Colour Vision II:
The post receptoral basis of colour vision and acquired color vision deficiencies

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Colour Vision 2 - post receptoral

1. Pre-requisites: cone types, the principle of trichromacy, univariance, tests for the inherited color vision deficiencies
2. Connection of cones to retinal neurons: cone opponency and colour vision
3. Cells types for RG, BY and achromatic vision
4. Testing of RG, BY & Ach vision:
   1) Farnsworth Munsell
   2) Monitor displays and selective color vision tests
5. Acquired color vision defects: glaucoma, ARM, Type 2 diabetes, phototoxicity, optic neuritis.
6. Kollners Rule

26th Oct 2017

How is colour coded?

- Each colour produces a unique pattern of relative activities in the three cone types
- The outputs of the three cone types must be compared for color to be determined. This is done by 2 types of cone opponent process, starting in the retina.

Post receptoral pathways for color vision:

L/M (red-green) cone-opponency - midget ganglion cells of retina & LGN – also called P cells.

S cone-opponency - bistratified ganglion cell & K cells of LGN.

Luminance (black/white or achromatic):

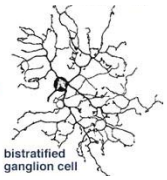
- P cells – fine spatial detail and acuity.

- M cells. Parasol (M) cells are specialized for flicker and project to the motion sensitive areas of the brain – about 10% of retinal ganglion cells.

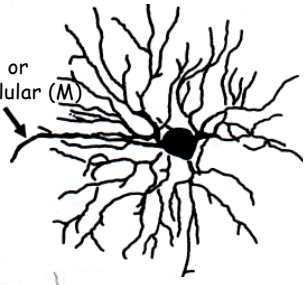
Retinal ganglion cells with defined functions

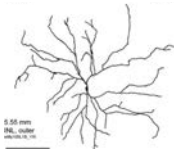
1. Midget or Parvocellular (P)

2. Bistratified



3. Parasol or Magnocellular (M)





4. Melanopsin filled

Sketch of Primate retina

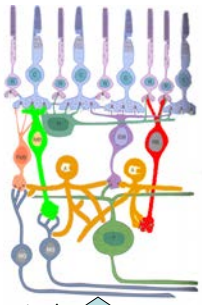
Rod and cone receptors (R)

Horizontal cells (H)

Bipolar cells (B)

Amacrine cells (A)

Ganglion cells (G)



Outer segment

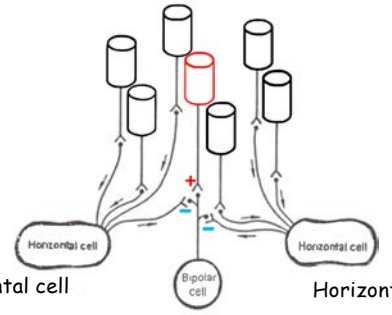
Inner segment

Cell body

Light

Optic nerve fibers (to LGN in thalamus)

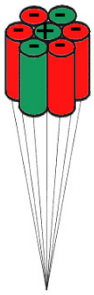
Cones connect to bipolar and horizontal cells with opposite sign



Horizontal cell

Horizontal cell

Bipolar cell

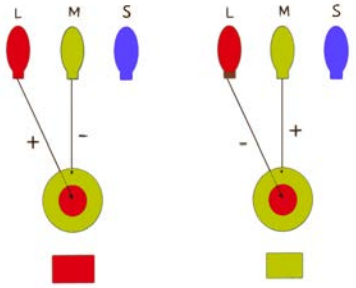


Post receptoral neuron

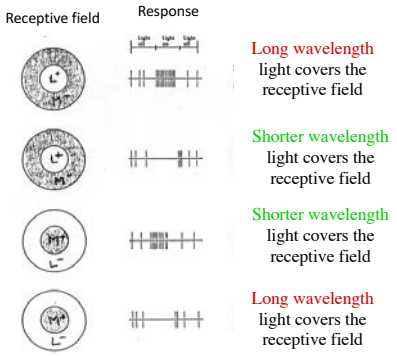
Cones connect to retinal neurons forming “centre” and “surround” subgroups, with different signs. For color vision these subgroups are also cone specific. The neuron illustrated is cone opponent as its excitatory and inhibitory signals have different spectral sensitivities, ie, one cone type in the centre but cone mixed in the surround.

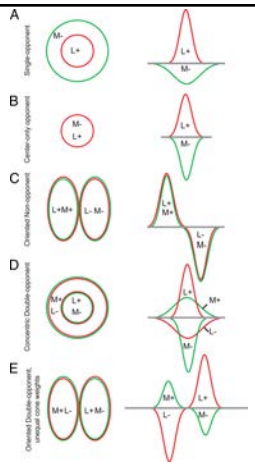
http://webvision.med.utah.edu/index.html

Red-green colour vision is formed from the opponent combination of L and M cones in the midget ganglion cells (P cells) of the retina (L vs M cone opponency), which comprise 80% of the retinal ganglion cells



Chromatic receptive fields: P cell responses to red and green light covering entire receptive field





Diagrams of model receptive fields to show the top view (left) and cross section (right) for L/M (RG) opponent neurons.

A. Type 1, P cell, -with spatial and cone opponency.

B. Type 2 cell with cone opponency but no spatial opponency.

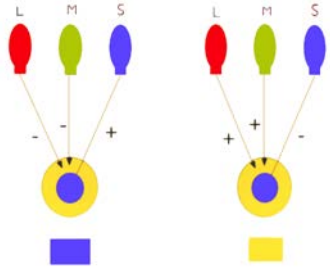
C. Achromatic cell – orientation tuned.

D. Dual opponent cell - with cone opponent sub regions in centre & surround.

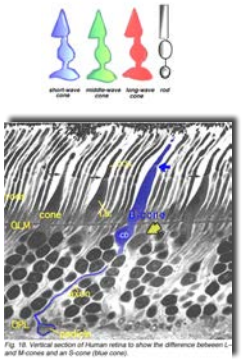
E. Dual opponent cell – orientation tuned.

C-E are only found in the cortex. A & B (single opponent cells) are found in the retina, LGN and V1 cortex.
Source: Figure 3 from Conway et al 2010, Advances in Color Science: From Retina to Behavior, Journal of Neuroscience, 30, 14955–63.

Blue-yellow colour vision is formed from the opponent combination of S with L and M cones in the bistratified ganglion cells (and other types) (S vs (L+M)) cone opponency) (about 5% of retinal ganglion cells).



S cones of the retina



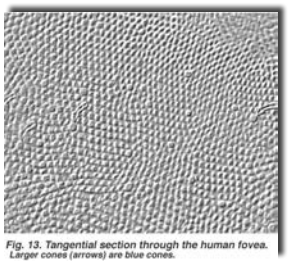
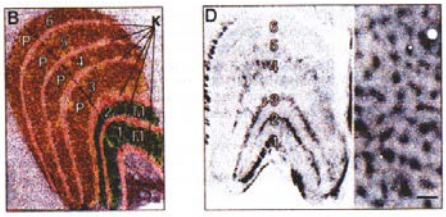


Fig. 13. Tangential section through the human fovea. Larger cones (arrows) are blue cones.

Layers of the LGN: Magno, Parvo and Koniocellular

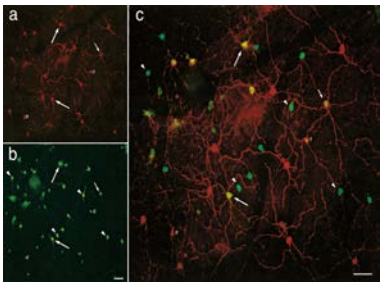


B. Note the koniocellular layers ventral to each primary layer.

D. Cells stained for CamII kinase which probably project to the "blobs"

(Hendry & Calkins, 1998)

Melanopsin-filled ganglion cells > supra chiasmatic nucleus



Melanopsin/PRV152-labeled ganglion cells. (a) Melanopsin-expressing ganglion cells in a retinal wholemount from an animal (hamster) with an intact visual system. Long arrows indicate intensely labeled ganglion cells; short arrow indicates a lightly labeled cell. In this image, melanopsin-labeled displaced ganglion cells (d) in the inner nuclear layer are also revealed after deconvolution of optical sections. (b) PRV152 transsynaptically labeled ganglion cells in the same field as in (a). (c) Combined image of (a) and (b) illustrating melanopsin/EGFP double-labeled ganglion cells. Arrowheads indicate PRV152-labeled cells that are not melanopsin immunoreactive. Scale bars = 50 [mu] (Solars et al Vis Neuroscience 20, 601, 2003)

Additional light sensitive cells not involved in colour vision

Melanopsin filled ganglion cells: > supra chiasmatic nucleus – synchronizes the circadian oscillator to the day/night cycle. Also control pupillary responses. First found in mice but in 2007 also found in primates – probably about 3,000 cells per retina. Respond very slowly and are very sluggish, remaining active for a long time after stimulation. Respond best to blue light (460nm).

How do we test these pathways?

1. Clinical color vision: Farnsworth Munsell 100 hue or Panel D15

2. Electronic displays & computer graphics with control of cone activation

Farnsworth Munsell

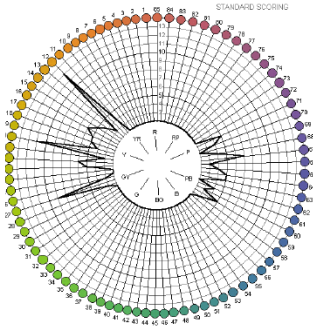
100 Hue Inherited and acquired color vision deficiencies

Red-green, blue-yellow and non-specific deficiencies

Show axial effects

D15

Scoring the Farnsworth Munsell 100 hue test

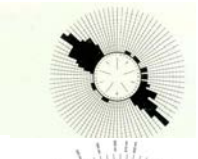


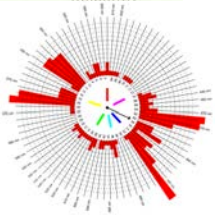
Online scoring program: http://www.torok.info/colorvision/fm100.htm

Farnsworth Munsell 100 hue test - inherited deficiencies

Protan

Deutan



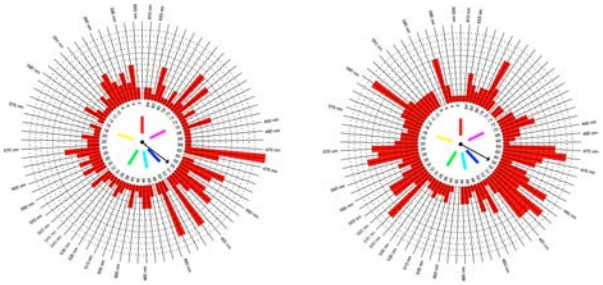


Tritan

Subject with severe chronic optic neuritis: subject 1

Left eye

Right eye

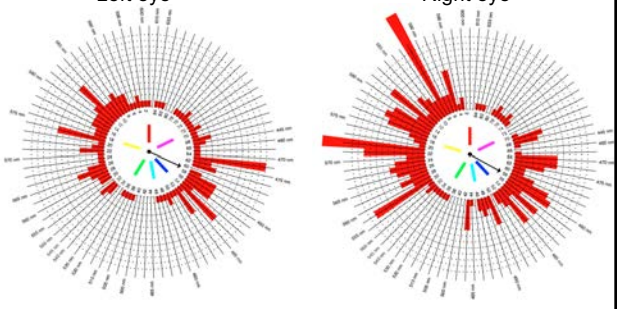


252 Error score 329

Subject with severe chronic optic neuritis: subject 2

Left eye

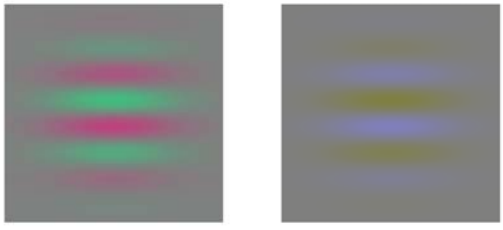
Right eye



172 Error score 272

A Gabor pattern with colors that activate only the L/M ('red-green' cone opponent process

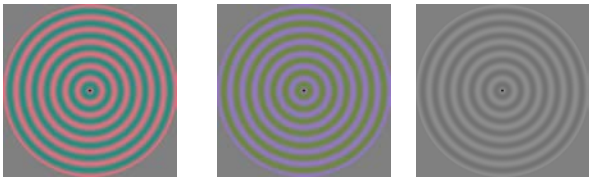
A Gabor pattern with colors that activate only the S/L-M ('blue-yellow') cone opponent process



A sinewave grating presented in a Gaussian envelope

Sinewave radial (ring) stimuli (0.5cpd)

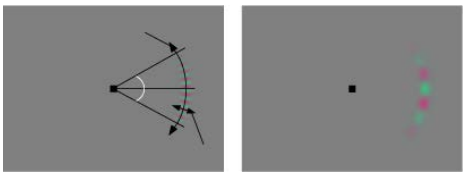
Stimuli are matched in multiples of detection threshold (x 25) and so are approximately equally visibly but have different contrasts



RG: 4% BY: 30 % Ach: 11%

Patterns with colors that activate the L/M ('red-green'), S cone ('blue-yellow') cone opponent processes, and the achromatic system. Designed for full field activation, for example for fMRI experiments.
(Mullen et al, European Journal of Neuroscience, 2007)

A pattern with colors that activate only the L/M ('red-green') cone opponent process: designed for peripheral vision.
(Mullen et al, Perception, 2005)



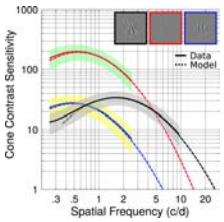
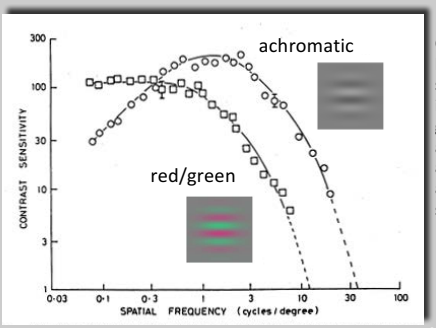


Figure Legend:

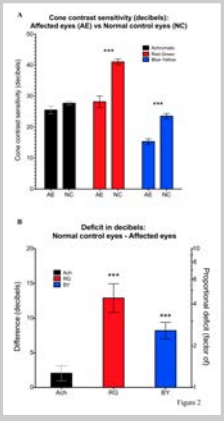
Measured CCS as a function of spatial frequency for the Ach (solid black line), RG (solid red line), and BY (solid blue line) conditions under monocular viewing. The average across the 51 subjects is shown. The dotted lines indicate the log-parabola model estimation, which is reconstructed with the average estimated values for each of the three parameters by the qCSF. The averaged model parameters are reported in the Table. The shaded regions represent ± SD.

Contrast sensitivity of red/green and luminance gratings in normal vision



Mullen J. Physiology, 1985

Colour vision has a lowpass contrast sensitivity function that is very good at detecting gradual colour changes across relatively large areas but has low acuity and is very poor at seeing fine spatial detail

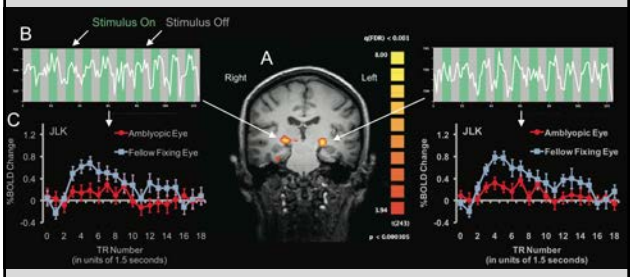


Loss of red-green, blue-yellow and luminance contrast sensitivity in optic neuritis (chronic) – shows selective colour vision loss that is greatest for red-green (L/M opponency. Compatible with P retinal ganglion cell axon loss and some S cone RGC axon loss.

Al-Hashmi, Kramer & Mullen 2011. Human vision with a lesion of the parvocellular pathway: an optic neuritis model for selective contrast sensitivity deficits with severe loss of midget ganglion cell function. *Experimental Brain Research, 215, 293-305.*

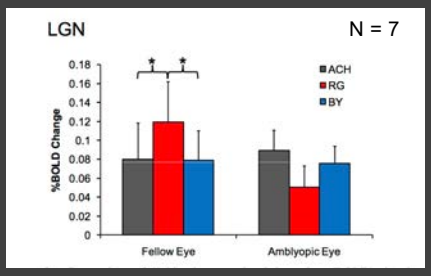
AMBLYOPIA

LGN BOLD activation compared between amblyopic and fellow eyes



From Hess, R.F., Thompson, B., Gole, G. & Mullen, K.T. European Journal of Neuroscience, 29, 1064-1070, 2009.

The amblyopic LGN – BOLD responses:
RG, BY and ACH responses in normal fellow eyes (left) and amblyopic eyes (right): greatest deficit is for RG contrast

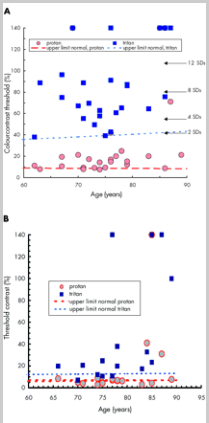


From Hess, R.F., Thompson, B., Gole, G. & Mullen, K.T. Journal of Neurophysiology, 104(1), pp475-483, 2010.

Acquired S cone deficiencies:

Examples from AMD and Diabetic retinopathy

AMD- fellow eyes



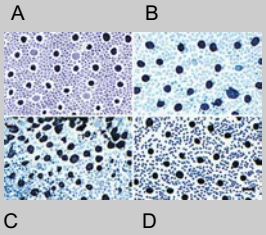
"Colour vision testing as an aid to diagnosis and management of age related maculopathy (ARM)"
(Arden & Wolf, BJO, 2004)

A. Small stimuli used (1.5 degrees):
S cone thresholds (blue squares) and L cone thresholds (red squares) in the asymptomatic fellow eye of an ARM patient group. Compared to normal limits (dashed lines) there are mild L cone deficits but S cone deficits are much greater.

B. Large stimuli used (6.5 degrees):
S cone thresholds (blue squares) and L cone thresholds (red squares) of the same group. Compare to normal limits L cone function is normal and S cone loss is significant.

Comment: For a well matched control comparisons use unaffected or less affected fellow eye in a unilateral condition.

Diabetic Retinopathy
Human post mortem



Cho et al Arch Ophthal, 118, 13931400, 2000, 'Selective loss of S cones in Diabetic Retinopathy.'

Tangential sections at the level of the photoreceptor inner segments located 10 to 20 arc degrees from the fovea. Enzyme histochemical reaction for carbonic anhydrase (CA) produces a black reaction product, which labels the dominant L/M-cones.

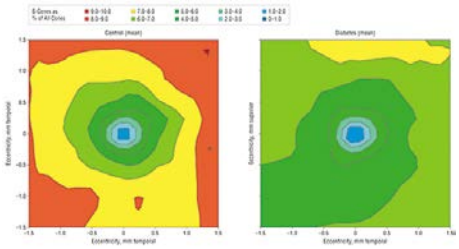
A, Section from a 68-year-old woman with no known history of ocular disease (control C5, Table 1). Roughly 9% of the cones are blue sensitive (arrows, negative for CA).

B, Section from a similar area in another 68-year-old woman with proliferative diabetic retinopathy treated with laser photocoagulation (D5, Table 1). Fewer S (CA-negative) cones are present. There are also fewer rods than in the control section.

C, Another section from the same subject as in frame B showing a focal area with marked reduction in rods. The L/M-cone density is essentially unchanged.

D, Section from another diabetic retina (D6, Table 1). Note the lack of S-cones, decreased density of rods and poorly defined cone sheaths (toluidine blue counterstain, bar = 10 µm).

Topographic (2-dimensional) plots showing the percentage of cones that are S-cones (negative for carbonic anhydrase) vs retinal eccentricity for the maculae of all of the control eyes (left) and all of the diabetic eyes (right)

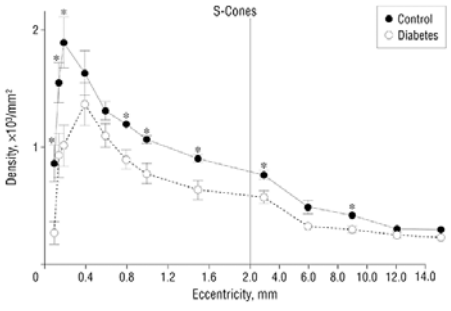


Cho, N.-C. et al. Arch Ophthalmol 2000;118:1393-1400.

Diabetic Retinopathy

ARCHIVES OF OPHTHALMOLOGY

Density of S-cones as a function of retinal eccentricity {+/-} SEM



Cho, N.-C. et al. Arch Ophthalmol 2000;118:1393-1400.

Diabetic Retinopathy

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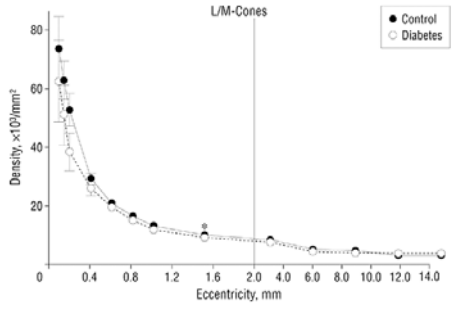
Density of L/M-cones as a function of retinal eccentricity {+/-} SEM



Cho, N.-C. et al. Arch Ophthalmol 2000;118:1393-1400.

Diabetic Retinopathy

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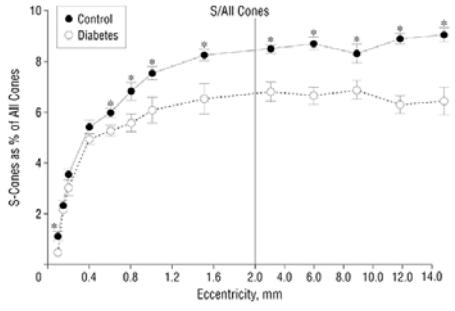
Percentage of cones that are blue sensitive as a function of retinal eccentricity (means for all directions) extending to 15 mm {+/-} SEM



Cho, N.-C. et al. Arch Ophthalmol 2000;118:1393-1400.

Diabetic Retinopathy

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Glaucoma

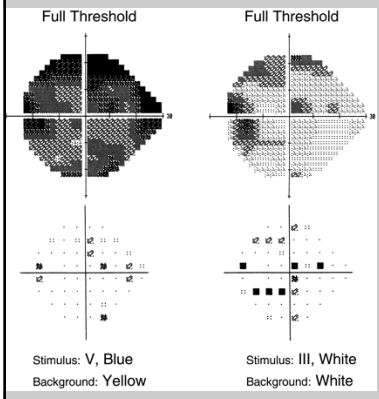

FIGURE 1 [3]. The same eye tested with SWAP (left) and conventional WW (right) perimetry. Appearance of grayscales of raw thresholds differ, with the SWAP field appearing more disturbed than the WW field. Probability maps of threshold deviations, which refer to age-corrected normal thresholds and normal limits, were more similar, and the WW test showed more test points with significant deviations than the SWAP test.

No S cone selective effects: need proper comparisons between L/M and S cone disorders that control for aging effects on optics

1. Pacheo-Cutillis et al BJO, 1999, Acquired colour vision defects in Glaucoma - their detection and clinical significance
2. Sample & Weinreb, IOVS, 1992 Progressive Color Visual Field loss in Glaucoma.
3. Bengtsson, IOPVS 2003. A New Rapid Threshold Algorithm for Short-Wavelength Automated Perimetry

Kollner's Rule (1912)

Lesions of the outer retinal layers affect blue yellow vision, lesions of the inner layers and optic nerve affect red-green vision

Revised version

S cones are physiologically vulnerable and so are more likely to be damaged by receptoral lesions than are L or M cones

Post receptoral lesions are more likely to affect both types of cone opponent neuron: red-green and blue-yellow.

Conditions quoted as having S-cone (tritan) defects appearing first:

Damage due to high light exposure
Retinal detachment
Pigmentary degeneration
Myopic retinal degeneration
AMD
Chorioretinitis
Retinal vascular occlusion
Diabetic retinopathy
Papilledema
Drugs: oral contraceptives, chloroquine

S cones are genetically robust but vulnerable physiologically

Conditions quoted as having RG (L/M) defects, but BY defects may also occur:

Lesions of optic nerve/pathway
Retrobulbar neuritis
Leber's optic atrophy
Compressive lesions of the optic tract
Progressive cone degeneration

L and M cones are physiologically robust but genetically vulnerable

- https://www.city.ac.uk/health/research/centre-for-applied-vision-research/a-new-web-based-colour-vision-test