colour separation in the retina

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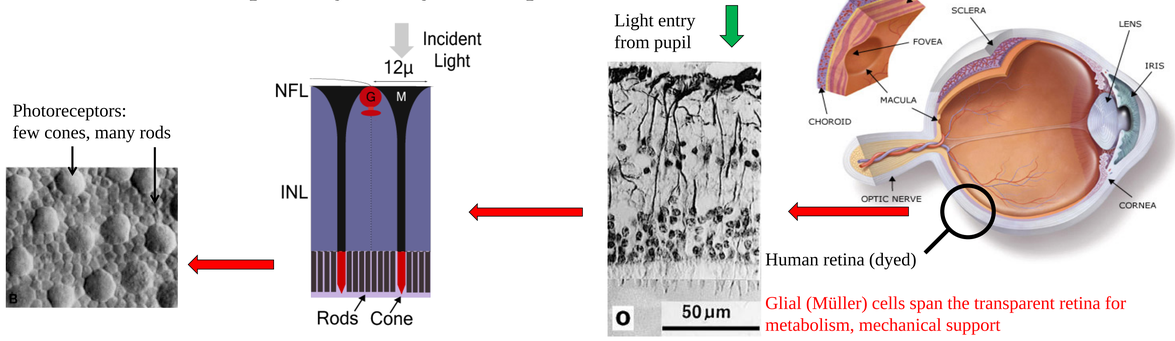
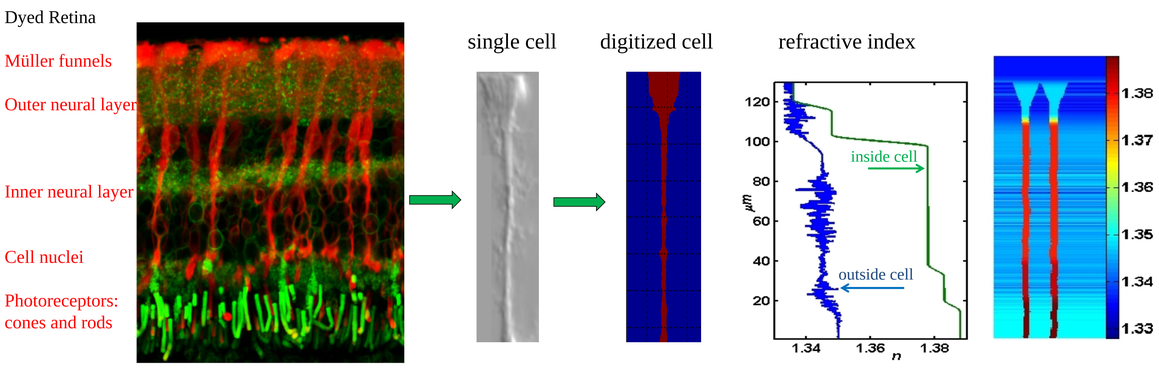
Puzzle: Our image of the world is detected by photoreceptors, lying at the ***bottom*** of the retina. Lateral neural layers, for processing the image temporally, spectrally, and spatially, come in front the photoreceptors, not behind them. These neural layers and their nuclei are scattering and aberrating the images. This reverse order of the retina is a long-standing puzzle, which we wish to explain by theory and experiment.



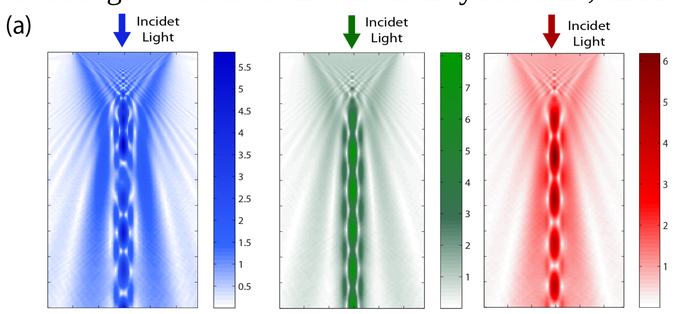
Glial (Müller) cells span the transparent retina for metabolism, mechanical support

It turns out that Müller cells have a higher refractive index (Franze *et al*. PNAS 2007) so we built a computer model to simulate their optical effect.

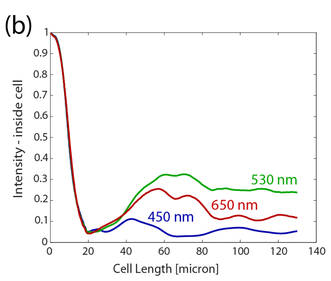


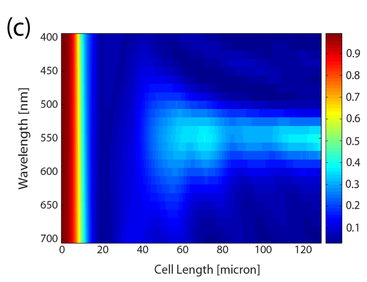
Theory and simulation: We use the fact that the refractive index contrast, between Müller cells and vicinity, is small. We propagate light of different colours at various angles into the retina, and watch the pattern. For that we wrote a beam-propagation code using the split-step Fourier method (FFT-BPM). The program was corroborated by modal analysis of the weakly guiding glial cells. We found that all colours are concentrated into the neck of the weak optical funnel, and then spread out. Green (~530 nm) is mostly recaptured back into the Müller cell, whereas blue gets scattered onto the nearby rod cells, and red in between.

Light profile in three colours. Green is best led by Müller cell.



Light captured inside Müller cell at three colours



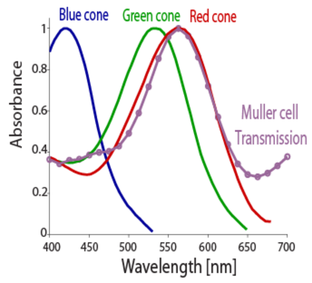


Light captured inside Müller cell at all colours

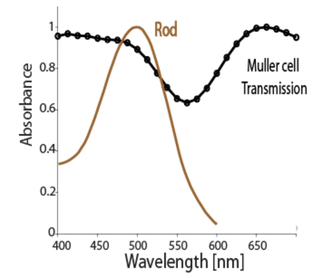
Müller transmission and cone pigments:

Cones are colour sensitive, mostly to blue, green and red light. colour-blind rods are ×100 more sensitive, and cover 95% of the retina (outside the small central fovea). So for day-time vision we need more light into cones, and preferably green-orange.

To our surprise, the spectra of the cones' pigments matched the colours transmitted by the Müller cells, according to our calculations for the human eye. Light is concentrated into the green and red cones by a factor of 8, into blue cones by a factor of four, and rods lose 15% of the light by the colour differentiation.

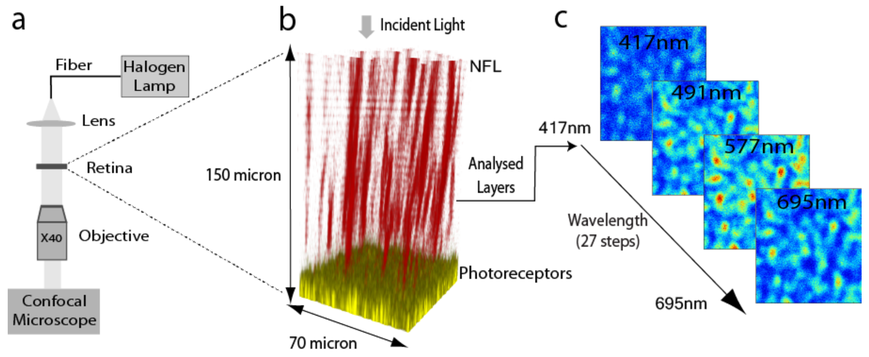


Müller transmission into cones matches the green and red pigments



Müller transmission outside the cones does not match the rod pigments

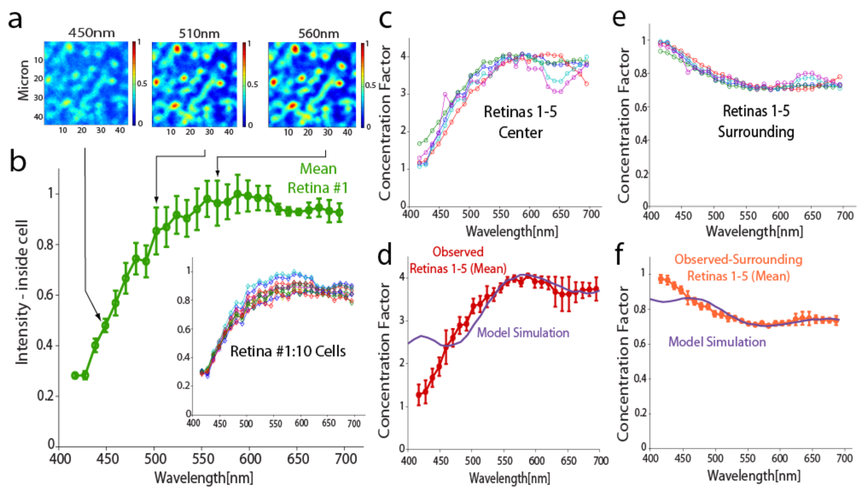
Experimental validation: We used retinas of guinea pigs to see if indeed light is differentiated by it. We modified a confocal microscope and added a white light source to it to see how it propagates through the retina. Indeed we found the expected light concentration according to colours.



Results:

Simulations and measurements match well for most colours except for the blue (d).

We also showed that Müller cells indeed lead the light into cones alone.



Summary:

Müller cells improve day-time vision without hampering night-time vision. There is a benefit in an inverted retina.

More details:

1. A. M. Labin and E. N. Ribak, "Retinal glial cells enhance human vision acuity," *Phys. Rev. Lett.* **104**, 158102 (2010).
2. A. M. Labin, S. K. Safuri, E. N. Ribak and I. Perlman, "Müller cells separate between wavelengths to improve day vision with minimal effect upon night vision," *Nature Communications* **5**, 4319 (2014).
3. A. M. Labin and E. N. Ribak, "color sorting by retinal waveguides". *Optics Express*, Accepted (2014)