, Naka-Rushton, and the QCM.

**Results:** The QCM model's isoresponse contours were in general agreement with previous work (Engel et al., 1997): maximum sensitivity was in the L-M color direction and minimum sensitivity was in the L+M direction, when stimulus strength is expressed as cone contrast vector length. The cross-validated RMSE for the GLM, Naka-Rushton, and QCM did not differ appreciably, showing that the QCM model generalizes in a cross-validated sense just as well as the more flexible models, but with fewer free parameters.

**Conclusions:** We conclude that the QCM model is an appropriate choice to model V1 responses to full field chromatic stimuli. Its parameters provide a succinct characterization of the quantitative color response properties as measured using BOLD fMRI.

**A 3-SENSOR TETRACHROMATIC SYSTEM SUITED FOR MEASURING REAL-WORLD COLOUR****Thomas Bangert and Ebroul Izquierdo**

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Tetrachromacy is generally associated with four colour sensors but formally it is defined by the number of independent channels that convey colour information. This designation is widely used, despite the fact that sensors of natural organisms almost always exist in pairs. Sensor measurements are rarely absolute but are instead a measure of difference; which requires a reference to differ from, and this generally requires sensors to be organized into pairs. The human visual system, on the other hand, has three colour sensors, which is not an even number that can easily be divided into pairs. The study of colour perception and the study of the physiology of the neural circuitry show that colour information in the human visual system is organized as if it had access to pairs of colour sensors; fundamentally into two information channels driven by two pairs of sensors that oppose each other. The organization of the human visual system is an anomaly in the natural world because it has three colour sensors. This stems from an unusual evolutionary history where our distant ancestors had four colour sensors but as these creatures increasingly specialized in nocturnal lifestyles, they lost one of their colour sensor pairs and became 'dichromatic'. As mammals returned to the diurnal world the need for colour vision increased and this led to the development of a third colour sensor. It is known from studying colour perception that our perceptual colour space is inherently two-dimensional, and that our third colour sensor is essential for this. This is illustrated by the standard CIE 1931 colour space which has a two-dimensional chromaticity space; and also by its extension, the CIE Lab colour space, which organizes chromaticity as two opponent colour channels (a = red-green, b = blue-yellow). However, the CIE chromaticity space is neither 'trichromatic' (inherently 3-sided) nor 'tetrachromatic' (inherently 4-sided) but rather a compromise between the two.

We present two simple related sensor systems that, on the one hand allow colours to be measured and coded using four spectrally restricted colour sensors arranged into opponent pairs and on the other hand allows colour to be measured in the same way using just three sensors, but at the cost of additional computational complexity. The sensor systems are related by the fact that the sensors used by the 3-sensor system are simply the sensors of the 4-sensor system with the spectrally narrowing optical filters removed. Even though only three sensors are used, the colour space is fully regular and is 4-sided rather than triangular. The four 'corners' of the colour space fall exactly on the same points as the four-sensor system, making it formally equivalent to the four-sensor system and therefore "tetrachromatic". This demonstrates that sensor systems using three sensors can be fully equivalent to systems with four colour sensors. Furthermore, we show that this system is effective in measuring colour for a wide variety of natural colour stimuli for e.g., flowers and frogs.

**OPERATIONAL BASED VISION ASSESSMENT: COLOR DEFICIENCY AND PERFORMANCE WITH HIGH CONTRAST PILOT VISOR COMPARED TO CLEAR VISOR****Steven Hadley, James Gaska and Marc Winterbottom**

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**INTRODUCTION:** Rigid external pilot helmet visors have been approved for flight by US military pilots since WWII era helmets. Initially helmet mounted articulated visors were clear and provided protection from wind blast in flight. Dark tinted visors were introduced for sun and glare protection. In the 1980s a yellow tinted "high contrast visor-HCV" was introduced to possibly improve contrast perception during flight. The yellow tinted high contrast visors are similar to "blue blocking" sunglasses marketed commercially. In this research, the OBVA lab compared two computer-based color tests to evaluate the loss of color vision in normal, protanomalous and deuteranomalous subjects using the high contrast visor and a clear visor.

**METHODS:** Twenty-five observers (7 normal 5 protans and 13 Deutans) participated in the study. The high definition OBVA Cone Contrast Test (CCT-HD) and the Color Assessment and Diagnosis test (CAD test) were compared in Achromatic, L, M and S conditions. For the Achromatic condition, observers were asked to identify the position of the gap in a Landolt C stimulus and the PSI procedure was used to estimate contrast threshold. Three different Landolt C optotype were used. Chromaticity values were different from the background and were chosen to selectively stimulate the L, M and S sensitive cones. The CAD test characterized the sensitivity of the color opponent mechanisms of the visual system, yellow-blue (YB) and red-green (RG). Each stimulus condition was viewed through a high contrast visor (HCV) and a clear visor and the results were compared by taking difference between the Log<sub>10</sub> contrast thresholds of the two conditions (Clear – HCV).

**RESULTS:** The Clear – HVC metric, averaged across all observers with a confidence interval of a two sided t-test with an alpha of 0.05. There are three major findings.

1. The HCV does not change achromatic contrast thresholds. This result was the same for all sizes.
2. There is a small and statistically significant increase in for the L and M cone stimuli and a larger statistically significant decrease in sensitivity to the S cone stimulus.
3. There is a very large and statistically significant decrease in CAD YB scores and no significant change in RG scores.

**DISCUSSION:** The large decrease in CAD YB scores demonstrates that the HCV will severely reduce color discrimination along this dimension. The S cone stimuli results are consistent with the CAD finding in showing a reduction in sensitivity to heterochromatic blue-gray contrast sensitivity. However, the magnitude of the effect is much smaller for the S cone stimulus than the CAD scores. The most likely explanation is that under normal CCT test conditions the S cone stimulus is detected by the yellow-blue opponent visual pathways and is a reliable measure of abnormality. However, because the HCV alters the normal test condition, the S cone stimulus may be detected by the achromatic visual mechanism.

Three other results of the study will also be discussed.

**DYNAMICS OF ADAPTATION DURING 1 HOUR OF WEARING COLORED FILTERS****Yanjun Li, Katherine Tregillus and Stephen Engel**

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The visual system continually adjusts its function to cope with a changing visual environment. Prior work has demonstrated that after putting on colored spectacles, people gradually adapt to the color changes that those filters produce. Our aim was to study the time course of this adaptation, over “medium-term” durations of 1 hour, in natural settings. Very little past work has measured time courses of adaptation at this time scale.

**Methods:** Three observers wore intense red lenses for 1 hour intervals and were tested twice daily, making unique yellow settings. Participants adjusted the color of a 0.5 degree square centered on a background image of a naturalistic environment (an office scene). An additional black square of 5.7 degrees separating the test patch from the background image. The goal was to set the small square to “unique yellow,” a chromaticity containing neither red nor green. Participants performed a 5 min block of this task, immediately after they put on the colored spectacles. They were also tested after 10 min, 25 min, 40 min, and 55 min of wearing the spectacles. Between tests participants took a short walk and watched videos of their choice on an LCD display. After 1 hour, participants removed the glasses and were immediately tested again. Further tests were performed 10 min, 20 min, and 30 min after removing the glasses. Critically, participants completed all tests in a fully lit room, with the aim of measuring perceptual experience with a context similar to their natural environment while adapting to the spectacles.

**Results:** Wearing the red spectacles caused a large shift in color appearance, making the world appear reddish. The hue angle of their unique yellow settings changed by 80 degrees on average in nominal MB-DKL space. Over the course of the hour of adaptation, the world subjectively became much less red, and unique yellow returned to a point 47 degrees from baseline, a recovery of 41%. Participants also reported a greenish aftereffect when they took off the glasses. This was confirmed with unique yellow settings, which rose to 17 degrees above baseline. The aftereffect decayed completely by 30 min following glasses removal. Our data provide a reliable characterization of hour-long effects of chromatic adaptation. Future work will investigate whether these dynamics change with experience gained through repeated wearing of the colored glasses.

**PREDICTING COLOR MATCHES FROM LUMINANCE MATCHES****Kassandra R Lee<sup>1</sup>, Alex J Richardson<sup>1</sup>, Eric Walowitz<sup>2</sup>, Michael A Crognale<sup>1</sup> and Michael A Webster<sup>1</sup>**<sup>1</sup> University of Nevada, Reno, United States<sup>2</sup> Color Savvy Systems, Springboro, United States*Corresponding author: kassandral@nevada.unr.edu*

Color vision varies widely across individual observers. This variability introduces errors when trying to reproduce consistent color information across observers on devices such as monitors. The variability is becoming especially problematic with the rise in systems with more narrowband primaries, leading to increased interest in implementing “color profiles” for individuals. Many peripheral visual factors contribute to normal spectral sensitivity differences, including differences in lens and macular pigment density, LM cone ratios, photopigment peak sensitivities, and optical density. Variability caused by these factors is reflected to various degrees in different visual tasks including color matching and luminance matching. Color matching functions (CMFs) fully describe an individual’s relative spectral sensitivity but are time-consuming, difficult to measure, and insensitive to cone ratios and thus luminance sensitivity. In contrast, luminance matches are simpler for testing observers, but are insensitive to some factors such as S-cone sensitivity. Our goal is to determine the simplest and most efficient methods to characterize an individual’s spectral and luminance sensitivity.

Here we modeled how well variations measured only by isoluminant settings can recover sources of physiological variation to predict the full color matches of an individual. We show that differences in lens and macular pigment density, which are among the largest sources of variation in color matching, and LM ratios tilt the isoluminant plane in different ways, allowing estimates of specific values for these factors. In particular, values for these three variables can be estimated from three independent isoluminant settings. We evaluate the stimulus spectra that are best for parceling out these factors and how the estimates are also affected by variations in the photopigment spectral peaks and optical density.

We next modeled CMFs for individual observers based on Monte Carlo simulations of 1) variability in only the lens and macular pigment; and 2) variations in both the preretinal pigments and the photopigments, using estimates from the literature of the normal variations in each factor (Webster and MacLeod, 1988; Asano and Fairchild, 2016). CMFs for the two simulated observers were compared to each other and to a standard observer, with discrepancies measured by distances ( $\Delta E$ ) in the CIE Lab uniform color space. This provides an estimate of the extent to which measured values for lens and macular pigment density alone could approximate the full CMFs for an individual. Our results suggest that quantifying preretinal screening alone can account for a substantial amount of the variance in individual CMFs, and we analyze the pattern of these predictions for typical display spectra. Our results reveal the potential and limits for simple practical assessments like isoluminant settings for color profiling observers.

**EFFECT OF CONE SPECTRAL TOPOGRAPHY ON ACHROMATIC AND CHROMATIC DETECTION SENSITIVITY****Ramkumar Sabesan<sup>1</sup>, Alexandra Neitz<sup>1</sup>, Xiaoyun Jiang<sup>1</sup>, James A Kuchenbecker<sup>1</sup>, Sara Patterson<sup>1</sup>, Maureen Neitz<sup>1</sup>, Jay Neitz<sup>1</sup> and Daniel Coates<sup>2</sup>**<sup>1</sup> University of Washington, Seattle, United States<sup>2</sup> University of Houston, United States*Corresponding author: rsabesan@uw.edu*

**Purpose:** The spatial and spectral topography of cone photoreceptors set the neural limits for achromatic and chromatic detection. Here, we sought to compare the spatial characteristics of mechanisms mediating hue perception, against those mediating chromatic/achromatic detection in individuals with known spectral topography and with optical aberrations removed.

**Method:** Adaptive optics (AO) densitometry was used to obtain the spectral types in color normal observers. Their L:M ratio was validated against electroretinography. A dual-wavelength (526 and 661nm LEDs, 10nm bandwidth) psychophysics instrument equipped with AO was used to generate diffraction-limited isochromatic and equiluminant red-green gratings. A specialized badal optometer compensated for ocular longitudinal chromatic aberration. Transverse chromatic aberration was minimized by a Vernier alignment task and pupil-monitoring once the longitudinal chromatic aberration was compensated. Under these optical conditions meant to minimize monochromatic and chromatic aberration, we measured isochromatic and red-green equiluminant detection sensitivity for grating targets varying in contrast and ranging in spatial frequencies from 4-60 cycles/deg. Next, in a 2-interval, 2-alternate forced choice paradigm, we measured the spatial frequency range over which subjects were not able to differentiate an isochromatic grating from one that was red-green equiluminant.

**Results:** Aberration-corrected isochromatic detection sensitivities followed known estimates, reaching maximum cut-off spatial frequencies of up to 53 cycles/deg, indicating the high fidelity of optical correction. The subject with the most skewed L:M ratio, typically posited to provide inferior chromatic discrimination, obtained the lowest spatial frequency cut-off of all subjects for equiluminant detection, equal to 35 cycles/deg. Subjects were able to discriminate colored from isochromatic gratings with a high spatial frequency cutoff of only 10-12 cycles/deg. While errors in the estimation of transverse chromatic aberration can certainly affect this measure, our calculations based on pupil displacement and known measures of chromatic aberration essentially rule out this confound. Thus, subjects were able to detect changing red-green wavelength content at high spatial frequencies without perceiving hue sensations.

**Conclusion:** Cone spectral topography limits equiluminant color discrimination once the effect of ocular optics is removed. The coarser spatial grain of hue perception compared to chromatic/achromatic detection reveals a fundamental bottleneck of the midget system separable from mechanisms limiting spatial resolution.

**SPATIOTEMPORAL PATTERN ANALYSIS OF CHROMATIC VISUAL EVOKED POTENTIALS****John Vanston and Michael A Crognale**

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Understanding how color information is represented in the brain across time and space is an enduring goal of vision science. Much of what we know about the spatiotemporal properties of color pathways comes from psychophysics and electroencephalography (EEG). These two techniques are complementary: psychophysics allows measurement of human perceptual abilities, but is limited in revealing underlying neural activity, while EEG indirectly measures this activity with high temporal resolution. EEG can also be leveraged to provide a topographic representation of activity across the scalp, and chromatic visual evoked potentials (VEPs) have been used extensively to characterize color processing as a function of space and time. The aim of the current study was to use psychophysics and pattern analysis of high-density EEG data to answer the following questions: to what degree are temporal and spatial patterns of EEG activity linked? What is the relationship between these spatiotemporal patterns and human behavioral performance?

Detection thresholds were measured using a temporal 2AFC task. Stimuli were Gabors (10 degree subtense, 1 cycle per degree) whose chromaticity varied between the background and a point along each eight chromatic axes in cone-opponent space. Contrast was varied between trials using an adaptive staircase procedure, with the average of the last eight of ten reversals comprising a subject's detection threshold.

Chromatic VEPs were recorded from 128 electrodes using stimuli with the same spatial profiles as in the detection threshold task. Gabors were presented to each subject with six chromatic contrasts ranging from 0.5 to 16 times their detection threshold along a given color axis ("test" stimuli). VEPs evoked by the neutral background were also recorded ("comparison" stimulus). Stimuli were shown in sinusoidal onset-offset format, with a contrast plateau of 200ms and a jittered ISI ranging from 500-700ms. Subjects performed a simple fixation task to ensure their attention.

Electrodes were grouped into 13 clusters, and a classification algorithm was tasked with identifying trials as being responses evoked by test or comparison stimuli based on the time course of activity at each cluster. Classification of EEG data was performed using a linear discriminant analysis algorithm. Training and testing was performed using leave-one-trial-out cross-validation, and permutation testing was used to determine statistically significant classification accuracy.

In general, classification accuracy increased with increasing chromatic contrast in occipital electrodes. This pattern tended to be weaker in parietal, temporal, and frontal electrodes, suggesting an important role for the traditional chromatic waveform, which is thought to originate in occipital cortex and whose amplitude and latency scale with stimulus contrast. In most cases the "threshold" for accurate classification was 8-16 times higher than the threshold for stimulus detection. This indicates that despite the clear presence of chromatic components in the averaged waveform, classification accuracy of the time course of EEG activity within a local region is a relatively insensitive measure compared to the intrinsic representations giving rise to psychophysical detection.

**CATEGORICAL EFFECTS ON COLOR APPEARANCE****Kara J Emery<sup>1</sup>, Courtney Matera<sup>1</sup>, Vicki J Volbrecht<sup>2</sup>, David H Peterzell<sup>3</sup>, Kavita Vemuri<sup>4</sup>, Paul Kay<sup>3</sup> and Michael A Webster<sup>1</sup>**<sup>1</sup>University of Nevada, Reno, United States<sup>2</sup>Colorado State University, Greenwood Village, United States<sup>3</sup>University of California, Berkeley, United States<sup>4</sup>International Institute of Information Technology, Hyderabad, India*Corresponding author: karaemery@nevada.unr.edu*

Color vision depends on physical spectra that vary continuously, yet we describe color in terms of a small set of discrete categories. A recurring question is the extent to which color appearance exhibits categorical biases (such that equivalent stimulus differences appear more similar when they fall within rather than between color categories) and whether these biases reflect actual appearance biases or post-perceptual factors. To examine the nature of categorical effects on color appearance judgments, we compared the magnitude and pattern of categorical biases in two different hue scaling tasks and in an analogous motion scaling task. For hue scaling, forty-six observers reported the proportion of red/green and blue/yellow in a pulsing square of color sampled from a scaled MacLeod-Boynton space around a plane of fixed luminance and contrast. For motion, forty-one observers reported the proportion of up/down and left/right in an array of dots moving coherently at a fixed speed. In both cases, each stimulus spanned 2° and was chosen randomly from 36 possible directions sampled in 10° intervals around the stimulus space. We modeled the amount of categorical bias in observers' scaling functions as a ratio of the slope at the transition between versus within categories, following the procedure in Webster and Kay (2012). We calculated the categorical bias at each of the boundaries between the four primary directions for color and motion. A Wilcoxon Signed-Ranks test indicated higher categorical biases overall in hue versus motion scaling,  $Z = 2.67$ ,  $p = 0.008$ . Additionally, observers showed a different pattern in the two cases, with the biases at the different boundaries correlated for motion and uncorrelated for color, suggesting that unlike motion there was not a general tendency to exhibit the same magnitude of color bias across categories. In a second hue scaling task, we used an alternative procedure in which text labels for the four opponent primaries were placed along the cardinal points of a circular display and observers then used a needle to select the angle for each hue in terms of how similar it was to the labeled categories. Twenty-nine observers completed the compass task and judged the same 36 colors presented in the previous hue scaling task. Overall, observers were less categorical in the compass compared to the proportion task,  $Z = -4.11$ ,  $p < 0.001$ , while the compass and motion tasks did not differ in the amount of categorical bias,  $Z = 0.93$ ,  $p = 0.35$ . However, the correlation pattern for the two hue tasks was similar (and again differed from motion), in that the biases varied independently across categories. These results reinforce previous work (Webster and Kay 2012) suggesting that the degree of categorical bias in color appearance depends on the specific task – even when both tasks involve hue scaling – suggesting that the biases may be post-perceptual. The differences between hue scaling and motion scaling also suggest that even though both attributes can be defined by a two dimensional geometry, how they are perceptually represented may be fundamentally different.

**AN EXPLORATORY ANALYSIS OF THE FARNSWORTH D-15 TEST****Benjamin EW Evans, Marisa Rodriguez-Carmona and John L Barbur**

City University of London, United Kingdom

*Corresponding author: benjamin.evans@city.ac.uk***Introduction:**

The Farnsworth D15 panel test is often used to screen for congenital colour deficiency. The 15 coloured caps are illuminated with daylight (D65) and the subject is required to order the caps so as to minimise the perceived differences between adjacent caps. Both red-green (RG) and yellow-blue (YB) colour signals and even luminance signals can contribute to what the subject perceives as a minimum difference between adjacent caps. Monochromats, dichromats and subjects with severe anomalous trichromacy are expected to fail, making multiple crossings, whilst subjects with normal colour vision or a mild colour vision deficiency are expected to pass, making at most one to two adjacent transpositions. 6.3% of normal trichromats make adjacent transpositions. To ensure that normals do not fail the test, up to two adjacent transpositions are usually accepted as a pass.

**Purpose:**

The purpose of this study was to investigate the different signals which rod monochromats, dichromats and subjects with normal colour vision make use of most when presented with the D15 test and to assess the likely outcomes. Reliable D15 statistics for normal, deutan and protan subjects were established. A model was also developed to predict the colour signals involved, and the expected cap orders generated when subjects with a range of colour vision deficiencies (CVD) carry out the test.

**Methods:**

RG and YB thresholds were measured in 590 subjects (325 deutans, 170 protans and 95 normals) using the Colour Assessment & Diagnosis (CAD) test. Each subject also completed the D15 test. A rod monochromat, a tritanope and several protanopes and deuteranopes were also tested using the D15 test under two protocols. Initially the D15 was completed using the standard protocol before the caps were separated into two groups (from caps P-8 and caps 9-15) and subjects were asked to repeat the task. The spectral radiance data measured for each of the 15 caps under D65 illumination were used to estimate differences in photoreceptor excitations and to model the colour signals involved for each class of colour deficiency.

**Results:**

When no crossings and up to two adjacent transpositions are allowed on the D15 test, 100% of normal trichromats, 56% of deutans and 47% of protans pass. 43% of protans and 23% of the deutans that pass have RG thresholds above 10 CAD units (one CAD unit describes the mean RG colour signal strength for young, normal trichromats). As predicted by the model, rod monochromats, deuteranopes, protanopes and tritanopes were able to complete the Farnsworth D15 test when the caps were separated into two groups, despite severe loss or even complete absence of colour vision.

**Conclusions:**

53% of colour deficient subjects, some with severe RG loss, pass the D15 test when up to two adjacent transpositions are accepted as a pass. Whilst the D15 test is normally used to test for severe colour deficiency, subjects with severe loss can still use combined, residual RG and YB signals to pass the D15 test.

**SPECTRAL OPTIMIZATION TO VARY COLORFULNESS OF INDIVIDUAL PAINTINGS WITH A TUNABLE LED LIGHT SOURCE****Eduardo G Vicente<sup>1</sup>, Sérgio MC Nascimento<sup>2</sup> and João MM Linhares<sup>2</sup>**<sup>1</sup> Department of Theoretical, Atomic and Optical Physics, University of Valladolid, Spain<sup>2</sup> Centre of Physics, Campus de Gualtar, University of Minho, Braga, Portugal*Corresponding author: eduardo.garcia.vicente@uva.es*

The original chromatic composition of art paintings matches to a large extent of the subjective viewer's preferences. Preference data obtained by rotation of the color gamut of several paintings showed that observers prefer a chromatic composition very similar to the original as compared to any manipulated version (Nascimento et al, Vision Research, 2017). However, it is unclear how the expansion and contraction of the color gamut of paintings affects viewers' preference. In other words, how much the perceived colorfulness of the paintings affects aesthetic judgments. The purpose of this work was to optimize the spectrum of a tunable LED light source to expand and contract the colour volume of individual paintings by variable amounts thereby varying the degree of colorfulness but preserving the colour of the light source.

Ten paintings from the collection of Museu Nogueira da Silva, Braga, Portugal, were digitalized using hyperspectral imaging. Their colours were simulated rendered under D65 and expressed in CIELAB. The colour volume of each painting under this illuminant was then computed using a convex hull algorithm. A customized 10-LED tunable light source (LEDIGMA) was used to simulated tunable illumination on the paintings. For each painting the spectrum of the LED system was optimized to produce variable amounts of expansion and contraction of the colour volume corresponding to variable amounts of colorfulness but with the same chromaticity of D65. It was found that the optimal spectrum for each condition varies considerably with the painting. Therefore, a single light source cannot produce the same variation of colorfulness for all paintings and individual spectral customization is necessary to investigate the effects of colorfulness on aesthetic preference.

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**PREVALENCE OF COLOR VISION DEFICIENCY AMONG SCHOOL AGE CHILDREN IN LATVIA****Evita Kassaliete<sup>1</sup>, Gatis Ikaunieks<sup>1</sup>, Aiga Švede<sup>1</sup>, Sergejs Fomins<sup>1,2</sup>, Gunta Krūmiņa<sup>1</sup>**<sup>1</sup> Faculty of Physics, Mathematics and Optometry, University of Latvia, Riga, Latvia<sup>2</sup> Institute of Solid State Physics UL, Riga, Latvia*Corresponding author: evita.kassaliete@lu.lv*

To assess vision problems for school age children vision screening was performed in 30 Latvian schools. Screening was carried out in standard schools and in special schools for children with learning difficulties. Vision complaints and basic vision functions were evaluated during vision screening: far and near visual acuity, binocular vision and stereoacuity, accommodation and vergence functions, and color vision. The main aim of this research was to find out how many children have color vision impairments in Latvian schools.

Vision screening was carried out by optometrists and students from the Masters program in optometry, University of Latvia. Color vision was assessed using the HRR and Rabkin pseudoisochromatic plates. If a child failed the screening section of the HRR or Rabkin, his/her color vision was then tested with the full HRR set. More than 11000 children took part in full vision screening. 49% of them were boys and 51% were girls. Age range was 7 to 18 years.

Color vision deficits (CVD) were found for  $\approx 4.0\%$  of boys and  $\approx 0.1\%$  of girls. The percentage of males with color vision deficiency was significantly higher (12 boys of 160 (7.5%)) in the special schools compared to standard schools (193 boys of 5151 (3.76%)). There was no significant correlation between color vision deficiency and other vision problems.

Our results show that the prevalence of color vision deficiency (CVD) among school age children in Latvia is less than reported levels for European Caucasian populations, for both male and female individuals (8% and 0.4%, respectively). Other tests are required to classify the type of color vision defect for these children.

Supported by European Regional Development Foundation (ERAF) project No 2011/0004/2DP/2.1.1.1.0/10/APIA/VIAA/027

**COMPARISON OF BRIGHTNESS PERCEPTION OF FACIAL SKIN WITH DIFFERENCES OF SKIN COLOR****Yuanyuan He, Taiga Mikami, Suguru Tanaka, Yoko Mizokami**

Chiba University, Japan

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The color of human skin is undoubtedly one of the most common colors which we see in every life. Skin color varies among different ethnic groups, and it can range from dark to light, and yellowish to reddish. The skin color distribution of young Japanese women measured with a colorimeter showed a trend that yellowish skin had higher lightness compared to reddish skin. On the other hand, it was shown that reddish skin appeared brighter than yellowish skin when both had the same lightness (Yoshikawa et al., 2012). This suggests that the color perception of facial skin color is special. However, the previous result was obtained from the experiments using Japanese faces with Japanese skin color and for Japanese observers. It is not clear how the brightness perception of facial skin is influenced by the diversity of skin face colors and observers. Here, we investigate the brightness perception of facial skin for Japanese and Thai observers. We used a young Japanese female face which was an average of 40 female faces. We prepared test faces with four skin color types that were the average skin color of Japanese, Thai, Caucasian, and African. The skin color of each face was modified by changing the ratio of  $L^*$ ,  $a^*$ ,  $b^*$  from each test face. Test images with constant lightness and different hue angle were generated. Scale images had the same hue angle corresponding to an original face color of each skin color type and different lightness. A test image and a scale image were presented side by side on a color-calibrated tablet display. Under indoor white lighting, observers sat in front of the tablet display and adjusted the lightness of facial skin on the scale image to match the brightness of the test image and the scale image. They evaluated four groups of stimulus images (20 images in total), three times each. We conducted the experiments for university students in Japan and Thailand. As a result, Japanese observers showed a trend that reddish skin color appeared brighter than yellowish skin color, but Thai observers showed the opposite trend. It implies that there may be the influence of ethnicity or environment on the brightness perception of facial skin.

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# NOTES

July 2019	Friday 5	Saturday 6	Sunday 7	Monday 8	Tuesday 9
<i>Registration desk open 8:30</i>					
09.00 - 9.30	Directors' meeting	Colour Appearance	Luminance and Colour	Anomalous Trichromacy	Grouping and Attention
9.30 - 10.00					
10.00 - 10.30		Coffee break	Coffee break	Coffee break	
10.30 - 11.00		Colour Vision Testing	Verriest - Medal Lecture	Colour Vision Assessment	Colour Constancy
11.00 - 11.30			Michael Webster		
11.30 - 12.00		Group photo	Excursion & Banquet	lunch	Business meeting
12.00 - 12.30					
12.30 - 13.00		Invited talk		Invited talk	
13.00 - 13.30		Beatrix Feigl		Sylvia Pont	Closing
13.30 - 14.00		Opening		Melanopsin and Colour Vision	Lighting and Material Properties
14.00 - 14.30	Central processing of colour				
14.30 - 15.00		POSTERS 1 & coffee		POSTERS 2 & coffee	
15.00 - 15.30	Coffee break				
15.30 - 16.00	Invited talk				
16.00 - 16.30	Paul Martin				
16.30 - 17.00	Retinal Mechanisms of Colour Vision	Colour in Painting	Colour Cognition		
17.00 - 17.30					
17.30 - 18.00	Walk to Dome Square	Free evening	Free evening		
18.00 - 19.00					
19.00 - 21.00	Reception				

