

XVIIIth Symposium of the International Colour Vision Society

Dear Participants,

We welcome you to the 18th Symposium of the International Colour Vision Society in Lyon at the Palais des Congrès overlooking the Rhône River. As in past meetings, we will take the next 5 days to recount and hear recounted the latest advances in all aspects of colour vision, from genes to spectral coding, from neurophysiology to perception, from retina to cortex, from development to evolution, from history to the future, from art to application, from normal to abnormal and anything in between or beyond. We wish you all an exciting scientific meeting, full of discovery, insight and new levels of understanding. We hope also that you will have the time during this short visit to Lyon and its environs, to appreciate some of its special qualities.

The organisers would like to thank the sponsors for their financial and material support, the team from the Inserm ADR (Anne-Marie Fononi, Christiane Cambon & Hélène Brun) and the students who loaned their time and helping hands (Cécile Bordier, Julie Petra & Romain Bouet). Also thanks to Marie-Catherine Vidal-Borderiou, Gaëlle Batou from the *Office du Tourisme* and Valerie Duc from the *Bureau des Guides* of Lyon. Finally, thanks to Christophe Colombo from the reprography of UPMF for printing the book.

Kenneth Knoblauch
David Alleysson

The International Colour Vision Society

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VDL: Ville de Lyon



LTC: Lyon Tourisme et Con-
grès



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1 14:15 - New developments in circadian photoreception (invited)

H. M. Cooper

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In mammals, a palette of non-image forming visual functions including circadian photoentrainment, pupillary light reflex and direct effects of light on behavior (masking) are mediated by the photic information transmitted from the retina. Early studies on the architecture of retinal projections to the suprachiasmatic nucleus (SCN), the response properties of photic integration by the circadian timing system, and studies in blind animals and humans had suggested that novel - non-rod and non-cone retinal photoreceptors were involved in photic irradiance detection processes. Recent studies have demonstrated that a sub-class of retinal ganglion cells that express the photopigment melanopsin are intrinsically photosensitive. Melanopsin, originally cloned from amphibian melanophores, is a bireactive photopigment and has both an intrinsic photo-isomerase activity and can act as a photosensory opsin using 11-cis retinaldehyde as a chromophore. Studies in different mammals have demonstrated that the peak of sensitivity is located in the blue-green region of the spectrum (480 nm). In rodents that lack all photoreceptors (rods, cones and melanopsin) circadian photoentrainment and pupillary reflexes are completely absent demonstrating that only these photopigments are implicated in irradiance detection responses. In animal models that conserve at least one of the photopigments, responses to light are altered but not abolished, suggesting that either these photoreceptor systems are redundant or play complementary roles. Ongoing studies in our laboratory on rodents and humans using electrophysiology, pupillary responses, behavior, and light suppression of nocturnal melatonin secretion suggest that the interactions between different photoreceptor systems may be additive and in some cases inhibitory. These interactions and the responses mediated by different photopigments also depend on several parameters including wavelength, intensity, stimulus duration, and previous exposure to light.

2 14:50 - Do the MC and PC pathways deliberately avoid S-cone input?

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There has been a recent suggestion that there is 10% S-cone input to the MC pathways (Chatterjee and Calloway, 2002). This is relevant to whether the MC pathway underlies a psychophysical luminance channel and to the specificity of retinal wiring. We used a newly developed technique to measure S-cone inputs to MC and PC ganglion cells. The stimulus is a uniform field of which the chromaticity is modulated around a circumference in a color plane in clockwise or counterclockwise direction. For a cell that receives linear combination of cone inputs, the cone weighting determines its preferred vector, which can be estimated by averaging the clockwise and counterclockwise response phases. We measured MC cells' response phases in a plane defined by L+M axis and S-cone axis and PC cells' response phases in an equiluminance plane at several temporal frequencies. Cone weighting estimates indicated, on average, little or no S cone input. We also measured the errors introduced by using cone fundamentals with inappropriate macular pigment density and self screening. Chatterjee and Calloway used 2 deg cone-fundamentals for their extrafoveal measurements. We found that using 2 deg rather than 10 deg Smith-Pokorny cone fundamentals introduced an apparent 10% S-cone input. Finally, we considered the implications of the result in terms of retinal circuitry. If a ganglion cell's receptive fields receive indiscriminate inputs from mixed cone types as in the random wiring model, the S-cone input should

have the polarity of PC cells' surrounds and of MC cells' center. This was not consistent with our data from either cell type. We suggest that MC and PC ganglion cells' receptive fields may have a mechanism to avoid S-cone inputs, as is the case for H1 horizontal cells (Dacey et al. 1996).

Chatterjee, S. and E. M. Callaway (2002). "S cone contributions to the magnocellular visual pathway in macaque monkey." *Neuron* 35: 1135-1146.

Dacey, D. M., B. B. Lee, Stafford, Pokorny, and Smith (1996). "Horizontal cells of the primate retina: Cone specificity without spectral opponency." *Science* 271: 656-659.

3 15:10 - Temporal sensitivity of macaque ganglion cells; a reappraisal

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²University of Göttingen, Germany

We previously described the temporal response of ganglion cells to luminance and chromatic modulation, using a peak rate measure (Lee et al., *JOSA A*, 7, 2223-36, 1990). PC cells responded to red-green modulation up to 30-40 Hz, much above human chromatic flicker fusion. This led to the suggestion that this pathway undergoes central low-pass filtering. It has recently become clear that cells' response variability increases rapidly with temporal frequency (Sun et al., *Vision Res.* 44, 19-23, 2004). We have reanalyzed cell responses in this context. First, we constructed ROC curves from cell Fourier amplitudes to single modulation cycles as compared to blank trials. Cell sensitivity was estimated by fitting Weibull functions to data at different contrasts. The resulting temporal response was very low pass with a low-frequency sensitivity of 1-2% cone contrast. The temporal response extended to ~30 Hz. Such an "ideal observer" approach has high contrast sensitivity at low temporal frequency, but the fusion frequency is still high. We then simulated a central peak detector consisting of an integrator with a critical duration of 300-400 msec. Its output was then subjected to ROC analysis. The resulting temporal response largely maintained low-frequency sensitivity, but the temporal response cut off at 10-15 Hz, as in human psychophysical data. This type of approach can help constrain central detection mechanisms; we will discuss further facets of this form of analysis, and its application to the MC pathway and luminance modulation.

4 15:30 - Topographic (un-)coupling of S- and M-cone mosaics in felids and other mammals

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The topography of the two spectral cone subpopulations present in most mammals, representing the ancient dichromatic color system, can be studied by anti-opsin antibody labeling. For human and other diurnal primate retinas the distribution of S-cones has been found to have largely concentric gradients albeit at ratios around 10:1. However, extension of studies to species such as rodents, rabbit or cat have shown spatial independence of the S-cone gradients peaking in other regions than the temporal area centralis defined by M-cones and related interneurons. To study the variability of S- versus M-cone topographies we have collected eyes and analyzed the spectral topographies from 7 felid species : cheetah, lion, tiger , jaguar, Siberian manuls, Eurasean lynx and domestic cats (obtained from animals delivered to veterinary pathology from Austrian animal parks and zoos. In addition data from previous or ongoing studies on other mammalian groups are added for comparison beyond phylogenetic relationships.

All Felid species have central areas located in the superior temporal quadrant established by M-cones, but the maximum densities varies strongly. Cheetah by far outnumbered other species (max. 41000 M-cones/mm², as compared to 17000/1300 in Lynx), total estimated cone numbers (9,5 Mio M-cones + 1,5 Mio S-cones, as compared to 5,5 + 1,5 Mio in tiger) or S-cone proportion 14% (cheetah) versus 2% in manul. The overall topographic pattern is clearly uncoupled in the two smallest species, the domestic cat and the manul, while it is more congruent in the larger species. The cheetah's extreme visual streak organization is unique among felids confirming the species' specialized adaptation as a diurnal open-terrain speed hunter. Across species, differences in M-/S-gradients appear to correlate with differences in species size (dorso-ventral a/symmetry), terrestrial versus semi-/arboreal behaviour (elongated versus concentric gradients) and between open versus closed habitats. Uncoupling is characteristic for smaller species with increased predatory risk approaching from the superior visual hemisphere. Thus the degree of overlap or uncoupling of cone topographies indicates species variant roles for color contrast versus spectral sensitivity functions of the S-pathway. A central region providing enhanced spatial vision may or may not concur with the maximum short wavelength sensitivity depending on the particular species' ecological position and behaviour. This suggests relative functional and ontogenetic independence of the S-cone systems were basic features of mammalian color system.

5 16:10 - Do rods influence the hue of foveal stimuli?

S.L. Buck, L.P. Thomas, N. Hillyer, E.M. Samuelson

Department of Psychology, University of Washington, Seattle, USA

For extrafoveal stimuli, rods produce three separable influences (biases) on the hue percepts determined by cones. To understand both the generality and mechanisms of these rod hue biases, we examined whether they are present for small foveal stimuli. The wavelengths associated with spectral unique hues (Ublue, Ugreen and Uyellow) were determined for small disks (e.g., 0.2° and 0.6° diameter presented for 1-s duration) presented foveally by means of a psychophysical staircase procedure. The foveal fixation array was composed of four dim tungsten-illuminant dots, each located 3.4° from the stimulus location. For each condition we assessed rod influence by comparing unique hue wavelengths under two different adaptation conditions: during the cone plateau from 3-8 min after a xenon flash bleach (BL) and after 30 min of dark adaptation (DA). For this comparison, all stimuli were scotopically matched at a value that ranged from 1.0 to 2.0 log scotrolands, depending on the stimulus condition. For each of three observers, the pattern of rod hue biases was consistent across the two sizes tested but differed for each observer. One showed no rod influence (shifts < ±s.e.). One showed a small Ublue shift (3.6 ± 2.7 nm, 3.5 ± 2.0 nm). One showed a small Uyellow shift (-3.0 ± 0.8 nm, -2.8 ± 1.8 nm). No foveal stimulus tested so far yields rod hue shifts of the size and reliability across observers that we have previously found for extrafoveal stimuli. We are uncertain as to the source of the present small residual shifts, and even their dependence on rods. In any case, the absence of reliable and substantial rod hue shifts in the fovea (1) suggests that the effects observed extrafoveally do not depend on residual cone adaptation by the bleaching light and (2) provides no support for the hypothesis that rod hue biases are mediated by unstimulated but dark-adapted rods outside the area of the test stimulus, such as has been shown for rod effects on foveal cone-mediated flicker and acuity. Instead, the results are consistent with the hypothesis that light-initiated rod signals from the area of the test stimulus bias the chromatic pathways.

6 16:30 - Foveal or extrafoveal dominance in rod hue biases?

L.P. Thomas, S.L. Buck

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We have previously shown green (shift of unique yellow locus), blue (shift of unique green) and short wavelength red (shift of unique blue) rod hue biases with large, dimly-mesopic, extra foveal stimuli for most of our observers. However, these effects tend to diminish when stimuli are confined to a small area of the central fovea. The present study explores (1) whether the fovea dominates over potential rod influences on perception of U hues, and (2) whether large stimuli are as effective for revealing rod hue biases when foveally centered as when eccentrically centered. We assessed rod influence by measuring wavelengths of unique green and unique yellow (with 1-s duration, 1 log scot td stimuli and a staircase procedure) under cone plateau and dark adaptation conditions. We measured unique hues with foveally centered 2 deg and 7.4 deg disks, and 7.4 x 2 deg annuli, and 7.4 deg disk at 7 deg eccentricity. The rod green bias was typically <10nm and remained fairly constant across spatial configurations, indicating no special foveal influence. The rod blue bias varied more among observers and spatial configurations, reaching up to 42nm. For some observers, stimuli covering the fovea consistently produced less rod blue bias than extra foveal stimuli. For other observers, they did not. However, across all observers the smaller fovea condition (2 deg) produced the smallest rod blue biases. Thus, the present results add differences in spatial dependence between green and blue rod biases to the previously demonstrated differences in light-level dependence and time course. The present conditions provide no evidence of foveal dominance in the case of the rod green bias and inconsistent evidence in the cases of the rod blue bias.

7 16:50 - Scotopic color perception

J. Pokorny, M. Lutze, D. Cao, A.J. Zele

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Purpose: Human vision maintains a perceptual stability through the transition between daylight and twilight conditions in which real world objects, with broad reflectance spectra, do not abruptly change color with diminution in light level. Rather there is a gradual reduction in saturation and color gamut with decreasing light levels. Several studies document rudimentary color vision under scotopic illumination conditions, presumably mediated by rods and L-cones. Here, hue perceptions of paper color samples were determined for a wide range of light levels including very low light levels where the L-cones did not contribute to color percepts. **Methods:** The appearances of 24 paper color samples from the Optical Society of America Uniform Color Scales (OSA-UCS) were gauged under successively dimmer illuminations in 0.5 log unit steps from 10 to .0003 lux. Sufficient time for adaptation was allotted following each decrease in illumination. Triads of colors were chosen for this study that photopically appeared red, pink, orange, yellow, green, blue, purple and grey and the samples within each color triad varied in lightness. The 50mm square samples were placed in black mounts that could be moved around on a black surface. The samples were $8 - 10^\circ$ of visual angle when viewed directly from 0.30-0.35m. Observers were instructed to sort the samples into groups that they could categorize with specific color names. The authors served as observers. **Results:** Observers sorted all samples into the same triads as the originally chosen color groups at illumination levels between 10 and 0.32 lux with few exceptions. At .01 lux, the originally chosen red and orange samples were usually correctly identified as either red or orange. The remaining samples tended to be grouped into two categories correlating with the level of reflectance of the samples. The lowest reflectance samples were grouped and named as black. For 3 observers, high reflectance samples were grouped and named predominately as green or blue-green while the fourth observer named the high reflectance samples as blue or achromatic. At the two dimmest levels there

continued to be conspicuous color percepts. Color categories were reliably assigned on the basis of the scotopic reflectances of the samples. The lowest reflectance samples that did not appear black were classified as orange or yellow (all four observers) and the higher reflectance samples as green or blue-green (three observers), or achromatic or blue (the fourth observer). **Conclusions:** There are two categories of color appearance and names that result at scotopic light levels. Except for the lowest light levels, there was a clear division of color appearance between samples predominantly reflecting longer wavelengths and the other visible samples; rods and L-cones presumably mediated these percepts. At the two lowest light levels, color appearance was associated with sample scotopic reflectance. Based on the scotopic luminous efficiency function, in a dim natural environment the spectral composition of objects with short- and medium-wavelengths appear brighter, and objects with longer wavelengths appear dimmer. With input solely from rods, the visual system estimates probable colors based upon prior experience.

8 17:10 - Magnocellular pathway mediates rod suppression of cone flicker detection

D. Cao, J. Pokorny, A.J. Zele

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Purpose: Dark-adapted rods in a region surrounding a luminance-modulated field suppress flicker detection. The interaction between rods and each of the cone types is unclear. A number of studies found the effect to be more profound for L- than for M-cones. No study considered the interaction with S-cones. In this study, the critical fusion frequencies (CFF) for receptor [L, M, S] and postreceptor luminance, [L+M+S], [L+M+S+Rod] and red-green chromatic [L/(L+M)] signals were measured in the presence of different surround light levels. The experimental design allowed evaluation of the retinogeniculate pathway(s) that show rod suppression of cone flicker detection. **Methods:** A 2-channel photostimulator, with 4-primaries for a central field and 4 for a surround, allowed independent control of rod and cone excitation. Receptor [L], [M], [S] and postreceptor luminance [L+M+S], [L+M+S+Rod], or chromatic [L/(L+M)] stimuli were temporally modulated in a 2° circular field set within a steady 10° surround positioned at a 6° temporal eccentricity. The time averaged center and surround chromaticities were metameric to the equal-energy-spectrum. The stimulus was sinusoidally modulated about 80 photopic Tds, using a 1-sec raised cosine envelope alternated with a 1-sec steady field. The [L], [M], [L+M+S] or [L+M+S+Rod] were modulated at 15% Michelson contrast, the [S] cone was modulated at 30%, and the [L/(L+M)] signal was modulated at 5%. Observers adjusted the modulation frequency of the 80 Td center to determine the CFF for each stimulus type in the presence of different surround illuminances (0, 0.05, 0.5, 5, 20 or 80 photopic Tds). Measurements followed either 30-min of dark adaptation or 2-min of light adaptation to a 10,000 Td broadband light. **Results:** For [L] or [M] cone modulation and luminance modulation, the CFF was constant for the dark and dim surrounds but increased abruptly when the surround retinal illuminance was above cone threshold. Following light adaptation, dim surrounds did not lower the CFF. The CFF for [S] cone and [L/(L+M)] postreceptor signals were unaffected by surround light level or light or dark adaptation. **Conclusions:** From physiological studies (Yeh et al, 1995), magnocellular pathway units would respond vigorously to all stimuli except [S] or [L/(L+M)] modulations; parvocellular pathway units do not respond strongly to the [S] or luminance signals; and koniocellular pathway units would respond vigorously to [L], [M] and [S]. From this pattern of response, the results indicate that rod-cone interaction in cone mediated flicker detection occurs exclusively in the magnocellular pathway.

Yeh, T., Lee, B.B. & Kremers, J. (1995) *Journal of the Optical Society of America A* 12, 456.

9 17:45 - Monge

Professor John D. Mollon

University of Cambridge, Cambridge, UK

10 8:50 - X-Chromosome Inactivation and M/L Cone Ratios in Polymorphic New World Monkeys and in Knock-In Mice with an M/L Opsin Gene Polymorphism

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During mammalian development a majority of the genes on one of the two X chromosomes in female embryos are inactivated in somatic cells to achieve gene dosage compensation. Unlike their catarrhine cousins, most platyrrhine monkeys have only a single X-chromosome opsin gene with multiple alleles. X-chromosome inactivation provides heterozygous females of these species with a mixture of M and L cone types thus allowing a receptor basis for trichromatic color vision. In such animals it is conventional to assume that M/L cone ratios must largely reflect the dynamics of X-chromosome inactivation. To evaluate that influence we determined M/L cone ratios in a sample of 60 heterozygous platyrrhine monkeys. These animals represent a variety of species and embody various combinations of M and L cone types. Cone ratios were estimated by determining the relative weightings of M and L cone spectra required to best fit flicker photometric ERG spectral sensitivity functions. Consistent with a random inactivation process, the mean M/L ratio is close to unity. At the same time, however, significantly unbalanced ratios were relatively common with ~10% of animals having 80% or more of one receptor type. A second case involves a polymorphic knock-in mouse engineered to mimic the opsin gene arrangement of platyrrhine monkeys. M and L cone weightings were determined for a sample of ~60 heterozygous mice using techniques similar to those noted above. The M/L cone weightings in these mice are on average biased somewhat in the M-cone direction. Despite that bias, the dispersion of individual cone weights is similar to that seen in the monkeys with at least 10% of these mice having an 80% or greater contribution from one cone type. If M/L ratios in polymorphic mice and monkeys are completely determined by X-chromosome inactivation these observations suggest limits on the size of the pool of precursor cells at the time of X-chromosome inactivation.

11 9:10 - Topographical Maps of L and M Gene Expression in Adult Human Retinas

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Previous measurements of the ratio of L:M messenger RNA in small tissue patches suggested that the proportion of L cones rises with increasing eccentricity. Microspectrophotometry results from one eye also suggest a considerable L cone dominance near the ora serrata compared to the fovea. Here, we report experiments to produce topographical maps of L and M gene expression for eleven male human donor retinas that were flat-mounted onto nylon filters printed with a 3-mm^2 grid. Real-time quantitative polymerase chain reaction (PCR) was used to estimate the relative amount of L in the total L plus M mRNA for each grid square along the horizontal and vertical meridians. Near the ora serrata, the amount of L approached 100% of the L plus M mRNA, and was dramatically higher than near the fovea where the largest quantities of M pigment mRNA were observed. In the adult macaque retina, a foveal-to-peripheral

gradient of L and M gene expression was less striking. Primate retinal development proceeds from the center outwards in a wave that is mirrored in the observed gradient of the relative abundance of L pigment mRNA. A model for the mechanism that forms the mosaic of L and M cones must explain their topographical distribution. Nathans and colleagues have demonstrated that interaction between the locus control region (LCR) and the proximal promoter of the L or M gene is crucial for gene expression. Recent results from our laboratories investigating the developmental expression pattern of the X-chromosome pigment genes from humans and Old World monkeys have provided evidence for a model in which there is a competition between gene expression and gene silencing within incipient L and M cone photoreceptors. It is proposed that the probability of a cell becoming L versus M changes over time as a function of the relative extent to which silencing mechanisms have acted on the genes. Epigenetic modifications that result in gene silencing are heritable. Thus, according to the model, the change in the proportion of L cones with eccentricity is produced because cells that populate the peripheral retina derive from progenitors that have undergone a greater extent of gene silencing and thus have a greater starting probability of becoming L cones compared to cells in the center.

12 9:30 - Regulation of L and M Pigment Gene expression

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An essential step in the evolution of full trichromatic color vision in primates was the duplication of the ancestral pigment gene to form the L and M pigment gene array on the X chromosome. Previous work using transgenic mice has indicated that a locus control region, adjacent to this array of genes plays an important role in their mutually exclusive expression in respective cone cells (Smallwood et al. 2002). We now show that cells of the undifferentiated human retinoblastoma cell line WERI exhibit mutually exclusive expression of the L and M pigment genes in each cell and therefore are a good model for studying this process. Furthermore, clonal analysis showed that single WERI cells that express either the L or the M pigment mRNA divide and generate a mixed population with varying ratios of L or M pigment mRNA-expressing cells. These results suggest, first, that cell division resets L or M pigment gene expression in a stochastic manner. Second, that determination of L vs. M cone identity may not require external or internal molecular cues. Third, aside from having different pigments, L and M cones are not intrinsically different. It was previously shown that thyroid hormone (T3) together with 9 cis-retinoic acid (RA) play an important role in directing photoreceptor cell fate by favoring the formation of L/M cones at the expense of S cones. The mechanism by which this is accomplished is unknown. Using WERI cells as a model, we have shown that thyroid hormone directly induces expression of both the L and M pigment genes. This suggests that the mechanism by which T3 and RA induce L/M cone differentiation involves direct induction of expression of L/M cone-specific genes.

Smallwood PM, Wang Y, Nathans J: Role of a locus control region in the mutually exclusive expression of human red and green cone pigment genes. *Proc Natl Acad Sci U S A* 99:1008-1011, 2002

13 9:50 - An urn model of the development of macaque and human adult L:M cone ratios

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Purpose: In old world primates, including humans, fetal and adult retinas differ dramatically in L:M pigment mRNA ratio. There is also tremendous variation in the adult L:M cone ratio. A simple model that explains these observations involves a dynamic competition between the L and M gene promoters for interaction with the locus control region (LCR) in which each time the LCR/promoter complex is disrupted, the promoters compete anew. When a promoter is not interacting with the LCR, it is exposed to gene silencing. Thus, in an incipient L/M cone, each LCR/promoter interaction changes the relative probabilities that L vs M will win in the next round of competition until, finally, the probability of association with one or the other promoters is reduced to zero. **Methods:** The process was modeled as an urn containing an initial ratio of L:M balls. When an L-ball is drawn, r L-balls are added and r M-balls withdrawn; when an M is drawn s M-balls are added and s L balls withdrawn. These parameters with the total number of balls, N , specify a Markov chain with transition matrix of $N+1$ states and two absorbing states (for each of L and M). The transition matrix determines the final L:M distribution in which each ball is either L or M. **Results:** The curve relating final to initial %L-cones is sigmoidal. Changing the L/M replacement rule for a fixed number of states produces parallel shifts along the axis of initial %L. Increasing the number of states (balls in the urn) steepens the curve. A 100-ball urn requires a replacement rule of 8/1 for macaque and 2.5/1 for humans to predict the correct final ratios from the initial ratios. For human, the final %L varies from about 0.35 to 0.95 as the replacement rule varies from 2/1 to 4/1. Ninety-nine percent of the cones are committed as L or M in 68 steps for macaque and 84 for human. Thus, the process would near completion at birth for each species if the LCR dissociates once per day. **Conclusions:** The model predicts that subtle individual differences at the photopigment gene locus that would produce small changes in the dynamics of the competition occurring during development could explain large individual differences in adult cone ratio.

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14 10:10 - The genetics of colour deficient with unusual anomalous scope matches

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The majority of colour deficient observers require either more red or more green light to match the colour appearance of a spectral yellow field (as in a Nagel match) and this observation is often used to detect and classify the type of colour deficiency involved. "Extreme" colour deficient, on the other hand, can accept unusual matches that are often difficult to explain. Some subjects accept most, but not all of the red-green mixture range, others require significantly more red or green light in the match, but only accept a very narrow range of red-green mixtures that yields a red-green discrimination index (RGI) equivalent to or better than a normal trichromat. Some studies have also reported poor correlation between the parameters of the yellow match and the subject's ability to discriminate colour differences under more

normal conditions of illumination. The purpose of this investigation was to carry out a number of related studies:

- To model the Nagel match and to examine how shifts in I_{max} , changes in optical density of photoreceptors and post-receptors amplification of L and M cone signals can affect the parameters of the yellow match and can be used to account for "extreme" anomaloscope matches.
- To investigate how loss of chromatic discrimination sensitivity in congenital colour deficiency correlates with the parameters of the yellow match.
- To carry out genetic analysis in a group of extreme colour deficient observers to investigate the correlation between predicted and observed colour vision losses.
- To use the genetic predictions to constrain the parameters of the model so as to establish more closely the parameter changes needed to account for extreme colour matches
- To investigate and account for the lack of correlation between the parameters of the yellow match and the subjects' loss of chromatic discrimination sensitivity under more normal conditions of illumination

Nagel matches and colour discrimination thresholds were measured in 225 normal trichromats and 250 colour deficient observers. 24 subjects that exhibited extreme or unusual anomaloscope matches were selected for further study. The loss of chromatic sensitivity was re-examined in each of the 24 subjects using the Colour Assessment and Diagnosis (CAD) test under conditions that isolate the use of colour signals. Genetic analyses were also performed for each of the 24 subjects to estimate the relative number of L and M genes on the X-chromosome, to predict the spectral separation between L-class pigments for deuterans and M-class pigments for protans, and to determine whether there were other amino acid differences between L- or M-class pigments that might produce consistent differences in optical density or in post-receptoral amplification factors among cones.

Predictions based on genetic data in relation to the class and severity of colour vision loss were in complete agreement with the measured psychophysical data. All Nagel matches in "extreme" protanomalous observers could be predicted by appropriate changes in optical density and post-receptoral amplification in the absence of L-cone photopigment. Extremely good predictions of the mean and narrow range of red-green mixture settings observed in some extreme protanomalous and deuteranomalous observers could also be obtained by simple adjustments in I_{max} and post-receptoral amplification.

All "extreme" anomalous Nagel settings examined in this study are consistent with the genetic data and can be accounted for by appropriate changes in I_{max} , photoreceptor optical densities and / or post-receptoral amplification of cone signals. The Nagel match represents a sensitive method of detecting changes in a number of different parameters, but neither the mean red-green mixture setting nor the RGI show good correlation with other measures of chromatic discrimination sensitivity. These observations are consistent with observed changes in model predictions when the spectrally narrow lights are replaced with broader illuminants.

15 10:30 - A novel mutation in the short-wavelength sensitive cone pigment gene associated with a tritan colour vision defect

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Congenital tritan colour vision deficiency is caused by defects in the function of the short wavelength sensitive (S) cones. This disorder shows autosomal dominant inheritance, with tremendous phenotypic heterogeneity. It has been shown to be caused by missense mutations in the gene encoding the S cone photopigment, and to date all known amino acid sequence variations in the S cone pigment are associated with tritan colour vision deficiency. Here we report the identification of a healthy 30 year old male who made errors on standard colour vision tests consistent with the presence of a mild tritan colour vision deficiency. We tested the hypothesis that his colour vision impairment was due to a mutation in the S cone photopigment gene. He was found to be heterozygous for a missense mutation that substituted proline for a highly conserved leucine at amino acid position 56 in the S cone photopigment. This mutation was absent in 564 S cone photopigment genes from 282 subjects who did not make tritan errors, and who had normal colour vision or who had red-green colour vision defects. Thus, we conclude that this missense mutation disrupts the normal function of S cones.

16 11:10 - Paradoxical shifts in human colour sensitivity caused by constructive and destructive interference between slow and fast signals from the same cone class and by the suppression of the fast signals

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Paradoxical shifts in human colour (spectral) sensitivity occur on red background fields. As the intensity of the red background is increased from low to moderate levels, the spectral sensitivity for detecting flicker of moderate frequency shifts towards shorter wavelengths, but by more than is predicted by selective chromatic adaptation (Eisner & MacLeod, 1981). Remarkably, though, at higher intensity levels, the spectral sensitivity then shifts precipitously back towards longer wavelengths (Stockman, Montag and MacLeod, ARVO, 1991). Here, we show that the effects are due to two factors. First, they are the result of destructive and constructive interference between slow and fast signals generated by both the M- and the L-cone types, which, contrary to the conventional model, feed into a common luminance or achromatic pathway. Since the slow M- and L-cone inputs are always opposite in sign, when one destructively interferes with the fast signals, the other constructively interferes, causing frequency-dependent spectral sensitivity shifts. These shifts are intensity-dependent because the polarity of the slow signals changes from L-M to M-L as the intensity of the red field is increased. Second, the paradoxical shift towards longer wavelengths is also the result of a strong suppression of the fast M-cone signals by intense red fields.

Eisner, A. & MacLeod, D. I. A. (1981) JOSA 71, 705-718.

17 11:30 - Colour appearance shifts induced by different illuminants; effect of field size and adaptation time

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A successive asymmetric colour-matching task was used to study the changes in colour appearance of simulated Munsell samples under different illuminants. Colour shifts were induced with two Planckian illuminants, standard illuminant A ($u^* = 0.256$, $v^* = 0.524$) and illuminant S ($u^* = 0.174$, $v^* = 0.392$). Observations were made with 10 equally spaced Munsell samples value 7 and chroma 4, on a neutral (N7) background. The set consisted of the following sequence: 10P, 10PB, 10B, 10BG, 10G, 10GY, 10Y, 10YR, 10R and 10RP. All 10 Munsell samples were presented in the centre of a computer monitor, subtending 2° , surrounded by a neutral background (N7) subtending either 20° or 180° . Data are presented in CIE LUV space (CIE 1976). Adaptation period varied from 1s to 30s for the smaller field and from 1- 60s for the larger field. Colour shifts were measured using a modified Brunswick Ratio (BR). BR was consistently higher when the larger field was combined with longer adaptation periods. Supplementary experiments showed that the differences between the small and large field data were related to a small but perceptible shift in the colour of the background. The role of photoreceptors was examined by plotting cone contrast ratios for the different viewing conditions. As in previous work, weaker colour constancy is associated with failures in adaptation of S-cones. A model based on cone-opponent interactions suggests there are quantitative, but not qualitative differences between observations made under the small and large field conditions.

18 11:50 - Color adaptation contingent on eye saccades

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During a forty minute adaptation phase, we presented briefly and alternatively a red patch on the left and a green patch on the right of a computer screen and required subjects to perform repeated eye saccades from one patch to the other. In order to measure partial adaptation to the contingency between color change and direction of eye saccade, a test stage involved the successive presentation of two yellow patches, either in the left-right or the right-left order. To measure the color change necessary to obtain subjective equality, the hue of the test patches was manipulated, varying from reddish to greenish yellow. Opposite PSE-shifts were obtained for left-right and right-left eye saccades, being consistent with an adaptation of color judgements on the direction of eye saccades. By manipulating the distance and the respective position of the two patches in the test stage, we showed that the amount of adaptation, as measured by the PSE-shift, was dependant on the size and orientation of the eye saccades but not on the departure and arrival positions of the saccades. This dependency on the properties of eye saccades argue for an interpretation in sensorimotor terms of the present effect.

19 12:10 - The gap effect in the parafovea

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In central vision, the discrimination of colours lying on a tritan line is improved if a small gap is introduced between the two stimulus fields. Boynton et al (1977) called this a 'positive gap effect'. The gap effect was negative if the discriminanda differed in luminance and was absent or negative if they differed in the ratio of long- and middle-wave cone excitation. The positive gap effect for tritan stimuli disappeared if a forced-choice procedure was used; and Eskew (1989) found that the effect also disappeared if the stimuli were brief.

In parafoveal vision, using forced-choice and brief stimuli, we have found a robust gap effect. The stimulus patches were sectors of an annulus centred on the fixation point. Their width was 2 degrees of visual angle and their centres were located on an imaginary circle of 5 degrees radius. Their centre-to-centre separation varied from 2 to 5 degrees in separate experimental blocks. At the smallest separation they were adjacent. The stimulus duration was 100 ms. The chromaticities of the reference and test patches were specified in an analogue of MacLeod-Boynton space, using 10-deg fundamentals more suitable to our parafoveal stimuli. In this space, the grey background corresponded to equal-energy white. In separate experiments, we measured discrimination along the L/(L+M) and the S/(L+M) axes. Thresholds were measured with spatial two-alternative forced choice and a staircase procedure.

A gap effect was found for both chromatic axes, discrimination being optimal when the centre-to-centre separation of the targets was 3-4 deg. The effect was exaggerated when the width of the test patches was halved.

Boynton, R. M., Hayhoe, M. M. and MacLeod, D. I. A. (1977) The gap effect: chromatic and achromatic visual discrimination as affected by field separation. *Optica Acta*, 24, 159-177.

Eskew, R.T. (1989) The gap effect revisited: slow changes in chromatic sensitivity as affected by luminance and chromatic borders. *Vision Research*, 29, 717-729.

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20 14:00 - Is it possible to derive the maximum wavelength of M and L photo pigments using multiple-Rayleigh matches?

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Purpose: Measuring the ratio of two particular Rayleigh-type matches, He and Shevell (1994) investigated individual differences in cone photopigments of normal trichromats. They showed that the range of the results for 17 observers was too large to be explained by only individual differences in photopigment optical density and pre-receptor filtering. Their results were accounted for quantitatively by a small difference (3-5 nm) in the max of the L-cone photopigment. In our study, we propose to ask observers to make multiple colour matches, i.e. a series of Rayleigh-type color matches using various sets of test and primaries, in order to investigate differences in M- and L-photopigments. **Methods:** Observers were asked to perform colour-matches between a yellow test light and an additive mixture of red and green lights. A three-channel optical system was used and calibrated. A modified Maxwellian view layout allowed enlarging the exit beam at the entrance of the pupil so that the observer could see the 10 deg matching field in nearly natural viewing. The quasi-monochromatic test and primary lights were obtained using interference filters at three of five wavelengths in the medium longwave range of the visible spectrum. Among the 10 possible layouts that could be achieved with 5 filters, only seven that yielded photopic luminance levels were assessed.

1. $Y1(586nm)+G(551nm)=Y2(580nm)$
2. $R1(617nm)+G(551nm)=Y2(580nm)$
3. $R3(639nm)+G(551nm)=Y2(580nm)$
4. $R1(617nm)+G(551nm)=Y1(586nm)$
5. $R3(639nm)+G(551nm)=Y1(586nm)$
6. $R1(617nm)+Y2(580nm)=Y1(586nm)$
7. $R3(639nm)+Y2(580nm)=Y1(586nm)$

One neutral wedge allowed adjusting the amount of "Red" light and controlling the hue of the Red and Green mixture. Another neutral wedge allowed adjusting the amount of "yellow" light and controlling the brightness equilibrium of the Rayleigh match. Spectroradiometric calibration was achieved in situ. **Results:** The first part of the work consists of predicting the matches of a normal colorimetric observer and of typical deviate colour observers. The normal colorimetric observer is characterised by cone fundamental sensitivity functions as proposed by Stockman, Sharpe and Fachs. Deviate observers are characterised by cone fundamental sensitivity functions that differ from normal ones due to variation of one of five factors:

- the peak wavelength of the L-cone photopigment
- the peak wavelength of the M-cone photopigment
- the peak optical density of the visual pigments in the outer segments of L-cones and M-cones
- the peak optical density of the macular pigment
- the optical density of the lens

The second part of the study is experimental. Ten colour normal observers were asked to perform seven Rayleigh-like matches (6 repetitions). An algorithm allowed us to adjust the values of the five putative factors of variation in order to minimize the sum of squared differences between predicted and real results of matches. **Discussion:** Although the matches were easy to perform, and although the observers were reproducible, we faced several difficulties to derive individual factors of variation. First, we had to ignore three factors of variation: the peak optical density of the visual pigments, the peak optical density of the macular pigment, and the optical density of the lens, which were fitted by the algorithm with implausible values. This probably comes from the fact that the effect of these factors is too small at long wavelengths, compared to individual variability. So we fixed the values of these factors to the value proposed for the normal colorimetric observer. Second, for several observers, the algorithm provided identical peak wavelength for the L-cone and the M-cone photopigments. Several explanations can be given. Either the variability of the matches is too high to allow the fit to converge. Or the Rayleigh-type colour matches are highly correlated and the equations cannot be regarded as independent. Or the assumption that a unique L-cone pigment and a unique M-cone pigment oversimplifies the analysis.

J.C.He, S.K.Shevell, "Individual differences in cone photopigments of normal trichromats measured by dual Rayleigh-type color matches." Vision research, Vol 34, No 3, p 367-376 (1994)

21 14:20 - Illuminant and observer metamerism in colour vision tests

S.J. Dain

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The paper present at ICVS2003 identified the significant metamerism in the several editions of the Hardy-Rand-Rittler pseudoisochromatic plates (HRR) but did not proceed to quantify the consequences of that metamerism. Metamerism is almost inevitable when a printed colour vision test is reproduced in several editions. The widely used Ishihara pseudoisochromatic plates have also been identified as exhibiting clearly visible variation. Metamerism has two consequences, illuminant based changes in performance but also changes in performance with observer (less well known) when assessing anomalous trichromats. This study addresses the effects of illuminant and observer metamerism on the 4 editions of the HRR and also 4 representative editions of the Ishihara plates. The plates that are resistant to each form of metamerism are identified and the magnitude of observer metamerism illustrated by analogy with correlated colour temperature changes.

22 14:40 - The colour discrimination limits of "normal" trichromats - new method for detection and classification of minimal deficiencies

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Colour vision assessment requires a test that (I) provides true isolation of colour signals, (II) is based on data that describe the statistical limits of colour discrimination in "normal" trichromats, (III) has adequate sensitivity to detect "minimal" deficiencies and to classify them, (IV) has enough specificity by minimising measurement variance within normal trichromats, (V) can be used to detect and monitor "significant changes" in colour discrimination over time. The Colour Assessment and Diagnosis (CAD) test has been optimised to fulfil these requirements.

The moving, colour-defined stimulus is of the same mean luminance as the surrounding background and is buried in dynamic luminance contrast noise, a technique that isolates the use of colour signals (1, 2). The subject's task involves direction discrimination of the colour-defined, moving stimuli using a four-alternative, forced-choice procedure. Sixteen colour directions are employed to isolate both yellow-blue (YB) and red-green (RG) chromatic mechanisms. The distribution of colour detection thresholds along these directions in normal trichromats provides the information needed to classify minimal deficiencies and to detect statistically significant changes in chromatic sensitivity in repeated tests.

The statistical limits for the standard normal CAD observer are based on 234 randomly selected subjects (125 males and 109 females, mean age: 30 yrs, SD=10, range: 14 to 60 yrs). Eight of these subjects (~3%) produced RG thresholds that were clearly separated from the cluster of normal trichromats and were not therefore included in the analysis. The colour thresholds measured in the 225 normal trichromats were used to calculate the 2.5% and 97.5% limits and the mean threshold values for RG and YB discrimination. The 97.5% limits and the mean standard error associated with RG and YB thresholds were used to set upper threshold limits for the standard "normal" CAD trichromat. In addition to the group of normal trichromats, 250 colour deficient observers were also investigated. CAD thresholds, Ishihara scores and Nagel anomaloscope matches were measured in each subject. These data have been used to derive multiple comparisons for sensitivity and specificity between the CAD, Ishihara and Nagel tests.

The findings of this study suggest that the new CAD test and in particular the establishment of the standard normal CAD observer provides an accurate means of (I) detecting even minimal colour vision deficiencies that produce variable results with conventional colour vision tests, (II) classifying correctly RG chromatic sensitivity loss into protanomalous and deuteranomalous categories, with only one error in 250 subjects, (III) assessing quantitatively the severity of RG and YB colour vision loss (whether congenital or acquired) and (IV) providing automatic detection of significant changes in chromatic sensitivity when monitoring progress of disease or treatment.

1. Barbur, J. L., Harlow, A. J. & Plant, G. T. (1994) *Proc. R. Soc. Lond B Biol. Sci.* 258, 327-334.
2. Barbur, J. L. (2004) *Prog. Brain Res.* 2004. ;144. :243. -59. 144, 243-259.

23 15:00 - An innovative instrument for the psychophysical measurement of Macular Pigment Optical Density using a CRT display

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We describe a new instrument for psychophysical measurement of Macular Pigment Optical Density (MPOD) designed to overcome many of the difficulties usually encountered when performing subjective photometry on naïve subjects. The system employs a CRT monitor for stimulus presentation and incorporates an optical filter that overcomes the usual limitations of the phosphors of a CRT monitor. Part of the broad spectral emission of each of the three CRT phosphors is absorbed by the macular pigment. Therefore when employed as a stimulus for heterochromatic flicker or motion nulling photometry there is a systematic and significant underestimate in MPOD. To overcome this limitation we have designed a band blocking filter that blocks light between 460-640 nm. When viewed through the filter the spectra of the Red and Blue phosphors do not overlap and the Blue component is absorbed by the MP whilst the Red is not. Thus the subjective photometric measurements made using this configuration are close to those made with monochromatic lights. Test Stimuli are consecutively presented in concentric arcs between 0 and 8 degrees, with central fixation, thus allowing a MPOD profile to be measured. The design brief was that the instrument should measure MPOD in large groups of subjects, for example for screening or drug trials. Therefore we have incorporated two further novel features that improve subject performance and measurement robustness. We employ the motion nulling grating method of Cavanagh and Anstis (1983). A chromatic Blue-Red grating is displayed sequentially with a luminance grating. The gratings appear to drift either up or down. The direction of drift is dependant upon the relative perceived luminance of the Red and Blue Component. This stimulus is easy to see and setting luminance for a motion null is easily to perform: it is ideally suited to the Forced Choice Staircase psychophysical paradigm that we employ. The quality of any psychophysical MPOD estimate relies on knowing the exact retinal eccentricity that is being measured. We use a video based gaze tracking system to ensure that correct central fixation is maintained. The stimulus presentation sequence is inhibited unless the subject is accurately maintaining central fixation. Subject feed back is provided by a visual cue when fixation is correct. We report MPOD profile measurements made with the device and compare them to results in the literature using near-monochromatic lights (Mellerio, et al, 2002; Moreland et al, 2004).

Anstis, S. & Cavanagh, P. (1983) A minimum motion technique for judging equiluminance. In: Mollon, J.D. & Sharpe, L.T. (Eds.), *Colour vision: Psychophysics and physiology*. London, Academic Press, pp. 155-166

Mellerio, J., Ahmadi-Lari, S., van Kuijk, F. J. G. M., Pauleikhoff, D., Bird, A. C. & Marshall, J. (2002) A portable instrument for measuring macular pigment with central fixation. *Cur. Eye Res.* 25:37-47

Moreland, J.D. Macular pigment assessment by motion photometry. (2004) *Archives of Biochemistry and Biophysics*. 430:143-148

24 15:20 - Light scattering effect on contrast sensitivity of different colour Gabor gratings

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To assess the effect of light scattering on perception of colour stimuli with different contrast level, we have measured contrast sensitivity in fog using different colour Gabor gratings. Gratings were red, green, and blue with spatial frequencies 8, 13 and 23 cycles/deg. Experiments were performed in an artificial fog camera at visibility 6, 8 and 11m. Additional indoor experiments were carried out using light scattering PDLC polymer dispersed liquid crystal eye occluders that allowed to control the level of light scattering. The Gabor gratings with different contrast were displayed on LCD monitor. Contrast sensitivity was determined from psychophysical curves. Test subjects should recognize horizontal or vertical orientation of gratings using a 2-alternative forced-choice method. Due to the stronger short wavelength light scattering in fog the most reduction of contrast sensitivity was expected for blue colour gratings. Light scattering decreased contrast sensitivity of all three colour stimuli. Results showed better contrast sensitivity for green and red comparing to blue colour stimuli at all used spatial frequencies. Results for blue colour stimuli showed the most abrupt decrease of contrast sensitivity toward higher spatial frequencies. Additional ERG and VEP studies using reversal monochromatic (red, green, blue) stimuli of different Weber contrast together with scattering induced by PDLC obstacles are in progress.

G. Ikaunieks is thankful to the European Social Fund (ESF) for the support of this study.

25 17:00 - Colour space mapped by the reverse Stroop effect

H. Smithson, S. Khan, L.T. Sharpe, A. Stockman

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In the classic Stroop task, observers are instructed to respond to the ink-colour in which colour-words are printed. Conversely, in a reverse Stroop task, observers are instructed to ignore the ink-colour and to respond to the colour-word. In both tasks, response times (RTs) are faster with congruent combinations in which the word and the ink-colour match, than with incongruent combinations in which the word and the ink-colour do not match. We hypothesized that facilitation should occur when ink-colour belongs to the colour category represented by the colour-word and that interference should occur when ink-colour falls outside this category. Thus, we should be able to map out the cognitive colour space for each colour category. In a reverse Stroop task we manipulated ink-colour to measure the transition from facilitation to interference for multiple combinations of colour-words (RED, ORANGE, YELLOW, GREEN, CYAN, BLUE and PURPLE). Stimuli were presented on a calibrated CRT. In preliminary experiments, we chose colour stimuli that were the best examples of each colour-word and these were used as the congruent and incongruent extremes for each colour pair. Intermediate ink-colours were simple colour-mixtures between these extremes. Observers used a joystick to select, as quickly as possible, the coloured response-patch that corresponded to the colour-word, and RT was recorded. We found that the reverse Stroop task can be used to map the boundaries between colour categories and to measure the distortions of those boundaries caused by colour induction. The data identify differences between common and uncommon colour categories, and are broadly consistent across observers.

26 17:20 - Normal and dichromatic colour discrimination measured from transient isoluminat vecps

L.C.L. Silveira, B.D. Gomes, G.S. Souza, C.A. Saito, M. da Silva Filho

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To compare colour discrimination in humans measured with visual evoked cortical potential (VECP) recordings and psychophysics. Subjects with normal colour vision were tested ($n = 6$) and the results compared with those obtained from one deutan subject. Sinusoidal chromatic gratings were made from colour pairs located along 4 different colour directions centered in two reference points (E2, $u' = 0.219$, $v' = 0.48$; E3, $u' = 0.225$, $v' = 0.415$) were used. Spatial frequency 2 cpd; onset (300 ms) - offset (700 ms) presentation mode. HFP protocol was used to obtain the isoluminance condition for every subject for all colour axes. Monocular VECP was obtained from a bipolar derivation. VECP response amplitude was plotted against distance in the colour space to find electrophysiological thresholds. At least 8 colour pairs were used and the distance between the pair elements was progressively decreased to provide a reliable linear fitting. Psychophysics contrast thresholds were obtained by the adjustment method using the same stimuli. As previously described, we found a negative deflection in the VECP related to the colour contrast: as the contrast decreased, amplitude decreased and latency increased. We estimated for each colour axis the respective threshold contrast and plot the results in the colour diagram. For each subject, colour discrimination thresholds were plotted in the C.I.E. 1976 diagram, forming elliptical contours. VECP threshold for the zero amplitude level was slightly lower than psychophysics thresholds. Colour discrimination thresholds were very high in the deutan direction for the Daltonic subject with both methods. The present work extends the use of transient VECs as a tool to evaluate human colour vision. The VECP results were consistent with psychophysics methods.

SUPPORTED BY CNPq and CAPES.

27 17:40 - Chromatic vision as a general strategy of colour processing in man and animals

M. Vorobyev

Vision, Touch and Hearing Reserch Centre, University of Queensland, Australia

Perceptual separation of chromatic aspects of colour (hue and chroma) from luminance is a fundamental property of human colour vision. It has been suggested that chromatic vision is an ancient mechanism that helps animals to perceive colours largely invariant in conditions of patchy illumination in forests and shallow water (Maximov, 2000). However, little research has been done to find if non-human animals with colour vision perceive chromatic aspects of colour separately from luminance. Here I show that birds and bees have chromatic and luminance mechanisms that are functionally similar to ours. In humans, birds and bees, stimuli subtending large visual angles are discriminated on the basis of their chromatic properties — large variations in the intensity of light stimuli are ignored. In contrast, high spatial resolution vision is mediated by a luminance channel that is sensitive to changes in stimulus intensity, but is not sensitive to variation in the chromatic aspects of colour. The spatial resolution of chromatic and luminance channels varies greatly among different animal groups. Because colour vision in birds and bees evolved independently, separate processing of chromatic aspects of colour from luminance is unlikely to be a consequence of constraints imposed on colour processing. I conclude that chromatic vision probably evolved independently in different animals to achieve colour constancy in conditions of patchy illumination.

Maximov V.V. (2000) *Phyl. Trans. R. Soc. London. B* 335: 1239-1242

28 18:00 - Naturalistic Color Discriminations in New World Monkeys Having Different Combinations of M/L Pigments: Effects of Luminance and Viewing Time

M.P. Rowe, G.H. Jacobs

Neuroscience Research Institute and Department of Psychology, University of California at Santa Barbara

X-linked photopigment polymorphism produces six different color vision phenotypes in most species of New World monkey. In callitrichids, the three alleles underlying these phenotypic differences are present at unequal frequencies suggesting that selective pressures beyond heterozygous-advantage may be at play in these populations. Earlier we investigated this hypothesis with functional substitution, the use of a computer monitor to synthesize colors as they would appear to humans with monkey visual pigments instead of their own (Rowe and Jacobs, 2004). The stimuli were derived from measurements of ecologically relevant fruit and foliage. We found that, for some test conditions, discrimination performance depended on the relative spectral positioning of the substituted M and L pigment pair. The M/L pigment pair that has its absorption peaks separated by only 6 nm performed relatively poorly. More recent experiments have involved a systematic examination of two variables, luminance of the test fields and stimulus presentation time. Under some conditions, discriminability of the simulated fruits did not depend upon which phenotype was simulated. Conditions which favored phenotypes with the larger pigment peak separations tended to be those featuring higher luminance and shorter presentation times. These results indicate that an understanding of the selection pressures affecting photopigment allele frequencies will require careful study of the conditions that provide particular alleles with an advantage. Monkeys may compensate for genetic disadvantages by preferentially performing activities under conditions in which such disadvantages are minimized.

Rowe, M.P. and Jacobs, G.H. (2004). "Cone Pigment Polymorphism in New World Monkeys: Are All Pigments Created Equal?", *Visual Neuroscience*, 21:217-222.

29 18:20 - Determinants of chromatic contrast detection in inferred parvocellular pathways

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Purpose: PC-pathway discrimination for equiluminant chromatic stimuli is controlled by the chromaticity difference between the test field and the surround or border elements adjacent to the test field. Discrimination is best at the surround chromaticity and is independent of the size of the surrounding field. The value of border contrast is presumably related to ongoing eye movements generating retinal border contrast signals that are used by higher order processes for discrimination. The current study investigates the effect of the proximity in space and time of the test field to the surround on chromatic contrast discrimination. **Methods:** Chromatic contrast discrimination was assessed by a four-alternative spatial forced choice procedure. Thresholds were measured for a small test square presented in an inner quadrant (a corner located at the field center) or an outer quadrant (a corner and two borders abutting the surround) of a larger square pedestal that replaced a rectangular surround. The pedestal was presented as a Pulsed-Pedestal replacing the surround or as a Steady-Pedestal within the equiluminant surround. Temporal presentation was a single cycle of a 1.5 sec raised cosine envelope and pedestals varied in L-cone chromaticity at equiluminance (115 effective Td). The surround was either metameric to the equal energy spectrum, or of higher ($l = 0.76$) or lower ($l = 0.62$) L-cone chromaticity on a constant S-cone line. Observers were required to identify the test quadrant where the square was detected. **Results:** Inner quadrant

tests: For the Pulsed-Pedestal paradigm, discrimination was the best at the surround chromaticity, which is comparable to previous results. For the Steady-Pedestal paradigm, discrimination functions were flatter and less dependent on test or surround chromaticity. These functions indicate almost complete adaptation to the square-array and result in optimal or near-optimal discrimination at all test chromaticities. Outer quadrant tests: Results for both the Pulsed- and Steady-Pedestal were like the Pulse-Pedestal data for inner quadrant tests, with best discrimination at the surround chromaticity. **Conclusions:** Local chromatic spatial structure is an important determinant of chromatic discrimination for steadily viewed lights. Discrimination is best when a test is entirely embedded in a surround of the same chromaticity. Borders or surrounds dominate and degrade chromatic discrimination. However, borders provide a sustained chromatic contrast signal and prevent fading of steadily viewed images.

30 9:00 - Surface color perception in three-dimensional scenes with non-uniform spatial and spectral distribution of illumination: Estimating, representing and discounting the illuminant (invited)

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²Center for Neural Science, New York University

³Department of Psychology, University of Minnesota

Researchers studying surface color perception have typically used stimuli that consist of a small number of matte patches (real or simulated) embedded in a plane perpendicular to the line of sight (a ‘Mondrian’, Land & McCann, 1971). Reliable estimation of surface properties analogous to color is a difficult if not impossible computational problem in such limited scenes (Maloney, 1999). In more realistic, three-dimensional scenes the problem is not intractable, in part because considerable information about the spatial and spectral distribution of the illumination is usually available. We describe a series of experiments that (1) explore how the human visual system discounts the spatial and spectral distribution of the illumination (SSDI) in judging matte surface color and (2) what cues the visual system uses in estimating the SSDI of in a scene. We find that the human visual system uses information from shading, cast shadows and specular reflections in estimating the SSDI and, when more than one cue type is present, combines these cues effectively. The SSDI can be very complex in scenes with many different light sources. We examine (3) the limits of human visual representation of the SSDI, reporting an experiment intended to tests these limits. Our results indicate that the human visual representation of the SSD of the illumination in a scene is well-matched to the task of perception of matte surface color perception.

Land, E. H. & McCann, J. J. (1971), Lightness and retinex theory. *Journal of the Optical Society of America*, 61,1-11.

Maloney, L. T. (1999), Physics-based approaches to modeling surface color perception. In Gegenfurtner, K. R., & Sharpe, L. T. [Eds] (1999), *Color Vision: From Genes to Perception*. Cambridge, UK: Cambridge University Press, pp. 387-422.

31 9:35 - Cortical computations involving color, orientation and 3D shape (invited)

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The human visual system has the remarkable ability to accurately perceive 3-D shapes in 2-D images. There is a controversy over whether purely chromatic information is sufficient for this process. To provide definitive answers to this question, we examine the cortical computations involved in identification of 3-D curvatures and slants. For shape from texture variations, we show empirically that the critical step is the extraction of signature orientation flows around lines of maximum surface curvature (Li, & Zaidi, Three-dimensional shape from non-homogeneous textures: carved and stretched surfaces. *Journal of Vision*, 4(10), 860-878, 2004). In images with putatively equiluminant orientation flows, 3-D shape can be perceived, but there is no way to guarantee the absence of luminance artifacts over the complete extent of the image. Instead, we exploit a special case where the image contains achromatic orientation flows, but 3-D shape perception is hindered due to masking by neighboring non-critical orientation modulations. We show that in this case, correct shape perception requires 3-5 times more total cone-contrast for achromatic flows than for chromatic flows, which rules out all possible luminance artifacts. The results show that chromatic flows are masked significantly by achromatic orientation modulations, even if it is only half as much as masking of achromatic flows. Identification of 3-D shapes thus requires orientation selective neurons that are tuned to combinations of chromatic and luminance stimulation (Johnson, Hawken & Shapley, Cone inputs in macaque primary visual cortex. *J Neurophysiol.* 91(6):2501-14, 2004). Orientation flows are also the critical component in shape identification from shading (Ben-Shahar & Zucker, On the Perceptual Organization of Texture and Shading Flows: From a Geometrical Model to Coherence Computation, *Proc. IEEE Conf. on Computer Vision and Pattern Recognition*, Vol. 1: 1048-1055, 2001) and specular reflections (Fleming, Torralba & Adelson, Specular reflections and the perception of shape. *Journal of Vision*, 4(9), 798-820, 2004). These flows, however, extend around lines of minimum surface curvature, and are thus orthogonal to the flows extracted from texture deformations. For both types of flow extraction, we will show the successes and failures of population-coding and template-matching models. In particular, we will show the integral role played by neurons responsive to chromatic stimulation in the computation of 3-D shape from monocular 2-D images.

32 10:10 - Cortical areas involved in the global integration of local color differences evoking color transparency

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Purpose: Surface color perception requires the global integration of local tristimulus contrasts as well as top-down processes to differentiate shadows, illuminance gradients and transparent layers from the intrinsic spectral characteristics of the surface. We exploit the phenomenon of color transparency to identify cortical areas involved in the integration of local contrasts to extract global surface characteristics. **Methods:** Nine observers participated in an fMRI study (3 Tesla Bruker scanner, Functional T2*-weighted EPI images: TR = 3 s, TE = 14 ms, flip angle = 80°, voxel size = 3x3x3.3 mm³, Structural MPRage sequence: TR = 12ms, TE = 4.6 ms, voxel size = 1 mm³). The stimulus was a 10.3 deg field of randomly placed colored disks (1.2 deg). Within an annular test region (1.0 and 6.9 deg, inner and outer

diameters, respectively), the disks were modulated (0.67 Hz) either coherently (evoking the appearance of a transparent overlay) or incoherently, along one of two axes in color space (near either the LM or S axis) at one of three modulation levels. Nine randomly chosen stimuli were presented in a block (27 sec). A scan session consisted of 20 blocks, alternating between coherent and incoherent blocks, during which 180 functional scans were acquired. For each observer, one structural scan and 4 functional scan sessions were acquired. In half of the scan sessions, a dark contour (2.6 min) was added to the inner and outer edges of the annular test region. These conditions comprised a factorial design permitting the comparison of region segmentation by coherent chromatic change with that generated by a real contour. **Results:** Neither the interaction nor the main effect of contour resulted in significant differential activations. The factor coherence resulted in significant differential activity in multiple visual areas in ventral occipital cortex, including striate and extra-striate areas. Significant activity was also observed bilaterally in the parahippocampal gyrus (right: [19, -50, 0 mm] and left: [-15, -50, 1], MNI coordinates), confirming previous results obtained by us (all results corrected $p = 0.05$). **Conclusions:** The activations observed cannot be attributed simply to a saliency effect linked to coherent contrast modulations as the introduction of a contour to increase the saliency of the test region generated no significant differential pattern of activation. The distribution of activity observed supports a role for a ventro-occipital network in the integration of local cues in transparency perception. The activity of the parahippocampus links the extraction of a transparent layer with a site activated by object-related properties of an image.

33 10:50 - The perceptual structure of color corresponds to singularities in reflection properties

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One of the most basic aspects of color vision, namely the special role of the colors red, green, blue and yellow, is usually assumed to have a purely neuronal cause. We will show a fact that suggests a fundamentally different origin: from the viewpoint of human photopigments, red, green, blue and yellow surfaces alter light in a simpler way than all other surfaces. This is demonstrated by constructing a biological restriction of the physicist's notion of reflectance that takes into account the statistical constraints satisfied by natural illuminants and the limitations induced by human photopigments. Using a dataset of natural and artificial reflectances, we then show numerically that the existence and the identity of four singular hues is actually to be expected from trichromatic theory alone, independently of any opponent mechanisms. This approach very directly provides correct quantitative predictions for psychophysical data about unique hues, hue cancellation, and cross-cultural data about color naming.

34 11:10 - Colour constancy is a function of the velocity of a moving surface

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Recently it has been demonstrated that colour constancy increases significantly if a surface moves across a textured background (Werner, 2004), as compared to an equivalent static condition (typical Mondrian presentation). This was found to be selective for object motion, suggesting the involvement of higher order motion mechanisms. Different motion processes can be distinguished on grounds of their temporal characteristics. In order to evaluate the involved motion processes, the temporal tuning of the effect of motion on colour constancy was determined. The background pattern consisted of a static heterochromatic checkerboard pattern (18 x 18 deg, $L_{mean} = 19.3 \text{ cd/m}^2$) in front of which a testfield (1.8

x 1.8 deg, $L_{test} = 19.3 \text{ cd/m}^2$) moved horizontally with constant speed. The chromaticity of the testfield was identical to the mean chromaticity and was under standard condition achromatic ($u^* = 0.197$, $v^* = 0.468$). Colour constancy was tested for a simulated homogenous illumination change across the entire test-pattern from D65 towards a perceptually green illumination ($u^* = 0.166$, $v^* = 0.472$) resulting in a chromaticity shift of testfield and background along an equiluminant L/M axis ($\Delta E^*_{uv} = 22.88$). Colour constancy was measured using a hue cancellation method for the achromatic appearance of the testfield after a 5 s adaptation period to the new illumination, whereby the testfield moved continuously with one of 8 different speeds (0.3 to 14 deg sec⁻¹). Three subjects with normal colour vision (Cambridge Colour Test) and normal visual acuity participated in the experiments. Colour constancy was found to increase nearly linearly with speed, reached a maximum value around 2 deg sec⁻¹ and then dropped off sharply at higher speeds. The corner value for higher velocities (velocity at which the motion induced increase of colour constancy has dropped to $\frac{1}{2}$ of its maximum value) is equivalent to a temporal frequency of 2 Hz. It is therefore consistent with the temporal properties of the relatively slow third order motion/feature tracking system, which can be linked to tracking the position of objects moving across a scene (Lu & Sperling, 2001; Seiffert & Cavanagh, 1999).

The study was supported by the DFG (grant # We 1710 1/1) and the fortune programme (Faculty of Medicine, University of Tübingen; grant # 1059).

Lu, Z.-L. & Sperling, G. (2001) *Journal of the Optical Society of America, A*, 18, 2331-2370.

Seiffert, A. & Cavanagh, P. (1999) *Vision Research*, 39, 4172-4185
Werner, A. (2004) *Journal of Vision*, 4, 58.

35 11:30 - Color Appearance of Natural Objects

T. Hansen, S. Walter, K.R. Gegenfurtner

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Assigning a basic color name to an object and rating the amount of a particular hue is a fundamental visual capability. Traditional measurements of color appearance have used increment flashes or isoluminant stimuli of a homogeneous color. Natural objects, however,

do not contain a single color, but are characterized by a distribution of different chromatic hues. Here we study color appearance using photographs of various natural fruit objects.

The stimuli were briefly presented on a CRT monitor. The stimuli were either homogeneous spots, or digital photographs of fruit objects (banana, orange, etc) and were displayed on a homogeneous white background. In some of the experiments, the luminance of the background was varied above and below the medium gray. The chromaticity of the stimuli was varied in 36 equally spaced chromatic directions in the isoluminant plane of the DKL color space. For each stimuli, subjects rated the amount of red, green, blue and yellow in the stimulus in a scale from 0 to 8. On a given run, each stimulus was presented twice in random order, and each run was repeated 5 times for a total of 10 judgments for each chromatic direction.

In agreement with earlier studies we have found that the peak ratings for each color do not coincide with the cardinal axis of DKL color space. Further, ratings generally do not differ depending on the background luminance. Here we only found a small effect for yellowish color directions, which receive higher ratings at higher relative luminance values. For the fruit objects, we found a selective increase in the rated color appearance in the direction of the natural fruit color. For example, the average rate for yellow was 5.14 (64%) for the color spots compared to 6.68 (84%) for the banana image.

We conclude that the distribution of hues within natural objects can have a profound effect on color appearance and needs to be taken into account when predicting color appearance.

36 11:50 - Illuminant-independent judgements of surface colour in natural scenes

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Observers can readily judge surface colour in images of natural scenes during illuminant changes (Amano et al., 2004). Some theories of such judgements assume that the spectral properties of the illuminant are used by the observer (D’Zmura and Iverson, 1993; Maloney, 1999). To test this hypothesis, a surface-colour-matching experiment was performed in which the illuminant was unambiguous and clearly visible to the observer. Images of natural urban scenes were presented on a computer-controlled colour monitor with 10-bit resolution per gun. The scenes were reproduced from data obtained with a high-resolution hyperspectral imaging system (Foster et al., 2004). The colours of sky and test-surfaces were manipulated independently. Sky colour was chosen from the daylight locus, so that it was initially neutral, bluish, reddish, or more reddish. Test-surface colour was chosen so that it was initially neutral, reddish, bluish, greenish, or yellowish. Each experimental session used just one sky colour and one test-surface colour, yielding twenty conditions in all. In each trial of each experimental session, two images of a natural scene were presented in sequence, each for 1 s with no interval, under two different daylight illuminants: the first with correlated colour temperature 25000 K, the second 6700 K. The spectral reflectance of the test surface in the second image was changed randomly, consistent with a local change in daylight. The images, viewed at 100 cm, subtended approx. $17^\circ - 14^\circ$ at the eye. The observer’s task was to decide whether the test surface in the two images was the same. Performance by 6 observers with normal colour-vision was quantified with a constancy index in which 1 represents perfect constancy and 0 perfect inconstancy. Mean performance over observers ranged from 0.56 to 0.88. There was, however, no significant effect of sky colour ($F(3, 15) = 1.3$, $p > 0.3$) or of test-surface colour ($F(4, 20) = 0.8$, $p > 0.5$). This result suggests that surface-colour judgements in natural scenes can be performed independently of the inferred illuminant, consistent with a theory based on relational judgements (Foster, 2003).

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D’Zmura, M. and Iverson, G. (1993) *Journal of the Optical Society of America A*, 10, 148-2165.

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Foster, D. H. (2003) *Trends in Cognitive Sciences*, 7, 439-443.

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37 12:10 - Color Vision in Flatland: a Model of the Retinal and Cortical Circuitry for Coding Color Computer Implemented for a One-Dimensional Cone Array

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How does the visual system represent color? What operations does it perform to transform cone signals into a color code? What forms the circuits? To address these questions we have developed a model for the neural coding of color in which the cortical circuits for red-green color vision arise by hijacking the preexisting blue-yellow system. The model extends a random wiring hypothesis for red-green color vision that others have proposed. The initial assumption is that ancestors to modern primates had

a preexisting midget ganglion-cell system that signals differences in quantal catch between an individual cone photoreceptor and the average of its neighbors. Thus, if L and M cones are randomly distributed, any cone cell that has some neighbors of the other spectral type will automatically form the basis for a spectrally opponent ganglion cell. This solves the problem of deconfounding color and intensity information from the cones without any L/M cell-type specific postsynaptic neurons in the retina. However, the spectrally different cones are at slightly different spatial locations and this introduces a new confound of color and luminance-edges at the level of the ganglion cells—diffuse colored light can produce exactly the same response in a spectrally opponent ganglion cell as a dark/white edge. To deconfound the ganglion cell signals, the cortex must perform an operation on the ganglion-cell input (which arrives via the LGN) that is analogous to that carried out by the midget ganglion-cell circuit on the cone signals. Thus, our model extends the random wiring hypothesis to the cortex by introducing a circuit that indiscriminately differences the response from an individual neural input and the average of its neighboring inputs. This forms cortical circuits that resolve the confound between diffuse colored light and luminance edges, which is inherent to ganglion responses, without introducing any cell-type specific L/M connections and without invoking Hebbian learning to inform the appropriate neural wiring. Six different circuits, corresponding to 6 distinct percepts—black, white, red, green, yellow and blue, are imposed by the character of the peripheral receptor mosaic and by post-receptoral elements early in the neural pathway as a natural consequence of the proposed cortical circuitry that indiscriminately compares the activity of a cell with its immediate neighbors. Unexpectedly, in a departure from earlier random wiring theories that did not consider higher processing, the model predicts that L/M opponent ganglion-cells without S cone input will not contribute to circuits for hue perception formed in the cortex; instead, they form circuits that respond to edges. These are presumably responsible for the percepts of black and white edges. As in the DeValois and DeValois multistage color model, all four hue percepts are the result of circuits with input from S cones and the relationship between cone inputs and hue percepts are as they have proposed: red, (L+S)-M; green, M-(L+S), blue (M+S)-L and yellow L-(M+S). This model extends the DeValois model in proposing a straightforward mechanism to form these circuits. Quite simply, midget ganglion cells that have inhibitory S cone input in their surround become the basis for hue circuits in the cortex. The cone forming the receptive field center can be either L or M; ganglion cells can be either ON or OFF center. The resulting four possible combinations correspond to our four hues. An M cone center with S and L surround through an ON-center ganglion cell makes M-(S+L) green; the same receptive field through an OFF-center ganglion cell makes (S+L)-M red. An L cone center with an M and S surround makes L-(M+S) yellow; that receptive field through an OFF-center cell produces (M+S)-L blue. To demonstrate that the model functions as predicted, we have developed a computer program that implements it in a simplified visual system with a one-dimensional cone photoreceptor mosaic. The behavior of the computer model closely matches human hue perception.

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38 8:50 - Color shifts induced by S-cone patterns: Spatial structure at the S-cone or postreceptoral level?

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Purpose: This study investigated chromatic induction from an inhomogeneous background pattern. The background had a pattern detected by only S cones. Previous studies showed a background with an S-cone pattern induced strong color shifts in a nearby test area (Monnier & Shevell, 2003). In previous work, the S-cone patterns were composed with constant L- and M-cone stimulation over the entire background; in terms of L and M cones, therefore, the background was uniform. S-cone stimulation was

varied over space to produce the S-cone-isolated background pattern. These S-cone-isolated patterns, however, established spatial structure (the pattern) at both the receptor level (S-cone stimulation) and the postreceptor level (S/(L+M)). Here, these two levels of pattern representation were unconfounded to determine whether color shifts induced by S-cone-isolated patterns were due to spatial structure at the receptor or postreceptor level. **Methods:** The color appearance of a test field was measured with several different background patterns composed of concentric circles alternating between two chromaticities. Pattern 1 had both S-cone and post-receptor S/(L+M) variation. Pattern 2 had post-receptor variation (as in Pattern 1) but no S-cone variation. Pattern 3 had S-cone variation (as in Pattern 1) but no post-receptor S/(L+M) variation. The properties of Patterns 2 and 3 were achieved by adjusting the luminances of the two chromaticities composing the pattern. Color shifts induced by these patterns were measured using asymmetric matching. **Results:** Pattern 1 induced large shifts in color appearance, corroborating previous studies. Similar shifts were produced by Pattern 2 (only postreceptor spatial structure) but not by Pattern 3 (S-cone spatial structure). **Conclusion:** The large shifts in color appearance induced by S-cone patterns are mediated by signals in a postreceptor S-cone pathway. These results are consistent with a cortical neural mechanism with +s/-s spatial antagonism, as found in V1 (Conway, 2001) and V2 (Soloman, Peirce & Lennie, 2004).

Conway B. R. (2001) *Journal of Neuroscience*, 21, 2768-2783.

Monnier P. & Shevell S. K. (2003) *Nature Neuroscience*, 6, 801-802.

Soloman, Peirce & Lennie (2004) *Journal of Neuroscience*, 24, 148-160.

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39 9:10 - The discoloration illusion

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The watercolor illusion is a long-range assimilative spread of color (coloration effect) emanating from a thin colored line running contiguous to a darker chromatic contour and imparting a figural effect across large areas stronger than the one induced by Gestalt grouping and figure-ground principles. The figural effect is due to the asymmetric luminance contrast principle (Pinna, 1995): all else being equal, given an asymmetric luminance contrast profile on both sides of a boundary (as is the case with the watercolor illusion made up of two juxtaposed parallel lines), the region whose luminance gradient is less abrupt is perceived as a figure, while the complementary more abrupt region is perceived as a background. This new principle strengthens the unilateral border ownership. When six different chromatic lines are placed parallel and contiguous on a white background to create a gradient of luminance contrast (e.g. from dark blue to light blue), the coloration disappears, whereas, a clear "lighting" illusion emerges with light and dark regions that model the volume by strengthening the 3D appearance of the inner region. Under these new conditions, if the inner region is physically tinted with a light chromatic color (e.g. light red), the inner region appears white: the light red totally discolors. The effect disappears when the gradient is reversed and the length is reduced. Through psychophysical experiments the discoloration illusion has been systematically measured. The results showed that the effect is not due to simultaneous contrast, differs from Craik-O'Brien-Cornsweet illusion, and depends on the "lighting" of the inner region. It is suggested that multiple lines stimulating neurons, selective for asymmetric edge profiles may signal not only border ownership (von der Heydt et al., 2003) but also the phenomenal "lighting".

40 9:30 - Temporal nulling of induction from spatial patterns modulated in time

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Introduction: Asymmetric color matching shows that receptive-field organization accounts for large color shifts induced by chromatic patterns (Monnier & Shevell, 2003). Here, we used temporally-varied chromatic inducing light to infer receptive-field organization using a method that does not require a color judgment. **Methods:** Time-varying chromatic induction from a background was nulled by adding time-varying chromatic light within the test area. The phase and amplitude of this added light were adjusted by the observer to null the perceived temporal variation in the test. The whole stimulus was composed of a test ring flanked on each side by 4 concentric circles, alternating between chromaticities initially appearing "purple" and "lime". The inducing chromaticities differed in only S-cone stimulation. In various conditions, either the contiguous or noncontiguous chromaticity was temporally varied sinusoidally from "purple" to "lime". The observer's task was to adjust the test ring's amplitude and phase in order to null its perceived temporal modulation. **Result and Conclusion:** The results showed that contiguous-chromatic temporal modulation required an out-of-phase nulling modulation of the test ring, implying assimilation. Non-contiguous-chromatic modulation required in-phase modulation of the test ring, implying contrast. The experiments here also showed that increasing temporal frequency from 0.5 to 4Hz did not appreciably affect the induced color shifts. Overall, these results corroborate the +s/s cortical receptive-field organization inferred in previous studies that used asymmetric color matching. The response of this type of cortical receptive field increases with S-cone stimulation at its center and decreases with S-cone stimulation in the surround.

Monnier P. & Shevell S. K. (2003) *Nature Neuroscience*, 6, 801-802.

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41 9:50 - Induced Steady Color Shifts from Temporally Varying Surrounds

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Introduction: With a center-surround spatial configuration, varying the chromaticity of the surround slowly over time induces apparent temporal chromatic variation into a physically constant gray center. The magnitude of the induced temporal modulation in the center is strongly attenuated when the surround is at temporal frequencies above 3 Hz (DeValois, Webster, DeValois, & Lingelbach, 1986). Though the center does not appear to vary over time when the surround is modulated at these high frequencies, the center may still undergo a steady shift in chromatic appearance. This would occur if a nonlinear process precedes the site of neural attenuation of temporally varying inducing signals. The present study investigated whether a steady color shift was induced by a chromatically varying surround at high temporal frequencies. **Methods:** Induced color shifts were measured as a function of the temporal frequency of the surround. The test field was an equal-energy white (EEW) annulus within a larger circular surround. Both borders of the annulus were separated from the surround by a thin dark gap (3 min.). The surround was temporally modulated along the L/(L+M) direction of MacLeod-Boynton space at 6% Michelson contrast. Several different temporal frequencies were tested, ranging from 0.5 to 37.5 Hz. The time average of the surround was EEW. The observer adjusted the chromaticity of a separate annulus to match

the appearance of the test field. One match was to the peak and a separate match was to the trough of induced temporal modulation in the test annulus. If there was no apparent temporal modulation, the observer matched the steady appearance of the test annulus. Results and Conclusion: The measurements corroborate the low pass attenuation (above ~3 Hz) of induced temporally varying modulation from a chromatic surround (DeValois et al., 1986). At temporal frequencies above 3 Hz, however, color shifts were induced in the test area that appeared steady. A possible explanation for steady color shifts from a temporally varying chromatic surround is nonlinear temporal processing that precedes the low-pass attenuation of induced temporal variation. The low-pass filter attenuates the high frequency component from the inducing surround but not a DC signal that results in a steady color shift.

DeValois R.L., Webster M.A., DeValois K.K., & Lingelbach B. (1986) *Vision Research*, 26: 887-897. Supported by NIH grant EY-04802.

42 10:10 - Effects of Motion and Configural Complexity on Color Transparency Perception

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Purpose: The General Convergence Model (GCM) (D’Zmura et al., 1997) predicts that systematic chromatic changes in a linear color space, such as translation and convergence (or a combination of both), lead to the perception of transparency. While this model is neither a necessary nor a sufficient condition for perceptual transparency (Chen & M. D’Zmura, 1998; F. Faul & V. Ekroll, 2002), it describes in a simple fashion a large number of color changes that do evoke transparency. We tested whether motion and configural complexity affect perceived transparency generated by this model. **Methods:** Several chromatic changes consistent or not with the GCM were generated. The stimuli consisted of a bipartite or a checkerboard configuration (10x10 deg), displayed in the center of the monitor, with a central static or moving overlay (5x5 deg). The CIE LUV space was chosen to specify three vector lengths. Five chromatic transformations were considered: translation, convergence, shear, divergence and rotation. Three different luminance levels (vectors point to a higher, equal or lower luminance) were also explored. A total of 720 stimuli were presented to three observers. Subjects sat in a dark room, in front of the monitor at 50cm from the screen. The set of all patches was presented in a randomized sequence. For each patch, the observer judged whether the overlay was transparent or not. The relation between the classification judgments and the stimulus categories was evaluated using a log-linear model. **Results:** The main results showed that observers’ responses are influenced by each of the above cited parameters. Convergences appear significantly more transparent when motion is added for bipartite configurations, or when they are generated in a checkerboard configuration. Translations are influenced by both configuration and motion. Shears are observed as opaque, except when short vector lengths are combined with motion, then the overlay tends to be transparent. Divergences are strongly affected by motion and vector lengths, and rotations by a combination of checkerboard configuration with luminance level and vector length. **Conclusions:** Our results reveal different conditions which evoke opacity or transparency, that is when motion is added, or when stimulus configuration is changed. These results question the generality of the GCM across configurations when non-color cues change, and indicate that adding motion and stimulus complexity are not neutral with respect to the chromatic shifts evoking transparency. Thus, studies that have used motion to enhance transparency may yield different results from those that did not about the color shifts supporting transparency perception. The same might be supposed for stimulus complexity.

V.J. Chen & M. D’Zmura (1998) Test of a convergence model for color transparency. *Perception*, 27:595–608.

M. D'Zmura, P. Colantoni, K. Knoblauch, & B. Laget (1997) Color Transparency. *Perception*, 26:471–492.

F. Faul and V. Ekroll (2002) Psychophysical model of chromatic perceptual transparency based on subtractive color mixture. *J. Opt. Soc. Am. A*, 19(6):1084–1095.

43 10:50 - Maximal and minimal hue shifts in the near periphery: is there a link with ambiguous and unambiguous (unique) hues?

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Colour perception changes markedly as a function of retinal eccentricity. The magnitude of the perceptual shift depends strongly on hue and is largely defined by shifts in hue and saturation. We recently reported the independence of the saturation and hue effects (*Journal of Vision*, 2004, 4(11), 10a; Fall Vision Meeting abstract). The use of very large stimuli minimises the saturation shift whilst the hue shift appears to be independent of stimulus size and luminance. Furthermore, the stimuli that show maximum hue shift are not the same as those that show maximum saturation shift. To explore the notion that the invariant hues (those which do not shift with eccentricity) may be linked with unique hues, we studied the peripheral colour vision of 9 colour-normal subjects, measuring their shifts in colour appearance and their unique hue functions.

In the colour appearance experiment, S matched a 1deg nasal test spot (diameter 1deg) with an 18deg nasal probe spot (diameter 3deg). Test and probe were flashed simultaneously on a white 12.5cd/sq m background for 380ms. S had free control over hue, saturation and luminance of the probe. 25 test chromaticities were equally spaced around a hue circle in MBDKL colour space. All 9 Ss showed similar hue and saturation functions. Four regions of colour space showed maximal hue shifts: to match tests with chromatic angles of 75deg and 255deg (approx blue and yellow), the mean probe hue was 30deg and 224deg (negative hue shifts), while 150deg and 330deg tests needed smaller positive hue shifts of between 5 and 10deg. There were 4 intermediate null points (showing no hue shift), with chromatic angles of 123, 170, 300 and 358deg. The same probe stimulus was used in a simple colour naming task, in which S assigned one of 4 colour names (red, green, blue or yellow) to each of 21 hues around the colour circle, randomly repeated 10 times. These gave rise to R, G, B and Y unique hue functions whose maxima showed a close relationship with the invariant hues previously measured. Green showed the poorest correspondence, and is known to show the greatest variation in unique hues. The hues that varied most with eccentricity showed a close relationship with the least unique hues (i.e. those which were equally likely to be called either of two adjacent colours). Whilst it might be argued that invariant hues may anchor our perception and be the candidates for unique hues, it is an equally attractive notion that those colours which show the greatest variation may be those which are most ambiguous.

44 11:10 - Colour stimuli perception in presence of light scattering

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Perception of different colour contrast stimuli (Landolt-C red, green, blue and yellow letters on white (grey) background) was studied in adverse viewing conditions: in a fog chamber in Clermont-Ferrand; and in laboratory where controlled light scattering decreasing the visual acuity at similar level was in-

duced by means of PDLC polymer disperse liquid crystal eye occluders (Ozolinsh and Papelba, 2004). Parallel to that other measurements: the presence of the red-green-blue (L/M and M/S) cone system sensitivity changes to the LCD display R, G, and B channel emission spectra in fog, and the decrease of the colour stimuli contrast sensitivity increasing the fog density were performed in both experimental conditions.

Blue (shortest wavelength) light is scattered in fog at the greatest extent, that can cause determination of vision quality especially for the monochromatic blue stimuli. However if the blue stimuli were presented on the white background visual acuity in fog for blue Landolt-C optotypes was the highest as compared to red and green optotypes. The colour intensity of Landolt-C optotypes presented on LCD screen was chosen corresponding to the blue, green and red colour contributions in achromatic white stimulus (equal computer R, G or B values for chromatic stimuli as in the achromatic white background). Thus the blue stimuli had the greatest intensity contrast, and besides: blue stimuli on white background correspond to uniform stimuli blue distribution within all stimuli area either within white background or within stimuli C optotype area and sequently the greater shorter wavelength scattering does not alter blue stimuli perception. Search time of different colour stimuli and dynamic visual acuity (up to stimuli speed 30 degree/sec) also were determined in simulated fog conditions using scattering obstacles with controllable degree of light scattering. These experiments also revealed the smallest increase of visual search times and better dynamic visual acuity in fog for blue-white colour contrast stimuli comparing with red-white and green-white combinations used in road and traffic signs.

Ozolinsh, M. & Papelba G. (2004), *Ferroelectrics*, 304, 207–212.

45 11:30 - Resolution of binocular color rivalry: Perceptual misbinding of color and form

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Purpose: How are separate neural representations of color and form combined to give a unified percept? Dichoptic presentation of rivalrous chromatic gratings with low luminance contrast reveals perceptual misbinding of color and form. This implies (1) resolution of color rivalry goes beyond simple color dominance and color mixture and (2) luminance contrast affects binding of color and form. **Methods:** An equiluminant square-wave red/gray grating was presented to the left eye and an equiluminant blue/gray grating to the right eye (the two chromatic components were in phase). After an initial percept of rivalry (less than 30 sec) these stimuli resulted in a perceived red/blue grating. This two-color perceived grating is not consistent with previous studies of dichoptic presentation of two chromaticities, which report either binocular color rivalry or binocular color mixture (Ikeda & Sagawa, 1979; de Weert & Wade, 1988). Instead, the percept reveals misbinding of the color presented to each eye to the fused perceived form. In experiments here, observers dichoptically viewed for 1 minute two rivalrous 2cyc/deg gratings with different chromaticities. The visibility time was measured for four percepts: left-eye stimulus, right-eye stimulus, fusion of the two colors, or a two-color (e.g. red/blue) grating. The chromaticities and luminance contrast of the gratings were varied systematically. **Results:** The percept of a two-color grating (misbinding) was not observed (1) with only S-cone contrast in the grating or (2) with Michelson luminance contrast in the grating above 20%. In general, either misbinding (at low luminance contrast) or color mixture (at high luminance contrast) was observed, but not both of them. **Conclusions:** The perceived two-color gratings show that the two rivalrous chromaticities are both represented neurally when color and form are combined to give a unified percept. "Resolution" of competing chromatic signals from the two eyes is not restricted to color dominance and color mixture. The transition from misbinding to color mixture caused by increasing luminance contrast implies that luminance contrast at edges has an important role in the correct localization of color and form.

Ikeda, M. & Sagawa, K. (1979) *Journal of Optical Society America*, 69, 316-321.
de Weert, C.M.M. & Wade, N.J. (1988) *Vision Research*, 28, 1031-1040.
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46 11:50 - A whiter shade of pale, a blacker shade of dark: Parameters of spatially induced blackness

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The surface-mode property of "Blackness" is induced by simultaneous contrast with adjacent, more luminant subtends. Numerous studies have shown that the degree of blackness induced within an achromatic test field is a function of the relative luminance of the adjacent chromatic inducing field, but not of its hue. The converse may not be true for chromatic test fields, where susceptibility to blackening has been reported to vary with wavelength. In the present study we questioned whether 'white' and 'black' sensory components function as opposites in blackness appearance. We recorded the appearance of a central monochromatic test field (with wavelength ranging across the visible spectrum) while a broadband white annulus was set to six luminance levels ranging across three log steps. Three colour-normal observers followed a colour-naming technique. All six opponent-hue names and their combinations were response options; blackness and whiteness in the test field could therefore be reported independently. Of primary interest were the achromatic responses, which revealed the 'white-to-black' dimension when represented within a multidimensional space, but in addition a quality (dimension) of 'desaturation'. Compared against chromatic properties of the test field, the results provide evidence that blackness induction is a function of field brightness (not luminance). This confirms observations made by Shinomori et al. (1997) using a different procedure. These findings have implications for the stage of visual processing involved in blackness induction. This necessarily occurs downstream from the origin of the Brightness signal from a combination of opponent-process channels.

Shinomori, K., Scheffrin, B. E. & Werner, J. S. (1997) *Journal of the Optical Society of America A*, 14, 372-387.

47 12:10 - Remote Induction Effects in Achromatic Color Perception and Their Modulation by Local Contrast

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Distance-dependent edge integration models (Reid & Shapley, 1988; Rudd & Arrington, 2001; Rudd & Zemach, 2004) assert that the achromatic color of a square surrounded by a frame is computed from a weighted sum of the contrasts, or log luminance ratios, at the inner and outer edges of the frame, with a larger weight given to the inner edge. Rudd and Arrington (2001) further posited that the weight given to the outer edge decreases in proportion to the log luminance ratio of the inner edge, an edge interaction effect that they referred to as 'blockage.' Here, the blockage assumption was tested in an achromatic color matching experiment involving two dark squares, each surrounded by a light frame. The frame surrounding the left (matching) square was wider than the frame surrounding the right (target) square. Two observers adjusted the matching square luminance to achieve an appearance match to the target as a function of the background luminance, which was varied over a range spanning the frame luminance.

For this display, all distant-dependent edge integration models predict that the target appearance, as measure by the observer's matching disk settings, will decrease monotonically with increasing background luminance. Consistent with this prediction, both observers' average match settings decreased as a linear function of the background luminance on a log-log scale. When the experiment was repeated with target squares of different luminances, the estimated weight given to the outer edge was found to be modulated by the local luminance ratio of the inner frame border, as predicted by the blockage model, but not by other edge integration models. However, the direction of the modulation was not always consistent with the blockage hypothesis. Depending on the contrast polarities of the inner and outer frame edges, and the background level, the effect could be one of either blockage or enhancement. To account for these findings, a neural model is proposed in which the modulation of remote induction effects by local contrast results from additive and subtractive gain control processes operating between oriented spatial filters that encode the log luminance ratios at edges.

Reid, R. C., & Shapley, R. (1988). *Vision Research*, 28, 115-132.

Rudd, M. E., & Arrington, K. F. (2001). *Vision Research*, 41, 3649-3662.

Rudd, M. E., & Zemach, I. K. (2004). *Vision Research*, 44, 971-981.

48 14:00 - The influence of circulating glucose and oxygen concentrations on cone and rod sensitivity in IDDM diabetics and normal subjects

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Visual function is critically dependent on a continuous oxygen supply to maintain the large energy requirements of the photoreceptors. A reduction of the oxygen supply is thought to play a major role in the development of a diabetic retinopathy. In this study we asked if it is possible to ameliorate early visual deficits in diabetics by increasing their blood oxygen level, and what effect this, as well as an increased glucose level, has on the sensitivity of the photoreceptors in normal subjects. Cone and rod function were monitored by recording dark adaptation curves while inhaling either air (20% O₂ + 80% N₂) or 100% oxygen. Pupils were dilated and the increment threshold for a green and a red stimulus, subtending 120 deg, was measured alternatively every minute for 40 mins after an initial 3 min bleach of around 5.24 log tds. The results of 12 IDDM patients with no (10) or mild (2) retinopathy (mean age 25.0 years) were compared to those of an age-matched control group of 12 healthy, non-smoking, subjects (mean age 24.75 years). Additionally, using a glucose clamp technique, we repeated the experiment in 10 of the control subjects with elevated blood glucose concentrations (mean 160 mmolL⁻¹). Oxygen inhalation led to a decrease in threshold for both the cone plateau and the final threshold in the results of the diabetic group but had less effect on the results of the control group. The cone plateau, but not the absolute threshold was significantly dependent on the glucose level of the blood in control subjects, showing a decrease in threshold with elevated blood glucose. These results show that oxygen inhalation improves both rod and cone sensitivity in diabetics without retinopathy. Cone but not rod sensitivity is dependent on the concentration of circulating glucose.

49 14:20 - Color vision in male and female asymptomatic carriers of LHON's 11778 mtDNA mutation

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Leber's hereditary optic neuropathy is a maternally inherited disease, associated with mitochondrial DNA point mutations and characterized by sudden and profound loss of visual acuity and dyschromatopsia. Only a small percentage of a pedigree becomes affected, with a much greater penetrance in men, (from a 2.5:1 to a 5:1 ratio of affected males to females, in different studies). Here we investigate the possibility of visual losses in clinically asymptomatic 11778 LHON carriers of both genders from a recently discovered extensive family living in a rural area in Brazil. Colour thresholds were determined monocularly with the Cambridge Colour Test (CCT) in 27 LHON carriers (10 male and 17 female) and 76 age-matched controls (39 male and 37 female). Inclusion criteria were absence of known ophthalmological complaints and 20/30 bc VA or better. We used the Trivector procedure of the CCT (CRSLtd), with a VSG 2/5 card and a Sony Trinitron video monitor, calibrated with a Minolta CS1000 photometer. McAdam Ellipses were obtained from carriers with altered Trivector thresholds. Abnormal protan and/or deutan thresholds were found in 83% of the carriers (57% protan and 76% deutan), those with higher thresholds also had elevated tritan thresholds (45%). Male thresholds were significantly larger than female's (Student t test; $p < .05$). Color vision abnormalities found in asymptomatic LHON carriers are consistent with the hypothesis that LHON should be considered as a chronic disease shared by the majority of the carriers, which may undergo an acute phase, triggered by mechanisms still unknown, in a small part of these patients. The higher penetrance of the disorder in males is reflected in the greater amount of losses compared to females.

50 14:40 - Color discrimination in long term type 1 diabetes mellitus.

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Recently we had the opportunity to re-examine a number of patients suffering from type 1 diabetes mellitus who were admitted to our Clinic in 1979-82 and in 1997 for a study of visual performance; in that study also color discrimination was thoroughly evaluated. Now the color discrimination was tested again to analyse the possible changes that occurred in the meantime. Nine informed and very collaborative patients, 7 female and 2 males (aged 40-58 yrs) suffering from type 1 diabetes mellitus were re-examined for the present study. Each subject was given a complete ophthalmic examination, including slit-lamp, tonometry, fluorescein retinal angiography, refraction, V.A., and ocular motility. All subjects were tested for color vision discrimination using Ishihara plates, Farnsworth-Munsell (FM) 100-hue test and the Lanthony desaturated 15-hue test. The results show that all patients but one, had good metabolic control without retinopathy or mild retinopathy; in spite of long term duration of the disease (24-30 yrs) color discrimination is not consequently impaired, but in some cases have had an improvement. We wonder if the progressive better metabolic control and the informed participation of the patients like autoregulation are responsible of the improvement.

51 15:00 - Functional specialisation for the processing of colour categories in the cortex—evidence from clinical studies

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"Opponent" processing of cone photoreceptor signals in neural substrates located early in the visual pathways is sufficient to generate two, polarity-sensitive signals that describe the four distinct "cardinal directions" in colour space. Cone contrasts based on thresholds for detection of yellow-blue and red-green colour changes show convincingly that equal S-cone increments and decrements lead to the perception of "blue" and "yellow" stimulus colours, respectively, whilst positive and negative L-M cone contrast signals of equal magnitude yield "red" and "green" colours, in the absence of S-cone signal changes. Many studies support the implication that the same neural substrates generate polarity sensitive signals that describe red-green and yellow-blue perceived colours, both in the retina and in the lateral geniculate nucleus (1-3). The processing of opponent colour signals and the generation of perceived primary colours in extra striate areas of the cortex is less well understood. Double-opponent cells in the primary visual cortex often possess both spatial and chromatic antagonistic organisation, but many other cells in V2 and more anterior areas of the cortex respond selectively only to a narrow range of wavelengths and are therefore no longer chromatically "opponent" (4). Studies in patients with diseases of the retina and the optic nerve tend to produce symmetric loss of red-green or / and yellow-blue chromatic sensitivity. Generally this is also the case in patients with cortical lesions when loss of colour vision is involved (5). In order to establish how damage to extra striate areas of the cortex may affect the processing of chromatic signals, we measured thresholds for detection of moving, colour-defined stimuli at the fovea and in each of the four quadrants (~6 degrees away from fixation) in 20 subjects with cortical damage. Chromatic thresholds were measured with the CAD test using stimulus conditions that isolate the use of colour signals. The results reveal a number of interesting findings suggesting that selective damage to neural substrates in the cortex can cause differential loss of colour, contrast acuity and first-order motion sensitivity. More specifically the results show that: ¶ Severe loss of red-green with almost normal yellow-blue sensitivity was observed in ten of these subjects. ¶ Two subjects showed significantly greater loss of "red" than "green" sensitivity. The loss can also be location specific i.e., the loss may only affect the foveal region or one of the four quadrants. Three subjects show the opposite effect when the loss of sensitivity affects mostly "green" stimuli. ¶ Four subjects showed significantly greater loss of sensitivity for "yellow", but not for "blue" stimuli. ¶ Chromatic sensitivity was spared selectively in two subjects that exhibited massive loss of contrast acuity and motion sensitivity at the same location in the visual field. The results show that the processing of chromatic signals in the cortex involves distinct neural substrates that map different regions of the visual field as has been shown in imaging studies (6). In addition, the results suggest that the processing of different colour categories is also carried out in distinct neural substrates and that selective damage to brain tissue can result in loss of chromatic sensitivity that affects selectively the perception of single colour categories. "Functional specialisation" in distinct areas of the cortex has been proposed to account for the intensive processing of specific stimulus attributes and the selective loss of visual function that follows destruction of such areas (7). The findings from this study suggest that this principle is an inevitable consequence of the need to extract unique stimulus features at some level of visual processing. More importantly the results imply that different neural substrates are involved in processing red-green and yellow-blue discrimination as well as single colour categories.

1. Smith, V. C. & Pokorny, J. (1975) *Vision Research* 15, 161-171.

2. De Valois, R. L. & De Valois, K. K. (1975) in *Handbook of Perception*, eds. Carterette, E. D. & Friedman, M. P. (Academic Press, New York), pp. 117-166.

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4. Kiper, D. C., Fenstemaker, S. B. & Gegenfurtner, K. R. (1997) *Visual Neuroscience* 14, 1061-1072.
5. Barbur, J. L., Harlow, A. J. & Plant, G. T. (1994) *Proc. R. Soc. Lond B Biol. Sci.* 258, 327-334.
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52 15:40 - Clinical color vision tests, Practical tasks and Discriminant analysis

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The purpose of this study is to determine which clinical color vision test can best predict the color naming performance on two slightly different sets of VDT colors. The first color set consisted red, yellow, green, blue-green, dark-blue, purple, white and grey. The second set consisted red, yellow, orange, green, dark green, light blue, dark blue and grey. One hundred color-normals and fifty two color-defectives participated in the study. Pass/Fail criteria for the color naming task was established based on number and types of color normal errors. Discriminant analysis was performed to determine how well clinical tests predict performance of the color defective group on the color identification tasks. The analysis showed that the combination of the Adams D-15, Farnsworth D-15 and HRR (third edition) were significant predictors of performance for the first color set with a specificity of 0.82 and a sensitivity of 0.75. The stepwise analysis showed that the minimum number of tests required to predict the performance was two, the Adams D-15 and Farnsworth D-15. The specificity and sensitivity was 0.82 and 0.75 respectively. For the second color set, the combination of the Farnsworth D-15, Adams D-15, HRR (third edition) and CN Lantern were significant predictors of performance with a specificity of 0.96 and sensitivity of 0.67. The stepwise analysis showed that the minimum number of tests required to predict the performance was only the Farnsworth D-15 with a specificity and sensitivity of 0.96 and 0.67 respectively.

The results were unexpected considering that the first color set had lower failure rate than the second color set. One would expect the less sensitive test to be the best predictor to separate the pass/fail in the first color set and the more sensitive test for the second color set. The reason why different tests emerged as best predictors for the first and second color sets was because the Discriminant analysis works to optimize the sensitivity and specificity of the clinical tests. For the first color set, the Adams D15 is weighted higher because its higher sensitivity compensates for the higher specificity of the Farnsworth D-15, adding the Farnsworth D-15 marginally improves the specificity of the clinical tests. In contrast, for the second color set, the Farnsworth D-15 emerges as the minimum test because its specificity is higher than the Adams D-15 and this compensates the Adams D-15's higher sensitivity. Although discriminate analysis does indicated which clinical test(s) can best separate between groups on a color-related task, one still has to look at both the sensitivity and specificity values to determine whether discriminate analysis model should be applied.

53 16:00 - Visual acuity with isoluminant coloured stimuli for amblyopic eye and defocused eye

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In real eye examination the visual acuity usually is determined using standard charts with black letters on a white background. At the same time Westheimer et al (2003) have applied the reversed-contrast chart (white letters on a black background) to show improving of visual acuity for older subjects. Visual acuity established by colour stimuli should be worse comparing to black-white stimuli, due to lowering of

the chart luminance contrast. We estimated difference in visual acuity with coloured stimuli comparing to that for high contrast black-white stimuli for real amblyopia and blurring cases. Tests were generated on computer screen. Visual acuity was detected using different charts in two ways: standard achromatic stimuli (black symbols on a white background) and isoluminant coloured stimuli (white symbols on a yellow background, grey symbols on blue, green or red background). Thus isoluminant tests had colour contrast only but hadn't luminance contrast. Visual acuity evaluated with the standard method and colour tests were studied for subjects with good visual acuity, if necessary using the best vision correction. The same was performed for subjects with induced blurring and real amblyopia. Blurring was realized with optical lenses placed in front of the good seen eye or in front of the best vision correction. Experiments were performed when eyes were adapted to dark room conditions and in the normal lightened room (approximately 200-300 lx). The obtained results applying the isoluminant colour charts revealed worsening of the visual acuity comparing with the visual acuity estimated with a standard high contrast method (black symbols on a white background): 2.4 ± 0.8 times decrease for defocusing, however only 1.7 ± 0.3 times for real amblyopia.

54 9:00 - Irregular sampling and photoreceptor non-linearity can "make sense" for color perception (invited)

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Let us think about the problem that Nature had to design a functional retina: which kind of trick would be optimal (or not so bad) to sample our three-dimensional world plus the wavelengths axis onto the two dimensions of a retina? Even if Shannon's theorem had existed several millions years ago, it would not have been of any help. In this talk I will address two problems: the one of the spatio-chromatic sampling and the one of compensating for the wide lighting's intensity range. For the first one, I will show how the irregular disposal of the three cone types on the retinal surface can lead to interesting properties about color coding (e.g. color-oppositions) and how this coding passes through the retinal spatio-temporal filter (high-pass filtering of luminance and low-pass filtering of chrominance). Concerning the second problem, I will show how the photoreceptor's compression law, able to adapt according to the temporal and spatial contexts, may lead to a robust color coding scheme and particularly to a simple color constancy process tied to the early stage of the visual system.

55 9:35 - Non linear and uniform filtering for estimating spatial information in the cone mosaic

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In the cone mosaic, spatial and chromatic information is mixed, i.e., the achromatic map (defined as the spatial information without chromatic content) is confounded with the chromatic map (distribution of chromatic information at constant luminance). We have previously shown (Alleysson & al., 2005) that in case of a regular arrangement of chromatic samples in the mosaic, a linear algorithm is able to extract achromatic spatial information and to interpolate chromatic information. In fact, the regularity of chromatic samples permits the localization of luminance and chromatic-opponent signals in the Fourier spectrum which in turn permits their separation using uniform linear filtering. However, in the case of an irregular arrangement, luminance and chrominance are no longer localized and a non linear algorithm is needed. Which non linear algorithm is best? We show that a non linear normalisation of photoreceptor

response follow by a uniform linear filtering is able to estimate accurately the achromatic information in the cone mosaic.

Alleysson, D, Susstrunk, S and Herault, J (2005) IEEE Trans. Image Processing, vol. 14, no 4.

56 9:55 - Theoretical limits of cone-excitation ratios

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The ratios of cone excitations produced by light reflected from two different surfaces remain "almost invariant" under changes in illumination, both for Munsell colour samples (Foster and Nascimento, 1994) and also for surfaces in natural scenes (Nascimento, Ferreira, and Foster, 2002). However, an important issue remains open: to what extent does this invariance of cone-excitation ratio depend on the population from which the sample is drawn? In an attempt to address this problem, we calculated the maximum of all the possible cone-excitation ratios (i.e. for all possible reflectances) for various sets of daylight spectra (correlated colour temperatures 4300-25000 K). The resulting ratios are far from invariant. It should be mentioned, however, that the maximum of deviation from the cone-excitation ratio invariance was achieved for ideal surfaces which either reflect all the light (for some wavelengths), or none (for the rest of the wavelengths). Such surfaces cannot be implemented in reality.

Foster, D. H. & Nascimento, S. M. C. (1994) Proc. R. Soc. London Ser. B 257, 115-121.

Nascimento, S. M. C., Ferreira, F. P., & Foster, D. H. (2002) J. of Opt. Soc. Am. A 19, 1484-1490.

57 10:15 - Macular Pigment: Nature's Notch Filter III

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The effect of changes in macular pigment (MP) in Normal and Anomals, assessed using a data set of 1782 reflectance spectra of natural and man-made colours, was reported at the Cambridge ICVS Symposium¹. It was found that increases in MP enhanced differences in both L and M cone responses: the effect being largest for Deuteranomal and smallest for Protanomal. Using cone fundamentals defined by the Stockman & Sharpe² photopigment template, chromaticities are computed for Normals and putative Protanomal (for whom the anomalous L pigment is shifted between the normal L and M spectral locations). The chromaticity diagram (an analogue of the MacLeod-Boynton³ cone excitation diagram adjusted to be approximately uniform for Normals) is sampled by a rectangular array of square cells. Cell size is set equal to one centred on Source C that contains just 29 of the 1782 colours from the data set. Changes in chromaticity variance, for 100 cells (containing at least 5 colours), are mapped in Normal and Protanomal colour spaces. The response of putative Protanomal to increases in MP is a continuous function of the anomalous L pigment location. A geographic analysis of local variance confirms the presence of systematic patterns: L-M cone enhancement factors show valley characteristics centred on the illuminant and oriented towards the centre of the MP transmission notch. S cone factors are all compressive: least for colours closest to the MP chromaticity and in approximately parallel zones.

¹Moreland, J.D. and Westland, S. (2003) Macular pigment: Nature's notch filter. In Eds J D Mollon, J Pokorny, and K Knoblauch. pp273-278 Oxford University Press, Oxford.

²Stockman, A. & Sharpe, L.T. (2000). Spectral sensitivities of the middle- and long-wavelength sensitive cones derived from measurements in observers of known genotype. Vision Research, 40, 1711-1737.

³MacLeod, D.I.A. and Boynton, R.M. (1979). Chromaticity diagram showing cone excitation by stimuli of equal luminance. J Opt Soc Amer, 69, 1183-6.

58 10:55 - Anomalous trichromats' judgements of surface colour in natural scenes under different daylights

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³Department of Physics, Gualtar Campus, University of Minho, 4710-057 Braga, Portugal.

Are anomalous trichromats disadvantaged in their ability to judge surface colour in natural scenes? To address this question, simulations of natural scenes were presented on a high-resolution colour monitor with 10-bit resolution per gun. The DeMarco-Pokorny-Smith cone fundamentals for anomalous trichromats (DeMarco et al., 1992) were used to calibrate a colour monitor for deuteranomalous and protanomalous observers, and the Smith-Pokorny cone fundamentals (Smith & Pokorny, 1975) were used for normal trichromatic observers. Eighteen scenes (which included rocks, foliage, and buildings) were obtained with a hyperspectral imaging system (Foster et al., 2004). Illuminants were drawn from the daylight locus. In each trial, two images were presented in sequence, each for 1 s, with no interval: in the first image, the correlated colour temperature of the illuminant was 25000 K or 4000 K, in the second, it was 6700 K. The spectral reflectance of a surface in the second image was changed randomly, from trial to trial, in a way quantified by an equivalent local change in daylight. The size and position of the test surface, which was indicated to the observer, varied with the scenes tested. The observer's task was to decide whether the test surface in the successive images was the same. Seven deuteranomalous, seven protanomalous, and twelve normal trichromats participated in the study. Surface-colour matching was quantified in terms of a colour-constancy index for which 1 represents perfect constancy and 0 perfect inconstancy. The overall discrimination ability of deuteranomalous observers was no different from that of normal trichromats with the two illuminant changes tested here. Mean constancy index values (SEM) were 0.85 (0.02) and 0.80 (0.02), respectively, for the 6700 K to 25000 K illuminant change, and 0.77 (0.04) and 0.75 (0.03) for the 6700 K to 4000 K illuminant change. Protanomalous observers' performance was poorer, with a mean index of 0.62 (0.04) for the 6700 K to 25000 K illuminant change, and 0.63 (0.05) for the 6700 K to 4000 K illuminant change. There seems to be no impairment of deuteranomalous observers' ability to judge surface colour under different daylights on natural scenes. In contrast, protanomalous observers seem at a significant disadvantage.

Supported by the Wellcome Trust (grant no. 064669/Z/01/Z).

DeMarco et al., 1992, *J. Opt. Soc. Am. A*, 9, 1465-1476

Smith & Pokorny, 1975, *Vision Res.*, 15, 161-171

Foster et al., 2004, *Visual Neurosci.*, 21, 331-336

*The experimental work was conducted at the University of Manchester, while RCB was a postdoctoral researcher.

59 11:15 - Local surface-colour matching in natural scenes correlated with global variance in cone-excitation ratios

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What factors influence our judgements of surface colour in natural scenes under different daylights? It might be expected that average scene hue, colourfulness, and the variation in these factors would all be

significant explanatory factors (Golz & MacLeod, 2002). To explore this issue, surface-colour matching was performed with images of natural scenes presented on a colour monitor with 10-bit resolution per gun. The scenes were recorded with a fast hyperspectral imaging system (Foster, Nascimento & Amano, 2004), giving an estimate of reflectance at 10-nm intervals at each point in a 1344 x 1024 digital representation. Scenes included flowers, foliage, trees, fields, and buildings, and each was recorded with a small sphere inserted in the field of view that was used subsequently as a test surface. In each trial, two images of a scene were presented in sequence, each for 1 s, with no interval. The images differed in illuminant, first a daylight with correlated colour temperature 25000 K and then 6700 K (other conditions were also tested). The spectral reflectance of the test surface in the second image was changed randomly in a way quantified by an equivalent local change in daylight. Observers (12 in all) reported whether there was an illuminant change or one accompanied by a change in the surface-colour of the test surface (initially grey, or reddish, greenish, bluish, or yellowish). In terms of a colour-constancy index in which 1 represents perfect constancy and 0 perfect inconstancy, average observer performance ranged from 0.69 to 0.97 over 21 scenes. This variation in performance was not correlated with the mean hue of the scenes or with their mean chroma, or with the variance in either of these quantities. It was, however, significantly correlated with the variance in cone-excitation ratios across pairs of surfaces sampled randomly from the whole scene: the larger the variance, the poorer the matches. The constancy of cone-excitation ratios is known to influence observers' judgements about illuminant and reflectances changes in Mondrian patterns (Nascimento & Foster, 1997). The present result suggests that performance in local surface-colour matching in natural scenes also depends on the global stability of these ratios.

Foster, D.H., Nascimento, S.M.C., & Amano, K. (2004). *Visual Neuroscience*, 21, 331-336.

Golz, J., & MacLeod, D.I.A. (2002). *Nature*, 415, 637-640.

Nascimento, S.M.C., & Foster, D.H. (1997). *Proceedings of the Royal Society of London Series B*, 264, 1395-1402.

60 11:35 - Spatial and temporal distributions of illumination in natural scenes

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The illumination in natural environments varies in a complex manner with time and location due to diverse physical factors, which include occlusion, mutual reflection, and solar elevation. The precise characterization of the range of this variation is important in understanding how human vision might function optimally in the natural world. The goal of this work was to characterize the spatial and temporal distributions of surface illumination in natural scenes. To this end, images of rural and of urban environments were obtained with a hyperspectral imaging system in the Minho region of Portugal (Foster, Nascimento & Amano, 2004). Spectral-radiance functions at each pixel were estimated from planar grey reference surfaces located in the scene and from calibration data obtained with a telespectroradiometer. The illumination for different locations and directions was estimated from several grey spheres inserted into the scene. To quantify the variation of illumination with time, the same scene was imaged over one complete day at regular time intervals. The CIE 1931 (x, y) chromaticities of the illumination and the corresponding correlated colour temperatures were computed as a function of location, direction and time of the day. Within the same scene, standard deviations of illumination chromaticities were less than 0.04 in CIE (x, y) units and about the same in both axis directions. Standard deviations of illumination chromaticities during the day for each location and direction were less than 0.05, with those in the y direction being smaller than those in the x direction. For the conditions tested in this study, the variation in the spectral composition of surface illumination within natural scenes was similar in extent over space and time,

suggesting that the visual mechanisms subserving colour perception have a common operating range.

Foster, D.H., Nascimento, S.M., & Amano, K. (2004). Information limits on neural identification of colored surfaces in natural scenes. *Vis Neurosci*, 21 (3), 331-336.

Poster

61 Repetition (dis)advantage: Does color-opponency count?

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Inhibitory effect (slowing RTs by 5 ms) has been reported when a target is preceded by a cue of the same color and location. The color-based repetition disadvantage was found using red and blue non-isoluminant stimuli. Here we investigate whether this phenomenon depends on the chromatic subsystem involved, L/M or S-cone, by employing isoluminant colors varying along either axis. Nineteen normal trichromats were exposed to 4z-stimuli. Expt1 replicated Law et al.'s (1995) study: After fixating magenta, either red or blue cue was presented, followed by magenta neutral attractor and, finally, by red or blue target. In Expt2, violet and yellow, cue or target, varied along the S-cone isolating axis. In Expt3, purple and turquoise, cue or target, varied along the orthogonal L/M axis. In Expt1 color repetition indeed resulted in slower RTs (4.7 ms, $p=0.038$). In Expt2, however, no significant color repetition effect was found ($p=0.39$). RTs to violet and yellow were not significantly different, though tending towards slower responses (2ms) for violet repetition, but faster responses (5ms) for yellow. Finally, Expt3 also showed no color repetition effect ($p=0.58$). However, RTs were overall faster for purple than for turquoise (22ms, $p<0.0001$). Furthermore, responses tended to be slower for purple repetition (4ms, $p>0.05$), but faster for turquoise (7ms, $p>0.05$). The findings demonstrate that color repetition is not always inhibitory, but may turn facilitatory depending on the colors employed. For color, disengagement of attention is an unlikely mechanism to explain previously reported inhibition of return, or repetition disadvantage. An alternative, perceptual explanation is suggested: Within the chromatic subsystem, response (dis)advantage may result from an imbalance of excitation and inhibition - depending on the opponent colors and cue-attractor-target constellation.

Law, M. B., Pratt, J. & Abrams, R. A. (1995) *Perception & Psychophysics*, 57, 402-408.

62 Color and brightness perception in the Watercolor and the Craik-O'Brien-Cornsweet effects

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Introduction: Brightness and color induction were measured using a matching method to determine the strength of a variety of visual phenomena: Craik-O'Brien-Cornsweet (COCE), Watercolor (WCE) and Cusp effect (WCE with spatial smoothing). In the present experiments, these patterns were examined to find out whether the double contour of the WCE is processed by the visual system similarly to a COCE sawtooth. Indeed, it is well known that the human spatial contrast sensitivity function for chromatic gratings is low-pass. Thus, we examined whether the double contour of the WCE might be smoothed by the visual system like a COCE sawtooth to yield long-range color spreading. **Method:** For all experiments, a neutral white background was used (CIE $x,y = 0.30, 0.33$) with a mean luminance of 45 cd/m². The luminance contrast of the contours were specified in units of Weberian contrast. Contours were adjusted to obtain a luminance contrast of 0.44, thus, the COCE contours has 0.44 for the brighter contour and -0.44 for the darker contour, whereas the luminance contrast for the WCE and the Cusp is only -0.44. To

use the same luminance contrast between the background and the inducing contour for all patterns, we measured only the negative side of the COCE. All these patterns were presented with three different contour widths (0.18, 0.36 and 1.36 deg). Three sets of experiments were performed using a color-matching (Experiment 1) and a color- and brightness-matching task (Experiment 2) for the chromatic patterns, but also a brightness-matching method for the achromatic stimuli (Experiment 3). **Results:** Over different contour widths, color shifts of the WCE followed closely the color of the inducing contour while this was not the case for the COCE and for the wider edges of the Cusp pattern. When color and brightness were matched, the magnitude of color spreading did not change with brightness for the COCE, but decreased for the WCE and was around the mean background for the Smooth WCE. With some achromatic patterns, brightness spreading became stronger with decreasing contour width. **Conclusion:** This research suggests that color and brightness are mediated by different mechanisms for the three patterns. Thus, WCE cannot be accounted for by COCE.

63 Visual evoked potentials to chromatic stimuli in schoolchildren

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The aim was to introduce into the study on the parvocellular visual system in schoolchildren VEP recordings to appropriate chromatic stimuli. Children (7-19 years) with normal colour vision were examined, 30 binocularly and 30 monocularly. To study the specificity of the method, five children with congenital anomalous colour vision were also examined. Isoluminant red-green (R-G) and blue-yellow (B-Y) stimuli were introduced. Isoluminant point was determined for each child subjectively by using heterochromatic flicker photometry, and objectively from recordings. The stimulus was a 7 deg large circle composed of horizontal sinusoidal gratings, with spatial frequency 2 cycles/deg and 90% contrast. VEP were recorded from Oz (mid occipital), O2 (right occipital) and O1 (left occipital) positions. The properties (latency and amplitude) of the major negative component (N1) were analysed. Results for R-G and B-Y stimulation were compared in each child. N1 properties were compared between youngest (age group 7-9 years) and oldest children examined (age group 16-19 years). Comparison between the two groups was made for monocular and binocular stimulation. N1 latency after B-Y stimulation was found significantly longer than after R-G stimulation when tested monocularly or binocularly. The N1 latency and amplitude values were bigger in the younger than in the older group, both to R-G and B-Y stimulation. On the other hand, in the deuteranomalous and protanomalous children N1 component was much less evident after R-G than after B-Y stimulation. We conclude that VEP to chromatic stimuli may be reliable enough for further studies on the parvocellular visual system in children.

64 Evidence for global integration of local color differences in the ventral parahippocampic gyrus

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Purpose: The visual system segments a scene, distinguishing surface properties from changes in viewing conditions. An example is color scission that requires i) the integration of local tristimulus differences to extract the global color of a transparent layer, and ii) the assignment of two colors to the same area of the retinal image (one for the transparent layer and one for the underlying surface). To identify candidate cortical areas involved in color scission, we manipulated local tristimulus differences

in color patterns to induce color transparency jointly with functional MRI. **Methods:** Twelve observers with normal color vision were examined at 1.5 T on a clinical MR scanner in 2 experiments. Exp 1 was aimed at localizing the functional responses produced by the introduction of chromatic contrast, Exp 2 at identifying functional responses related to color scission. For each experiment, 4 event-related fMRI scans were performed. During each scan, 3 different types of 0.5 sec events (images, 33 of each type) were presented, in pseudo-random fashion, at 2.5 sec intervals. For Exp 1, events corresponded to chromatic patterns, achromatic patterns and a Null-event (an isolated fixation cross). For Exp 2, Transparency events corresponded to chromatic patterns (composed of 23 colored rectangles), for which the tristimulus values in a central square test region underwent the same translation in tristimulus space, Non-transparency events, for which the tristimulus values in the central square region underwent a shearing transformation, and a Null-event. Absolute chromatic contrasts were the same around the test region, only their coherence being modified. For functional scans, an EPI GRE MR sequence was used (1.5T, TR/TE/Flip=2.5s/45ms/70°, FOV=256mm, matrix=64x64, head coil). The volume of interest was composed of 28 adjacent transverse slices with Voxel size 4*4*5 mm³. **Results:** For Exp 1, the group analysis for chromatic versus achromatic events showed significant bilateral activation within the posterior fusiform gyri (Talairach coordinates (TC), left: -28, -71, -13, right: 28, -70, -9), confirming results reported previously by others. Activation was also found in the superior parietal gyrus. For Exp 2, the [translation - shear] contrast revealed activation within the left parahippocampal gyrus ((TC, -16, -48, 2), i.e., distinct from that induced by the [chromatic - achromatic] contrast in Exp 1. No differential activation was detected in area V1/V2, for either the [translation - shear] contrast or the reverse. The [shear - translation] contrast indicated activation within the superior, right posterior parietal gyrus (TC, 32, -68 31). Specific analyses in the regions of interest sensitive to chromatic contrast, as previously delineated on the basis of the results of Exp 1, revealed no significant differences between translation vs shear, i.e., no differential involvement of the “chromatic sensitive” regions in color scission. **Conclusions:** Cortical areas identified to be differentially activated by manipulation of the coherence of local tristimulus differences so as to modulate the perception of a transparent overlay were found to be located in the anterior part of the parahippocampal gyrus. The neural areas activated by transparency are separable from those areas differentially activated when subjects view chromatic versus achromatic patterns.

65 Retinal microscotomas revealed with adaptive-optics microflashes

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We previously identified a dichromat (AOS1) with a genetic defect believed to cause degeneration of one class of cone photoreceptor after foveal development is complete. Retinal photographs of the cone mosaic made with adaptive optics revealed lacunae, equal in size to one or more cones, which likely represent the loci of the missing cone class. Here we used adaptive optics to test whether this patient has corresponding microscotomas in his visual field. Frequency-of-seeing curves were measured with disks subtending either 0.75 or 7.5 arc minutes, flashed for 45 msec with 550 nm light of randomly varying energy. Stimuli were randomly presented at any of 8 equally spaced loci 0.5 deg from fixation. A high data acquisition rate was achieved by randomly presenting 0 to 4 flashes per trial. By correcting for the eye's aberrations, adaptive optics produced retinal images of the small spot that were 3.4 μm whh, small enough to be largely confined within the typical cone diameter at this eccentricity. Two other dichromats and 5 trichromats were also tested. The frequency-of-seeing the small spots by AOS1 approached an asymptote of 74% detection, compared with 91% for the control subjects. This reduction is consistent with the observation that the lacunae occupy approximately 29% of AOS1's cone mosaic. We hypothesize that the unseen flashes fell on the lacunae identified photographically. That the large

spots always stimulated some cones is shown by the fact that the asymptotic frequency-of-seeing was 96% for AOS1 and 95% for the control subjects. AOS1's threshold for the small spot was 45% higher than that of the control subjects, reliably different from the controls' ($p < 0.01$, t test) but not reliably different from that expected given AOS1's reduced complement of cones. AOS1's threshold for large spots, however, was twice as great as the controls' threshold, a difference that is reliable and also reliably greater ($p < 0.01$, t -test) than the difference for small spots. This unexpected finding shows that spatial summation in AOS1's visual system is less than normal.

66 Multidimensional Scaling reveals a colour dimension unique to deuteranomaly

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Multidimensional scaling (MDS) has previously been used to disclose the subjective colour space of normal and anomalous observers (e.g. Paramei and Cavonius, 1999), but such studies have always had a phenotypic bias: the stimuli have been selected to be discriminable for the normal observer. In the present study, we included stimuli with reflection spectra that were near-metamers for normals but were calculated to be distinguishable by deuteranomalous observers. The 15 stimulus surfaces were prepared by mixing acrylic paints and were presented under a broad-band amber illuminant intended to minimise variation at short wavelengths. Normal observers, deuteranomalous observers, and carriers of deuteranomaly were asked to rate (on a scale of 1-10) the subjective difference of each possible pair. In the case of deuteranomalous observers, MDS analysis revealed a dimension not available to normal observers.

Dimensions including $S/(L+M)$, $S/(L'+L)$, L/M and L'/L were modelled, and the stimuli were ordered along them. These ordinal positions were then correlated with the ranks of the stimuli along the observers' subjective dimensions. L'/L correlated highly significantly with the first dimension of deuteranomals ($0.707 \leq r \leq 0.929$) and $S/(L+L')$ correlated significantly with their second dimension ($0.459 \leq r \leq 0.757$), whereas $S/(L+M)$ correlated significantly with the first dimension for normals ($0.579 \leq r \leq 0.748$). Since the stimuli were designed to minimise variation in L/M , the second dimension of normals did not correlate with this or any other dimension modelled, and smooth stress curves suggest that the normals' second dimension is likely to represent noise.

Paramei, G. V. and Cavonius, R. C. (1999) *Perception and Psychophysics*, 61, 1662-1674.

67 Designing a colour discrimination test to assess colour rendering of LED sources

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Recently we proposed a method to score the colour rendering properties of LED lighting using a Colour Discrimination Index (to be presented at AIC 2005). We set an experiment where we asked 57 colour normal observers to perform the desaturated Panel D15 from Lanthony (DD15) illuminated with various LED clusters:

- RGB LED cluster (RGB),
- RGBAmber LED cluster (RGBA),
- two-phosphor cold White LED + Amber LED cluster (2PWA),

and with a control continuous spectrum light. The method allowed us to classify light sources according to their efficiency to discriminate small colour differences better than the CIE Colour Rendering Index. It also revealed severe failures of RGB LED clusters for colour rendering. Half of the observers performed significantly worse with RGB LED sources than with continuous lights of the same colour temperature.

Here we propose to design a colour discrimination test dedicated to the evaluation of lighting quality. We manufactured a desaturated Panel-like discrimination test with 32 caps equally distributed along a colour circle in CIELAB ($L^*=80$, $C^*_{ab}=\text{constant}$, $\Delta E_{ab}=3\pm 0.9$ CIELAB units between adjacent caps). Such a design was possible through careful control of a regular inkjet printer. Compared with the DD15 that is designed to highlight confusion lines, the 32 caps test with equal hue steps allows to reveal low discrimination efficiency of a light source in any region of the hue circle.

68 Linear Dichromacy

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Colour phenomena may be represented by the association of a linear space (vectorial colour space) with a projective space (chromaticity chart/diagram). Dichromacy, though simpler than trichromacy, offers a rich structure, involving as it does the interplay of the two elements of the projective plane, points and straight lines. Some examples will be presented.

69 An Adaptation of the Cambridge Colour Test for use with Animals

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Behavioral testing has provided information about the dimensionality, acuity, and biological basis of color vision in many species of mammal. Recently, molecular biological techniques have presented new opportunities for addressing questions concerning the neural mechanisms involved in color coding, thereby rousing renewed interest in animal color vision testing. For example, we are conducting experiments to determine whether gene-therapy can be used to transform an adult dichromatic squirrel monkey into a trichromat. Measuring and comparing both pre- and post-therapy color vision profiles will be necessary for evaluating the effects of the treatment. To this end, we have modified the Cambridge Colour Test to make it suitable for use with animals. Here we describe experiments that fulfill the dual purpose of collecting pre-therapy color vision data for squirrel monkeys and assessing the validity and reliability of the testing method when used with non-human primates. The test is a computer controlled, CRT-based assessment tool that preserves the advantages of pseudoisochromatic plates (Reffin, Astell and Mollon, 1991). Because the chromatic stimuli and the achromatic backgrounds consist of small dots that vary in lightness, animals are not able to use luminance differences to make correct discriminations. Thus, in contrast to the usual methods for animal color vision testing that have been used previously, the Cambridge Colour Test does not require that time be spent in the equation of luminance for each chromatic stimulus examined. Furthermore, the CRT-based design of the testing apparatus can be easily replicated and applied for use with a wide variety of species. In the present experiments, the squirrel monkeys'

pre-therapy behavioral results agreed with the predictions for their color vision based on genetic analysis and ERG spectral sensitivity data. Repeated measurements of color vision behavior on individual animals were highly consistent. Thus, an adaptation of the Cambridge Colour Test provides a valid and reliable method for testing color vision in animals.

Reffin, J.P., Astell, S. and Mollon, J. D. (1991) In *Colour Vision Deficiencies X*, 69-76, Eds: Drum, B., Moreland, J. D. and Serra, A., Kluwer, Dordrecht.

70 Color-vision loss in patients with diabetes mellitus: A novel diagnostic approach

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Color-vision impairment was diagnosed in patients with type 2 diabetes mellitus (DM) without retinopathy by assessing the type and degree of distortions of individual color spaces. DMs (n=32) and age-matched controls (n=15) were tested monocularly in both eyes; all underwent ophthalmologic examination. Farnsworth (D15) and Lanthony (D15d) sets of caps were used in the triadic procedure (Bimler & Kirkland, 2004): the 32 caps from both tests were shuffled; random triads were presented to subjects, who chose the most dissimilar ("odd-one-out") cap in a triad. Subjective dissimilarities between the caps were computed from these choices. A non-metric multidimensional scaling (Statistica, StatSoft) procedure was used to reconstruct two-dimensional individual and group color spaces with the axes interpreted as the R/G and B/Y perceptual opponent systems. Compared to controls, 50% of DMs revealed a configuration with compression along the B/Y dimension (acquired tritan defect) and, in 55% of these patients, compression of the R/G dimension was also revealed. These numbers are higher than those when the D15d was performed in the original procedure, as an arrangement test: 24% with B/Y and, from these, 25% with R/G loss were revealed. The degree of the space compression varied dramatically among individual patients. The present findings agree with earlier studies demonstrating deterioration of blue-yellow discrimination in DMs (e.g. Kurtenbach et al., 2002). However, the proposed method of testing, which includes caps varying in saturation and lightness, as well as elaborated representation of results as color spaces, provides a vehicle for more differentiated, quantitative diagnosis of severity of color-vision loss. Along with fundoscopy, individual color spaces may serve for screening early functional changes and thereby support a treatment strategy.

71 Changes in spatial extent and peak double density of human macular pigment with age

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The function of macular pigment (MP) is not fully understood but appears to be fundamental for maintaining normal retinal function. The MP spatial extent and peak density have been studied with the aid of several physical and psychophysical techniques and for different populations but these studies have produced data with large variability (Hammond, B. R. et al., 1997; Chang, Y. et al., 2002; Robson, A. G. et al., 2003). The purpose of the present work was to estimate the changes in spatial distribution and peak double density of macular pigment with age. A fundus imaging system with high spatial and spectral resolution was adapted to form an indirect ophthalmoscope. An area of the retina of about 15 deg was illuminated sequentially by light from a xenon lamp filtered by a fast tunable liquid-crystal filter (VariSpec, VS-VIS2-10-HC-35-SQ, Cambridge Research & Instrumentation) at two wavelengths, 490 and 540 nm. Spectral images of the fundus were acquired in 2 sec with a low-noise Peltier-cooled digital camera (Hamamatsu, model C4742-95-12ER) with a spatial resolution of 1344 x 1024 pixels and 12-bit output. The retinas of 33 healthy subjects were divided into 3 groups with different average ages, 22.5 (N = 12), 35.9 (N = 12) and 57.8 (N = 9) years, and each imaged with this system. The spatial distribution of the macular pigment was derived for each subject by comparison of the estimated foveal spectral reflectance at each pixel at 490 nm with that at 540 nm. With this procedure, the double optical density as a function of the location in the retina was obtained. The full width at half maximum (FWHM) in the horizontal and vertical meridians and the peak double density were used to characterize the MP. The mean FWHM in the horizontal and vertical meridians and the mean peak double density showed a large inter-subject variability, but a tendency for slightly larger spatial distributions with age, a trend consistent with that found by Chang, Y. et al.(2002).

72 Colour naming and colour categorisation in case of inherited colour deficiencies

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Colour naming has been shown to be accurate among dichromatic subjects despite the fact that, most often, these observers lack the ability to discriminate among red - green hues (Jameson & Hurvich, 1978). This result is interpreted as the expression of the normative language system developed from learning subtle visual cues available despite an impoverished colour system.

In this study, consensus analysis was used to quantitatively appreciate the normative effect of language on colour categorisation among colour deficient observers and compare it with that observed in normal trichromats.

Four young adults (1 female and 3 males) diagnosed as deutan type (Colour Deficient, CD group) on Ishihara isochromatic plates and a control group of four normal trichomat observers (Normal Trichomat, NT group) were asked to sort or name 140 Munsell chips (20 hues each at 7 values, at the maximum chroma) over three tasks performed in the same order. First, a Free Sorting Task (FST) with an unlimited number of categories; second, a Constrained Sorting Task (CST) where the number of categories was limited to 8; and third, a Constrained Naming Task (CNT) using the 8 English basic colour terms. All tests were performed under the standard D65 illuminant.

For each task and each participant, grouping matrices are obtained in which the entry of each cell is

1, if two samples were placed in the same category, and 0 otherwise. From these matrices, two 12 x 12 correlation matrices (one for each participant group) are computed, and the square root of the average correlation within any given subset of correlations is computed to provide an approximation of the shared knowledge (or consensus) among subjects within that group (Romney et al., 1999).

The general consensus across tasks and participants is slightly lower in the CD group (61%) than in NT group (68%). In the two groups, the consensus specific to each task is lower than the general consensus for the FST (55%, CD and 60%, NT), is increased in the CST (64%, CD and 72%, NT) and is the highest in the FST (76%, CD and 86%, NT). In both groups, colour naming greatly increases the consensus among participants in sorting out the colour samples into categories. However, the mismatch between the normal trichromat colour vocabulary and the phenomenal experience of colour of colour deficient observers imposes a limit to the normative effect of language on colour categorisation.

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Romney, A. M., Moore, C. C., Batchelder, W. H., & Hsia, T.L. (1999). Statistical methods for characterizing similarities and differences between semantic structures. *Proceedings of the National Academy of Sciences*, 97, 518 - 523.

73 Red-green color vision loss in Duchenne Muscular Dystrophy

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Red-green color defect and Duchenne Muscular Dystrophy (DMD) are X-linked diseases caused by unlinked genes. About 65-70% of DMD patients have a deletion in the dystrophin gene, which results in the absence of the protein dystrophin. Alterations in the electroretinogram of DMD subjects with deletions downstream exon 30 have been recently shown. Our aim is to evaluate color vision in DMD subjects with a battery of color vision tests, and try to relate the findings with the type of gene deletion. The patients were classified in 3 groups: no deletions (n=20); deletion upstream exon 30 (n=7); deletion downstream exon 30 (n=27). Controls were 35 age-matched subjects. Color vision was evaluated with: Cambridge Colour Test (CCT), Neitz Anomaloscope, Ishihara and AO H-R-R plates. Color vision losses measured by the CCT were found in 34/54 (63%) subjects, the majority of which (27/34, 79%) had a red-green defect, confirmed by the Anomaloscope results (Wilcoxon test - Trivector $p = .602$; Ellipse $p < .999$). The AO H-R-R and Ishihara plates were less sensitive, revealing respectively, 24% and 16% of red-green color vision losses; and these results did not correlate with the Rayleigh matches (AO H-R-R $p = .016$; Ishihara $p < .001$). With the color vision test battery used we observed that red-green losses were more frequent and more severe in subjects with deletions downstream exon 30, involving the retinal dystrophin isoform Dp260. These results suggest a secondary effect of the dystrophin mutation in retinal function.

74 Electrophysiological Analysis of Chromatic Opponency in the Retina of Turtle (*Pseudemys scripta elegans*) with Tetrachromatic Stimulus

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Purpose: To investigate the influence of the input ultraviolet (UV) in the color-coding of recordings in ganglion cells and to describe the types of combinations of chromatic opponency in the turtle (*Pseudemys scripta elegans*) retina. **Methods:** Intracellular recordings were made in everted eyecup preparations. The retinas were superfused with oxygenated ringer solution (pH 7.5) and stimulated by optical system with centered spots, and annuli of light of same number of number of quanta in UV (370nm), blue (450nm), green (540nm), and red (620nm), at three intensities, largely according to the procedures described by Ventura and cols. (2001). After this recording, whenever possible, Neurobiotin was injected iontoporetically with positive current pulses of 2mA at the frequency of 1 Hz. Retinas with injected ganglion cells were dissected, fixed by immersion during 1 hour in 4% paraformaldehyde in 0.1M phosphate buffer, and then incubated in Cy3-streptavidin, for subsequent observation in confocal microscope (Zeiss model LSM3/4). The labeled cells were morphologically classified according to Ammermüller and Kolb (1995). **Results:** 42 recordings from cells were obtained, among them: 10 ganglion cells presented some type of chromatic opponency, two new combinations were found (UV+BGR-; B+UVGR-); 15 ganglion cells and eight amacrine cells were ON in response; one ganglion cell (tri-stratified) had an ON/OFF response; six ganglion cells and two amacrine cells had an OFF response. In the morphological comparison, we identified G2, G18 and G22 cells described previously by Ammermüller and Kolb (1995). **Conclusions:** The chromatic opponency using UV light had already been confirmed in previous studies (Ventura and cols., 2001). This study broadens the knowledge about the physiology of color coding in morphologically identified ganglion cells, in tetrachromatic organisms.

75 Sensitivity to color errors in images of natural scenes

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Color errors occur in all image-reproduction processes and their visual significance may be an important factor in influencing perceived image quality. Sensitivity to these errors has been estimated using pictorial images that due to a constrained camera gamut provide chromatically limited representations of real scenes. The purpose of the present work was to estimate sensitivity to these color errors using pictures synthesized from hyperspectral images of natural scenes that have no gamut constraints. Images of rural and urban environments were obtained by a hyperspectral imaging system (Foster, Nascimento & Amano, 2004) with a low-noise Peltier-cooled digital camera with a spatial resolution of 1344×1024 pixels (Hamamatsu, C4742-95-12ER), and a fast-tunable liquid-crystal filter (VariSpec, model VS-VIS2-10HC-35-SQ, Cambridge Research & Instrumentation, Inc., MA, USA) mounted in front of the lens. The spectral-radiance from each pixel of the images was estimated from a gray reference surface present in the scene and from calibration data obtained with a telespectroradiometer. These radiance values were then converted to points within the approximately uniform CIELAB color space. From each original image, a set of approximated images with variable chromatic errors was generated by chromatically segmenting each original CIELAB representation into cubes of side ΔE^*_{ab} of 4 and adding to each color located

inside each cube a vector with the same ΔE^*ab but with random direction from cube to cube within the image. Thus, each approximation could be characterized by a specific ΔE^*ab . The images were displayed on a calibrated 17-inch, RGB color monitor controlled by computer with raster-graphics card providing 24 bits per pixel in true-color mode. In each trial of the psychophysical experiment the observer was presented with a pair of images, corresponding to the original and one approximation, and had to indicate whether the images were the same or not. It was found that discrimination between original and approximated images needed a ΔE^*ab of about 2.5 for rural scenes and even smaller for urban scenes. Even in complex scenes observers appear sensitive to small chromatic errors.

Foster, D.H., Nascimento, S.M., & Amano, K. (2004). Information limits on neural identification of colored surfaces in natural scenes. *Vis Neurosci*, 21 (3), 331-336.

76 Psychophysical estimation of the best illumination for appreciation of artistic paintings

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The visual impression of an artistic painting is strongly influenced by the spectral profile of the illuminant. The aim of this work was to determine the illuminant preferred by observers when seeing art paintings and to investigate how their preferences correlate with the chromatic diversity of the paintings. Oil paintings from the collection of the Museum Nogueira da Silva, Braga, were imaged by a hyperspectral imaging system. The hyperspectral imaging system had a low-noise Peltier-cooled digital camera with a spatial resolution of 1344×1024 pixels (Hamamatsu, C4742-95-12ER), and a fast-tunable liquid-crystal filter (VariSpec, model VS-VIS2-10HC-35-SQ, Cambridge Research & Instrumentation, Inc., MA, USA) mounted in front of the lens. The spectral reflectance of each pixel of the paintings was estimated from a gray reference surface present in the scene. Illuminant spatial non-uniformities were compensated using measurements of a uniform surface imaged in the same location as the paintings. The radiance reflected from each painting under six different illuminants, CIE Standard Illuminants A, B, C and D65, Solux and tungsten light, was estimated. In each case, the number of discernible colors was estimated by computing the painting representation in CIELAB space and by counting the number of non-empty unit cubes in that space. The images resulting from these manipulations were displayed on a calibrated 17-inch, RGB color monitor controlled by a computer raster-graphics card providing 24 bits per pixel in true-color mode. In each experimental trial, the observer was presented with a pair of images, corresponding to two different illuminants and had to indicate the preferred image. Five observers with normal color vision participated in this study. It was found that observers systematically preferred the CIE Standard Illuminant D65 which produced the larger number of perceived colors. These results suggest that the ideal light source for illumination of this type of art paintings may correspond to the one producing larger chromatic diversity.

77 Normal L:M cone ratio variations and the acuity of color vision

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There is enormous variation in the proportion of L to M cones among males with normal color vision, ranging from about 45% to 95% L (or about a 20 fold range in L:M cone ratio). It is expected that individuals with a only a small proportion of L or M cones would have relatively fewer neurons carrying red-green chromatic signals and it has been reported that biased L:M cone ratios are associated with reduced chromatic contrast sensitivity (Gunther, KL & Dobkins, KR, 2002). Paradoxically, however, it

has been reported that subjects are able to perform well on standard color vision tests in spite of having biased cone ratios. For example, individuals with even the most extreme ratios can have error scores of less than 20 on the FM 100 hue test, classifying them as having superior color vision. Here we report results of experiments to test the hypothesis that individuals with highly biased cone ratios are able to use the relatively unrestricted time limits and large stimulus sizes in standard color vision tests to help compensate for having a reduced number of red-green chromatic signal carriers in the visual pathway. A modified version of the Cambridge Colour Test was used in which thresholds to three different colors were measured for three different stimulus presentation durations (2000 ms, 120 ms, and 60 ms), and two different sizes, subtending 5.5° and 2.75° of visual angle. Subjects with biased L:M cone ratios performed more poorly than those with ratios nearer 1:1 for all stimulus sizes and durations. However, the difference in performance increased substantially when stimulus duration was reduced. Individuals with extreme ratios performed most poorly compared to those with more nearly equal ratios under the condition in which the stimuli were both brief and small. We conclude that individuals with biased L:M cone ratios can perform well on standard color vision tests in which the colored areas are large and viewing time is relatively unrestricted; however, their disadvantaged color discrimination capacity can be exposed by limiting stimulus size and duration.

Gunther, K.L., and Dobkins, K. R. (2002). *Vision Research* 42(11):1367-78.

78 Acquired color vision defects and saturation

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The classic surface tests used to assess chromatic anomalies seek to keep the quantitative magnitudes of color constant by assigning values to their qualitative magnitude or hue. In a previous paper, Mattiello and Gonella (1970) suggested increasing the saturation of Panel D-15 for ergonomic purposes, proving that the errors made with Panel D-15 or the P. Lanthony desaturated test were thus mitigated. This led to thought being given to the use of saturation scales in just-noticeable steps to measure the depth of anomalies, an idea proved long ago by M. Marré (1973) for retinal disorders, by means of optical systems. Saturation scales, which are easy to build and measure, could replace certain commercial tests that, same time, are difficult to come by. In order to verify this assertion, 12 scales were analyzed, distributed between 400 and 700 nm, with a variable colorimetric purity of 0 and 1 and constant luminance and hue. It was interesting to test a defective population of people in the 70 to 75 age range who presented chronic illness requiring varied medication. This particular choice was based on the fact that the subject of old age is once more being analyzed but without considering being given to these circumstances. The task of the observers was merely to inform of the color threshold by observing the saturation scales in increasing and decreasing order and one cap at time

To date 30 eyes have been observed, and it has been noticed that greater saturation is required at intermediate frequencies, and very little at extreme frequencies. In the critical zone the cases present considerable variability that allows the sensitivity of the proposed test to be broadly endorsed. A Table indicating the ophthalmological data of the observers and their basic medication completes the study. The Table allows some conclusions to be drawn on the effects of drugs on color vision, while highlighting the difficulty of reaching a definite judgment when more than one drug is used.

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Marré, M. (1973) The investigation of acquired colour vision deficiencies, in *Color 73*, London, A. Hilger:99-135.

79 Magnocellular and parvocellular involvement in vernier acuity

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Purpose: In a vernier acuity task, observers are required to resolve an offset between two objects. For luminance-defined stimuli under optimal conditions, offset thresholds can be in the hyperacuity range, with offsets smaller than predicted from cone spacing in the retinal mosaic. Vernier thresholds for equiluminant stimuli are poorer than for luminance-defined stimuli, and are not in the hyperacuity range. Similar vernier thresholds for chromatic vernier stimuli and luminance defined vernier stimuli degraded by optical blur are found when stimuli are scaled in terms of threshold detection (Krauskopf & Farell, 1991), suggesting a common neural system mediates both. Physiological studies (Lee, Wehrhahn, Westheimer, et al., 1995) showed that MC cell responses correlate to human psychophysical hyperacuity performance and it has been proposed that MC cells can provide accurate information for vernier performance under equiluminance (Sun & Lee, 2004). Here, an alternative proposal is evaluated: might the PC system mediate luminance vernier acuity for offsets not in the hyperacuity range? **Methods:** Two vertical bars (15 min by 10 min), one placed above the other, were presented on a 1 deg square pedestal for 40 ms. Horizontal offset of the two bars ranged from 15 sec to 100 sec. Pedestal luminances ranges between 8 to 17 cd/m², above and below the adapting background luminance of 12 cd/m². In the Pulsed-Pedestal Paradigm, the pedestal was presented synchronously with the stimulus. The pulsed pedestal favors PC mediation (Pokorny & Smith, 1997). In the Steady-Pedestal Paradigm, the pedestal was presented continuously and either the MC or PC system might mediate vernier acuity. In both paradigms, the contrast threshold to resolve each Vernier offset was measured as a function of pedestal contrast. **Results:** The data showed a different signature for Vernier offsets less than 40 sec (i.e. hyperacuity offsets) than for larger offsets. For the pulsed-pedestal, the threshold deteriorated more dramatically as a function of pedestal amplitude for the smaller than for the larger offsets. **Conclusions:** For luminance-defined stimuli, vernier thresholds in the hyperacuity range may be mediated by the MC system. Vernier thresholds evaluated under conditions that do not produce hyperacuity may be mediated by the PC system.

Krauskopf, J., & Farell, B. (1991) *Vision Research*, 31 (4), 735-750.

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Pokorny, J., & Smith, V.C. (1997) *Journal of the Optical Society of America A*, 14, 2477-2486.

Sun, H., & Lee, B.B (2004) *Visual Neuroscience*, 21, 315-320.

80 A unique dichromatic color-vision defect with a novel form of the single L-cone/M-cone visual pigment gene

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In individuals with normal color vision, long- (L) and middle-wavelength-sensitive (M) visual pigment genes are arranged in a head-to-tandem array on the X chromosome. The dichromatic red-green color vision deficiencies are usually associated with a single pigment gene (a 5'L-M3' hybrid gene for protanopia or an L gene for deuteranopia). A total of 88 male dichromatic subjects (31 protanopes and 56 deuteranopes) have been clinically diagnosed using a Nagel model I anomaloscope. Here we report one dichromatic subject who presented a unique pattern of color matching. The subject accepted not only the entire matching range but also an extended yellow-scale range at each midpoint (i.e. 20 to 32 scale units at the green primary and 3.5 to 6 at the red primary). The slopes of regression lines were in the range of -0.34 to -0.23; the mean slopes for protanopes and deuteranopes were -0.38 and -0.01. Clinically, best-corrected visual acuity was 1.5, and no abnormal findings were observed on a fundus examination,

Goldmann kinetic perimetry and Ganzfeld full-field electroretinography. Long-range PCR was performed to determine whether the first gene in the array is L or 5'L-M3' hybrid, and whether the downstream gene is M or 5'M-L3' hybrid. The promoter region and each of 6 exons were amplified by PCR followed by sequencing. The subject had a novel form of the single pigment gene with the L promoter that consists of the L-gene exons 1 to 3 (S180), the M-gene exon 4 and a unique arrangement of exon 5 (V249, I274, F275, Y277, V279 from the L gene and A285, P298, F309 from the M gene). No mutation was found in the single gene. It is possible that unequal crossing over occurs commonly at this locus due to high homology of the L and M genes. The hybrid position within exon 5 indicates that a recombination event may have occurred between amino acid positions 279 and 285.

81 Low frequency of CNGA3 mutations in Japanese patients with congenital achromatopsia

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Congenital achromatopsia is a stationary retinal disorder with autosomal recessive inheritance and is characterized by loss of color discrimination, low visual acuity, photophobia and nystagmus. It has been demonstrated that mutations in the CNGA3, CNGB3 and GNAT2 genes were associated with the disorder in mainly European population. Here we tested the hypothesis that CNGA3 mutations are involved in Japanese patients with congenital achromatopsia. A total of 14 patients from 13 Japanese pedigrees were participated in this study. DNA from venous blood samples was prepared. We analyzed CNGA3 gene for mutation screening with PCR-single-strand conformation polymorphism followed by sequencing. In only one 22-year-old female patient with complete achromatopsia (rod monochromacy), we identified compound heterozygous mutations (p.R436W and p.L633P), one (p.L633P) of which was novel and not found in 100 Japanese control individuals. No mutations in the CNGB3 and GNAT2 genes were identified in the patient. Clinically, best-corrected visual acuity was 0.1 in both eyes. In color vision tests, the patient identified only the first plate in Ishihara plates. The Farnsworth Panel D-15 showed the confusion along the scotopic axis. No specific finding was observed in funduscopy. Ganzfeld full-field electroretinograms (ERGs) showed normal responses in scotopic and bright-flash ERGs but no response in 30-Hz flicker ERG. Spectral sensitivity on a white background revealed only one peak at around 500 nm that fits the absorption spectrum of human rhodopsin. The L633 within the cGMP-binding site is conserved among other mammalian CNGA3 proteins. Therefore, we conclude that the p.L633P is a disease-causing mutation. This is the first report of a Japanese patient with CNGA3 mutations. The frequency (7%, 1/14) of CNGA3 mutations was less than that (25-33%) in European patients.

82 The influence of test distance on the CN Lantern Test

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Introduction: Colored signal lights remain the primary device for conveying information to locomotive engineers on both the main track and in the yards. Sighting distances for the signal lights on the main track typically vary from 0.3 to 1.0 km. The relatively small size and low brightness contrast make identification of signal lights on the main track very challenging for person with a congenital red-green defect. However, in the yard, the sighting distances are shorter and are usually less than 0.2 km. One would expect that correct identification of signal lights within the yard would be somewhat easier. Because of the difference in the sighting distances between the main track and yard, it may be appropriate to have two different test distances for a railway lantern test. The purpose of this study is to determine

whether the lantern test distance affects the pass/fail results for the CN Lantern test (CNLan). **Methods:** The CNLan presents triplets of color lights which could be any combination of red, green and yellow. At the normal test distance of 4.6 m, the point brilliance of the test lights is equivalent to sighting distances ranging from 0.32 to 0.64 km. At a test distance of 2.3 m, the CNLan is equivalent to sighting distances ranging from 0.16 km to 0.32 km. Subjects were asked to identify the color of each light at each distance. There were 67 individuals with congenital red-green color vision defects who participated in the first part of the study. Sixty-six percent of the subjects repeated the experiment 10 days later. **Results** There was a significant ($p < 0.05$) decrease in the mean number of errors from 7.6 to 4.3 as the distance decreased. There was also a corresponding increase in the percentage of subjects who passed from 9.0% at 4.6 m to 20.9% at the 2.3 m viewing distance. None of the subjects who passed at the longer distance failed at the shorter distance. Interestingly the majority of individuals passing at the longer distance had a protan defect, whereas individuals who passed at the shorter distance were equally divided between protan and deutan defects. The replication results were statistically identical to the first session ($p > 0.05$). **Conclusion** Decreasing the CNLan viewing distance by 50% does decrease the number of errors and increase the pass rate. Nevertheless, the majority of color-defective individuals still fail the test. Although short term learning effects cannot be totally ruled out, the replication results suggest that the reduction in errors at the shorter test distance is not due to practice effects.

83 Color changes in a 50 year old AO HRR color vision test

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The original AO HRR color vision test (second edition) was validated by many studies, and considered one of the best designed plate tests. It is still accepted by many governmental agencies for color vision certification. In their 1954 publication, Hardy, Rand, and Rittler stated that specially compounded inks containing no linseed oil were used for printing to avoid color changes with time. Fifty years later, it is both important and interesting to determine whether the wear and tear causes significant color changes. The chance finding of a never-used second edition (unsealed in 2002, courtesy of Dr. Joel Pokorny) offers an opportunity to assess the color changes. A GretagMacbeth Spectrolino spectrophotometer was used to measure the chromaticities of the never-used book, and an extensively-used (well maintained) book. Four plates (#4, 7, 13, 16), selected from the four sections of the test, were analyzed. The colored dots from each of the 8 plates were plotted on a CIE chromaticity diagram. Isocolor lines were drawn to evaluate chromatic alignment. Chromaticities for plates #4 and 7 are significantly different between the two books. In terms of chromatic alignment, the never-used book is better for plate 7, but worse for plate 4. Chromaticities for plates #13 and 16 are essentially identical between books, all with good alignment with the isocolor lines. The overall comparison shows that the chromatic alignment characteristics of the extensively-used book are not worse than the never-used book. Since colors in these plates have to be aligned with both the protan and deutan axes, any significant color changes would have disturbed this delicate requirement. The findings of many plates with good alignment, and the lack of differences on plates #13 and 16 between books, suggest that there are no significant color changes over time. Differences between books on plates #4 and 7, which contain desaturated colors, were likely the result of color variation from the original printing process.

84 Achromatic parvocellular contrast gain in normal and color defective observers: Implications for the evolution of color vision

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Purpose: Parvocellular (PC) neurons are far more responsive to chromatic (L-M) than to luminance (L+M) stimuli. A luminance modulation is not an optimal stimulus for a chromatically opponent receptive field as revealed by measurements in PC cells showing achromatic contrast gain to be lower than chromatic contrast gain. In considering the evolution of color vision, some have suggested that PC-pathway chromatic contrast gain is matched to the chromatic content of the natural environment to avoid response saturation with large shifts in chromaticity. Anomalous trichromats, with less than normal separation of their L- and M-cone spectral sensitivities, should have diminished chromatic input to PC (L-M) cells and dichromats, with missing L- or M-cones, should have no chromatic input to PC (L-M) cells. When the constraint that PC neurons limit an observer's contrast gain to accommodate the range of chromaticities in natural images is removed, is there an improvement in achromatic processing in color defectives? **Methods:** This study employed a psychophysical method designed to isolate parvocellular (PC) vs magnocellular (MC) responses to achromatic stimuli (Pokorny & Smith, 1997). The stimulus display included four 1° squares on a large steady uniform background and, on a trial, one square differed in contrast from the other three. The observer's task was to choose the square that was different. Thresholds were measured as a function of the contrast of the four-square array to the background. In the Pulsed-Pedestal condition, the stimulus array appeared only during the trial period, with the test square at a higher or a lower retinal illuminance than the other three. In the Steady-Pedestal condition, the stimulus array was continuously presented within the background with only the retinal illuminance of the test square changed. Seven color defective observers, (2 protanopes, 2 deuteranopes, 1 protanomalous, and 2 deuteranomalous) and 4 color-normals served as observers. **Results:** For the pulsed-pedestal condition, isolating PC responses, data from all observers showed a V-shape, with greatest threshold sensitivity when the squares were equal to the background compared to when the squares had positive or negative contrast. There were no systematic differences in the slopes of the V-shaped functions between normal and color defective observers, implying no differences in PC achromatic contrast gain. **Conclusions:** PC pathway achromatic contrast gain appears to be the same in human normal and anomalous trichromats and dichromats. There was no enhancement of achromatic processing in the PC system in color defectives, implying that factors other than the environmental chromaticity gamut tune the PC system. PC achromatic contrast gains of dichromatic and trichromatic New-World primates have been shown to be similar to each other, and to contrast gain measured in macaque (Lee et al, 2000; Blessing et al, 2004). Thus PC pathway contrast gain parameters may have arisen in a non-trichromatic ancestor common to both old and new world primates.

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Lee, B.B., Silveira, L.C., Yamada, E.S et al. (2000) *Journal of Physiology (London)*, 528 (Pt 3), 573-590.

Pokorny, J. & Smith, V.C. (1997) *Journal of the Optical Society of America A* 14:2477.

85 Macular Pigment: Nature's Notch Filter II

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The effect of changes in macular pigment (MP), assessed using a database of 1782 reflectance spectra of natural and man-made colours, was reported at the Cambridge ICVS Symposium ¹. The population of colours was divided equally into 25 local areas in an analogue of the MacLeod-Boynton ² cone excitation diagram using the Normal and Anomalous cone fundamentals of De Marco, Pokorny and Smith ³ and applying the von Kries correction (VKC) for adaptation. Changes in mean local and global variance and in mean colour spacing were reported. VKC produced changes in mean local variance and in colour spacing that were incompatible with Moreland and Dain's ⁴ experimental finding of "tritan" confusions, associated with high MP. These findings are re-assessed here. It was found that removing VKC restored compatibility. A geographic analysis of local variance for Normals indicated the presence of systematic patterns but with only 25 colour areas the resolution was low.

¹Moreland, J. D. and Westland, S. Macular pigment: Nature's notch filter. In Eds J D Mollon, J Pokorny, and K Knoblauch. pp273-278 (2003) Oxford University Press, Oxford.

²MacLeod, D. I. A. and Boynton, R. M. (1979). Chromaticity diagram showing cone excitation by stimuli of equal luminance. *J Opt Soc Amer*, 69, 1183-6.

³DeMarco, P., Pokorny, J. and Smith, V. C. (1992). Full-spectrum cone sensitivity functions for X-chromosome-linked anomalous trichromats. *J Opt Soc Amer A*, 9, 1465-76.

⁴Moreland, J. D. and Dain, S. L. (1995). Macular pigment contributes to variance in 100 hue tests. *Doc Ophthal Proc Ser*, 57, 517-22.

86 The Macular Assessment Profile (MAP) test - a new VDU based technique for measuring the spatial distribution of the macular pigment

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Findings from recent studies suggest that the retention of lutein and zeaxanthin in the retina following supplementation with carotenoids is particularly evident in the near periphery of the visual field (1). This finding is of interest given the role carotenoids may play in improving visual function (2) and in retarding some of the destructive processes in the retina that lead to age-related macular degeneration (3). Although the effect of macular pigment (MP) on colour matches has long been recognised, the extent to which MP diminishes yellow-blue chromatic discrimination sensitivity remains controversial. The measurement of MP optical density therefore remains of great interest, and this is often performed using optical systems for heterochromatic flicker photometry (HFP) that employ short- and long-wavelength (SW and LW, respectively), narrow-band lights. 2D profiles of MP optical density are more difficult to measure using optical systems, largely because of the mechanical constraints imposed on generating stimuli of varying size at a number of locations in the visual field. The use of full, square-wave modulation also makes it difficult to set a flicker null point and this affects the accuracy of the match. MP systems

based on visual display units have numerous advantages and can be designed to overcome most of the problems associated with optical systems, but their use in MP measurement has been limited, largely because of the restricted luminance range of the blue phosphor and the extended spectral bandwidth of the blue and green phosphors. The latter causes the MP density to be underestimated (4). In order to overcome these problems we designed a new MAP test using a visual display that can be arranged to achieve high luminance with stable operation. A notch optical filter was incorporated in the design to separate the three phosphor outputs into two beams that can be modulated independently: one beam that is absorbed selectively by the MP (i.e., the SW beam) and the other that is not (i.e., the LW beam). A mean luminance level of 30 cd/m² can be achieved using this system with a maximum range of 1.3 log units for the SW beam. Stimuli of varying sizes are generated within the uniform background at the same location on the display using only 15% modulation of the long-wavelength beam and appropriate counter phase modulation of the short wavelength beam. The fixation stimulus is moved appropriately so as to position the flickering stimulus at a number of locations around it. Two techniques have been developed and tested. The first is based on nulling the flicker generated by the long-wavelength beam by appropriate adjustment of the short-wavelength beam. The second method is based on measurement of flicker detection thresholds (20 Hz flicker) at each location for each of the two beams. The latter technique provides a more accurate estimate of flicker thresholds, but takes longer to perform. A model was also developed to predict the expected relationship between peak MP density and that measured using the display-based technique. MP data measured using these two techniques, together with comparison data obtained in the same subjects using a Moreland anomaloscope modified for motion photometry. Since the Moreland anomaloscope employs narrow band stimuli, we were also able to test the model and to produce the calibration curve needed to convert the display estimates of MP density to expected peak values.

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87 The effect of macular pigment density on yellow-blue and red-green colour discrimination thresholds and other measures of visual performance

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The macular pigment (MP) exhibits band-pass spectral absorption characteristics with peak absorption in the short-wavelength range, thus acting as a pre-receptor filter for blue light. Large, inter subject variation in macular pigment optical density (MPOD) has been reported with differences as large as one log unit, as revealed from colour matching experiments (1). Absorption of blue light by the MP therefore affects trichromatic colour matches, but the extent to which this also affects chromatic discrimination sensitivity (as mediated by either the red-green (RG) or the yellow-blue (YB) chromatic mechanisms) remains less well understood (2,3). Dietary supplementation of carotenoids, mainly lutein (L) and zeaxanthin (Z), causes an increase in MP in the retina (4). In this investigation we have examined how the mean absorption of short-wavelength light by the MP in subjects with normal diets affects chromatic sen-

sitivity. We have also examined whether increased MPOD levels following supplementation with L and / or Z affects YB chromatic discrimination sensitivity and other measures of visual performance such as contrast acuity. Chromatic detection thresholds, contrast acuity, wavefront aberrations, sensitivity to scattered light and MPOD profiles were measured in 24 normal trichromats. In a separate study, ten placebo subjects were compared with 17 subjects who received L / Z supplementation for six months. MPOD profiles were measured up to an eccentricity of $\pm 8^\circ$ using a new flicker nulling technique implemented on a high brightness CRT display. Comparison of the MPOD-profiles before and after supplementation reveals a substantial increase of MPOD in the supplemented groups ($p = 0.005$) with the greatest and almost uniform percentage increase within a disc region of $\pm 4^\circ$ centered at the fovea. The improvement in contrast acuity was also statistically significant ($p=0.001$) in the group of subjects receiving L supplementation. All subjects showed excellent RG chromatic sensitivity that was independent of MPOD. Unexpectedly, YB thresholds were also normal and showed no correlation with MPOD. A model for threshold chromatic discrimination based on appropriate combinations of cone contrast signals was developed and the model predicts no significant change in YB chromatic sensitivity, even for MPOD levels as high as one log unit. The model also predicts a small increase in RG chromatic sensitivity that may however be too small to measure experimentally. The results show that MPOD can be increased significantly by supplementation with carotenoids and that supplementation can cause a significant reduction in achromatic contrast acuity thresholds. YB and RG thresholds, on the other hand, remain largely unaffected by the MP, even for high MPOD levels. The model accounts for the absence of correlation between MPOD and YB thresholds and predicts a small reduction in RG thresholds when MP is high. The findings suggest that at photopic levels of light adaptation an increase in MPOD does not affect detrimentally human chromatic contrast sensitivity and that achromatic contrast acuity thresholds may actually be reduced.

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88 Absence of Magnocellular and Parvocellular Deficits in Schizophrenia

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Early visual processing in parvocellular and magnocellular streams can be experimentally isolated by exploiting their different contrast gain properties (Pokorny and Smith, 1997, *JOSA*, 14). We tested psychophysically whether the global magnocellular dysfunction reported in schizophrenia (e.g. Schwartz et al., 2001, *Frontiers in Bioscience*, 6) also affects such early processes. Seven schizophrenic patients and 24 controls participated. The task was to discriminate the slightly brighter square target among four. Target luminance threshold was determined in 3 conditions: target was pulsed for 17 ms together with the 3 squares (pulse paradigm), target was presented on a steady background composed of 4 uniform squares

(steady paradigm), or target was presented alone (no background paradigm). The first study replicated previous results demonstrating that magnocellular and parvocellular processing could be dissociated in control participants. Moreover, no evidence for an early magnocellular deficit in the schizophrenic patients could be detected as the thresholds of all schizophrenic observers were within normal limits in the steady paradigm (presumed magnocellular mediation), as well as in the pulse paradigm (presumed parvocellular mediation). Magnocellular dysfunction, if present in schizophrenia, must concern more integrated processes, possibly at the level of parvocellular and magnocellular interactions.

89 "De Visu" software

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Pedagogic objectives We have developed a free software tool written in Delphi with advice from Ken Knoblauch (Inserm U371, Cerveau et Vision, Lyon) and David Alleysson (Laboratoire de Psychologie et NeuroCognition (LPNC) Université Pierre Mendès-France (UPMF), Grenoble) to introduce students to basic principles of color vision. The target audience is secondary school students (14 to 18 years old). In France, vision is one of the neuroscience courses taught in high school, but approached mainly through physics. With this software, we are trying to interest students and make them understand that seeing is a construction by the brain, not only a problem of photoreception. As we think that the scientific knowledge is now available to explain many visual phenomena, related to motion perception, colour perception and some visual illusions, this software can provide a provocative introduction, which will help students to delve into the scientific aspects of vision.

Contents The software provides 7 interactive demonstrations. Retina processing at the level of the cone photoreceptors: Students can build artificial sensitivity curves of the cones or choose a pattern of colour sensitivities and look at theoretical consequences on natural scenes. Students can also compare the discrimination capacity of the cones and the MPK systems; Influence of context on color perception: Students create screen patches of different colours and place them in various colored backgrounds; Detection of color vision deficiencies: Students has to create a colour as near as possible to a reference colour; Illusions of colour perception; Motion Illusions; Successive contrast: Students look at a coloured picture for a while, and describe after-image sensations perceived by looking at a grey screen; Lateral inhibition in receptive fields.

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