Haidinger's brushes: Perceiving the polarization of light via an entoptic phenomenon

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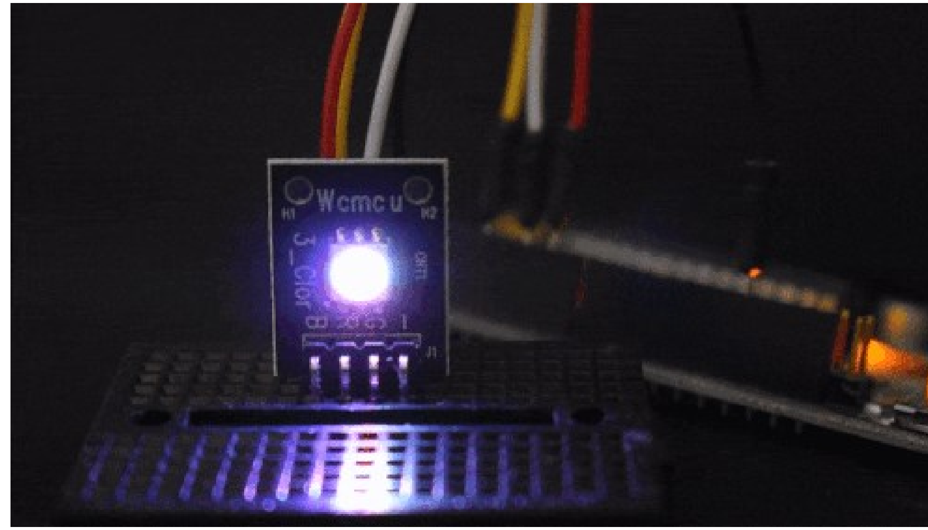
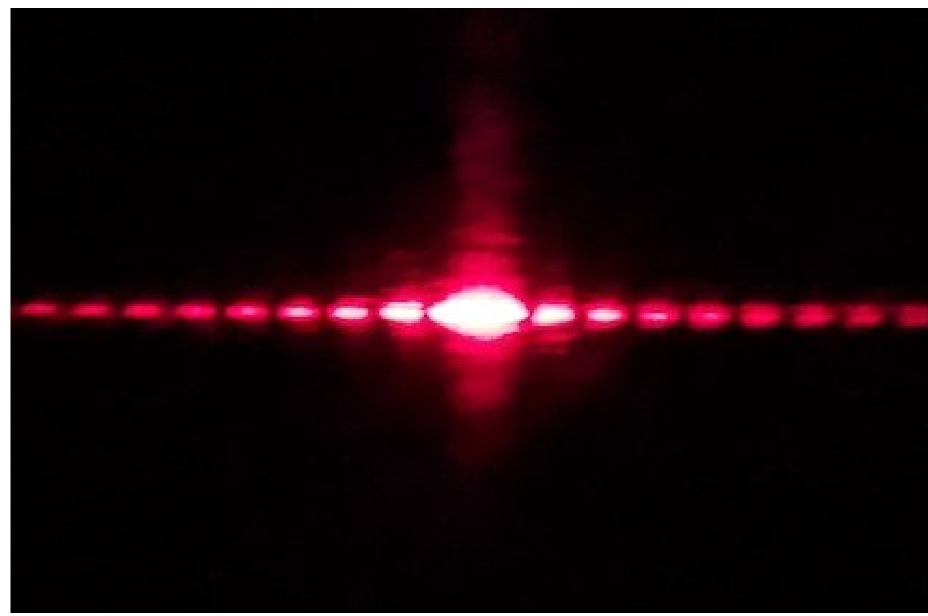
The perception of light

What are the properties of light that we can perceive?

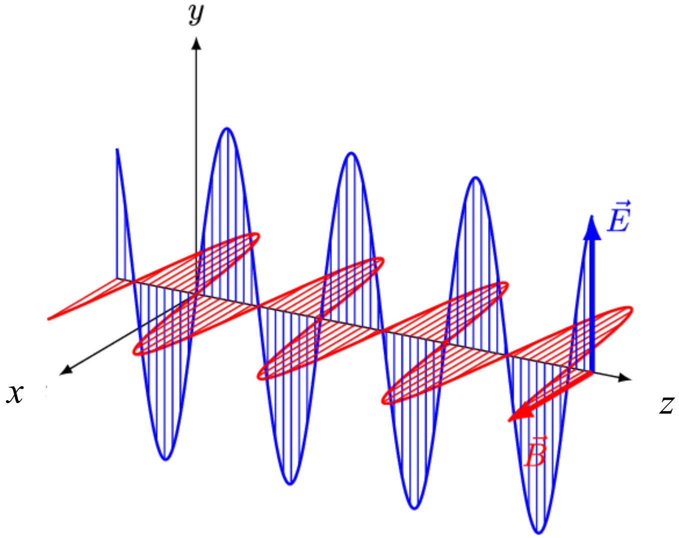
amplitude (intensity)	Y
wavelength (colours)	Y
phase	N
POLARIZATION	?



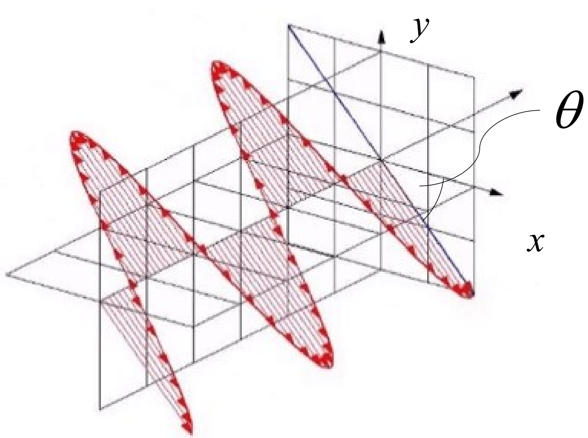


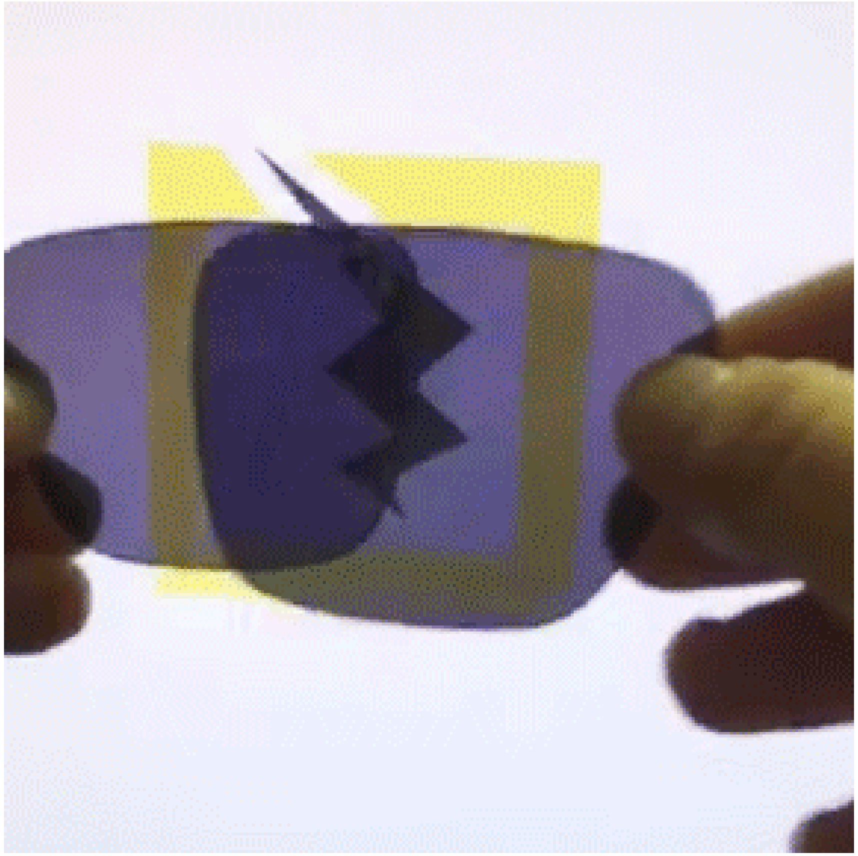
Polarization of light

Polarization is related to the oscillation plane of the electric field, *e.g.*, linear polarization. Using polarizing filters (polarizers) we transform polarization into intensity information:



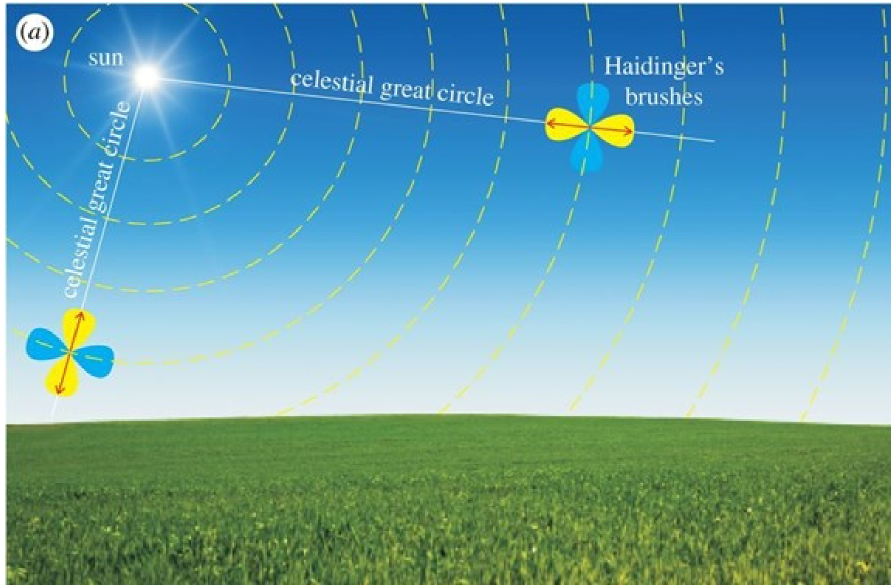
Linear polarization

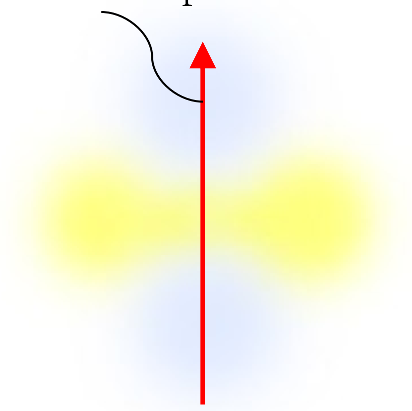




What if our visual system could perceive the polarization state without additional filters?

Haidinger's brushes



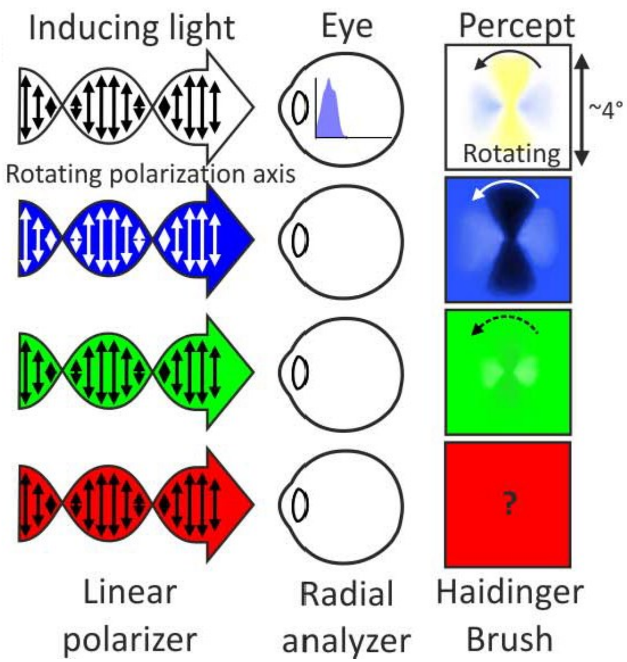


Entoptic phenomenon: not originated by an external object but due to the interaction of light with the anatomic structure of the eye. Noticed and described for the first time in 1844 looking the sky at 90° with respect to the sun. Main properties:

- It subtends a visual angle of approximately 3° around the locus of fixation
- Oriented mostly perpendicular to the polarization plane
- It is erased soon by neural adaptation unless the head slightly rotates around the primary visual axis
- Colour and contrast depend on the input illumination

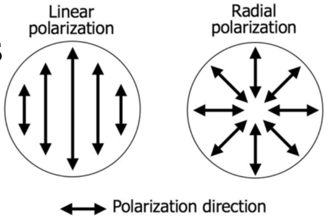
At the origin of HB formation: 2 hints

1. Strong dependence on the input wavelength:
- ➢ High contrast in blue light
- ➢ Low/absent in green/red light



Muller, P. L., *et al. Invest Ophthalmol Vis Sci* 57, 1448-1456 (2016).

2. The same pattern appears filtering linearly polarized light with a radial polarizer:



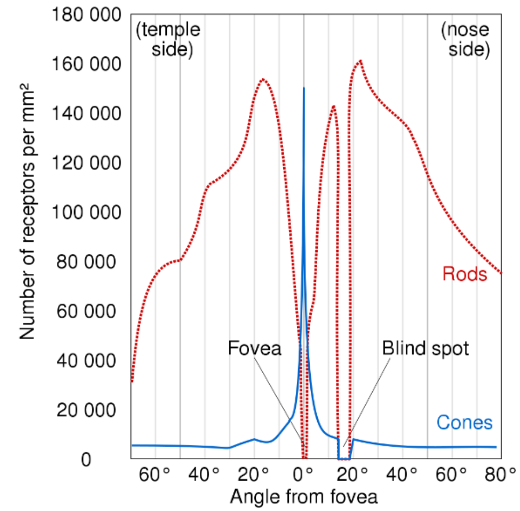
(in this case the object is real!)

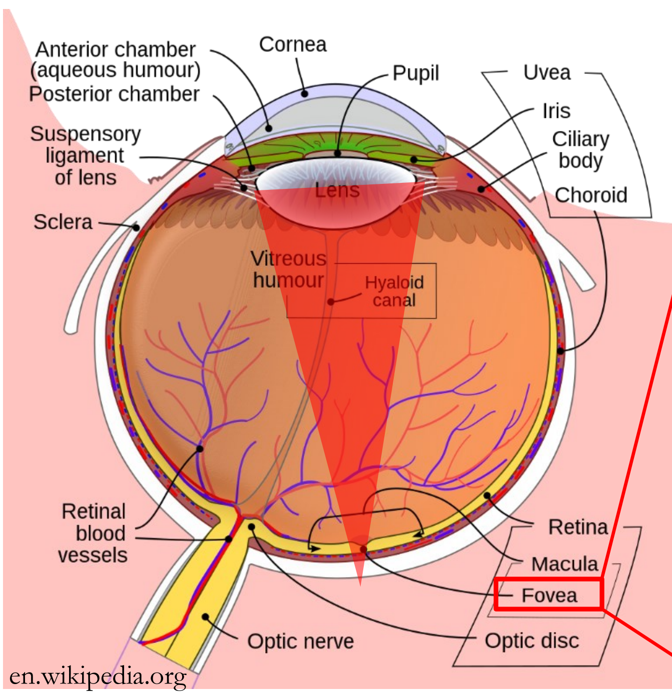
A RADIAL POLARIZER FOR BLUE LIGHT INSIDE THE EYE?

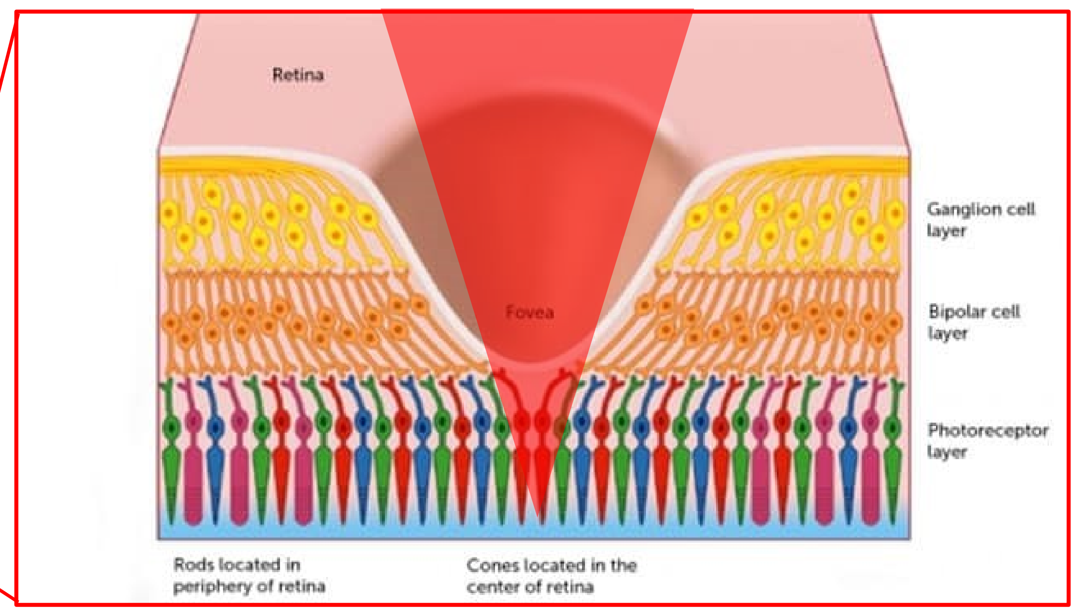
Human retina and foveal structure

The retina has a **multilayer (10) structure** made of specialized neuron cells and synapses for image translation into electric signals which are integrated, collected, and transmitted to the brain.

It is not homogeneous: in correspondence of the lens focus, it is much thinner in order to promote the exposure of photoreceptors (cones/rods) to light. Moreover, this zone (fovea) is characterized by a peak in the density of cones (maximum acuity).

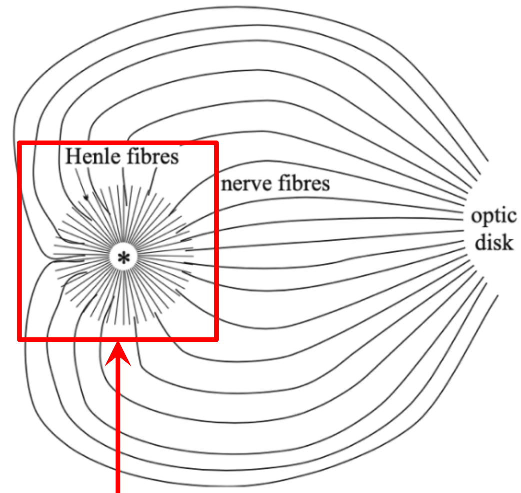


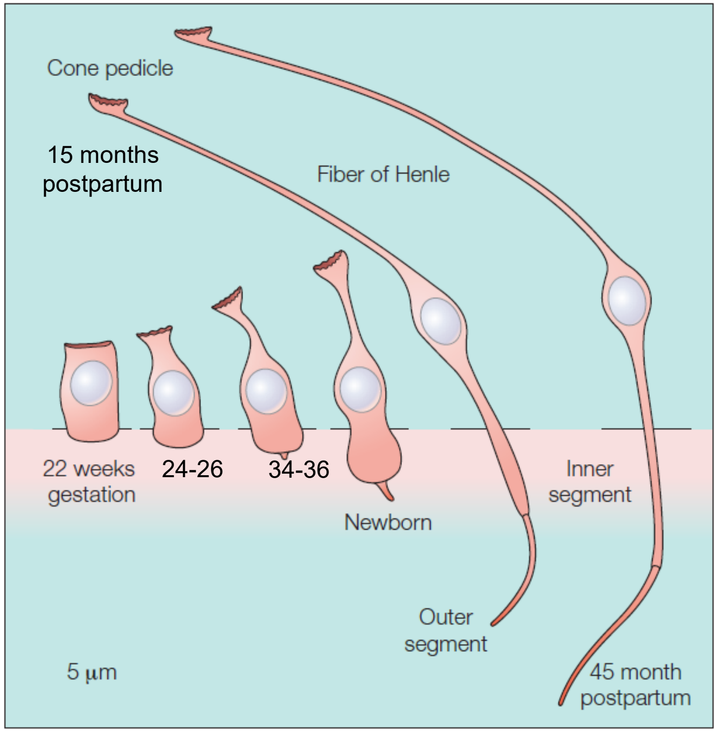


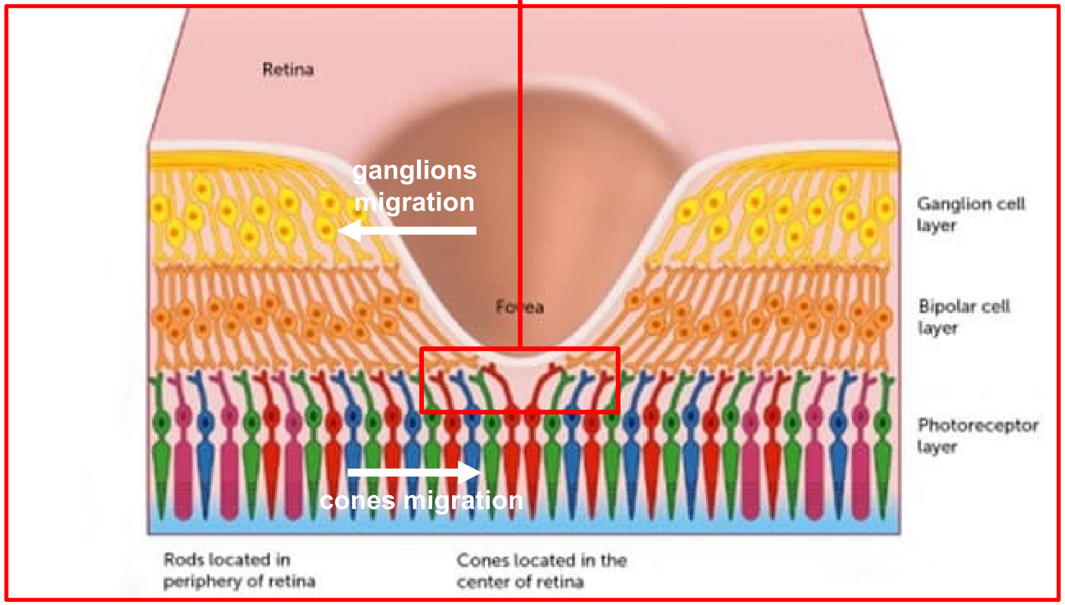


The foveal depression

Since birth, over about the next 25 weeks, foveal ganglion cells and inner nuclear layer cells migrate peripherally, creating the familiar foveal depression at about 15 months. Peripheral photoreceptor cells migrate towards the fovea from before birth to at least 45 months. **The result is a stretching and radial distribution of cone pedicles (Henle's fibres).**





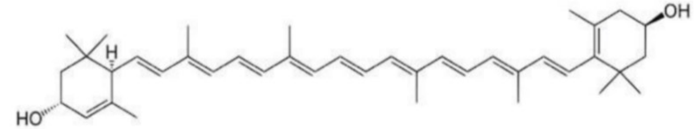


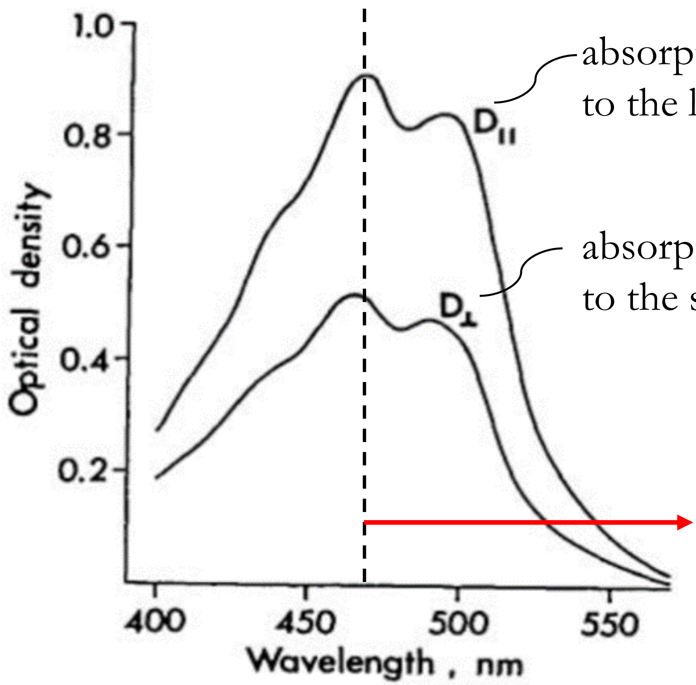
Adams, D. L. *Normal and abnormal visual development in Pediatric ophthalmology and strabismus* (ed. Hoyt, T.) 9-22 (2005)

Dichroism of macular pigments

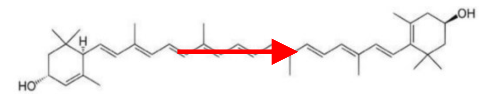
The macula is characterized by a high density of pigments. These pigments have long molecules and therefore dichroic behavior: they preferably absorb light polarized parallel to the long axis of the molecule.

e.g. lutein, or zeaxanthin (isomeric)

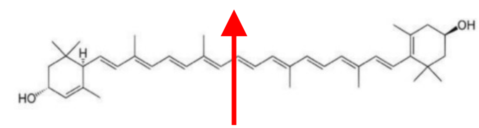




absorption for polarization parallel to the long axis



absorption for polarization parallel to the short axis

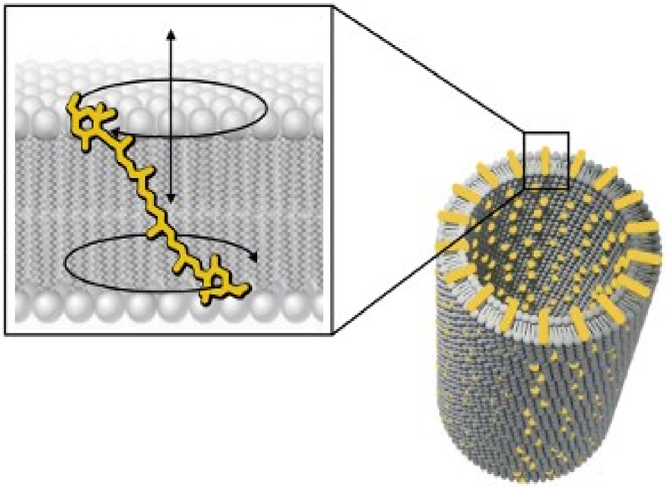


Absorption peak around 458 nm

Bone, R. A., & Landrum, J. T. (1983). Dichroism of lutein: a possible basis for Haidinger's brushes. *Appl. Opt.* **22**(6), 775–776.

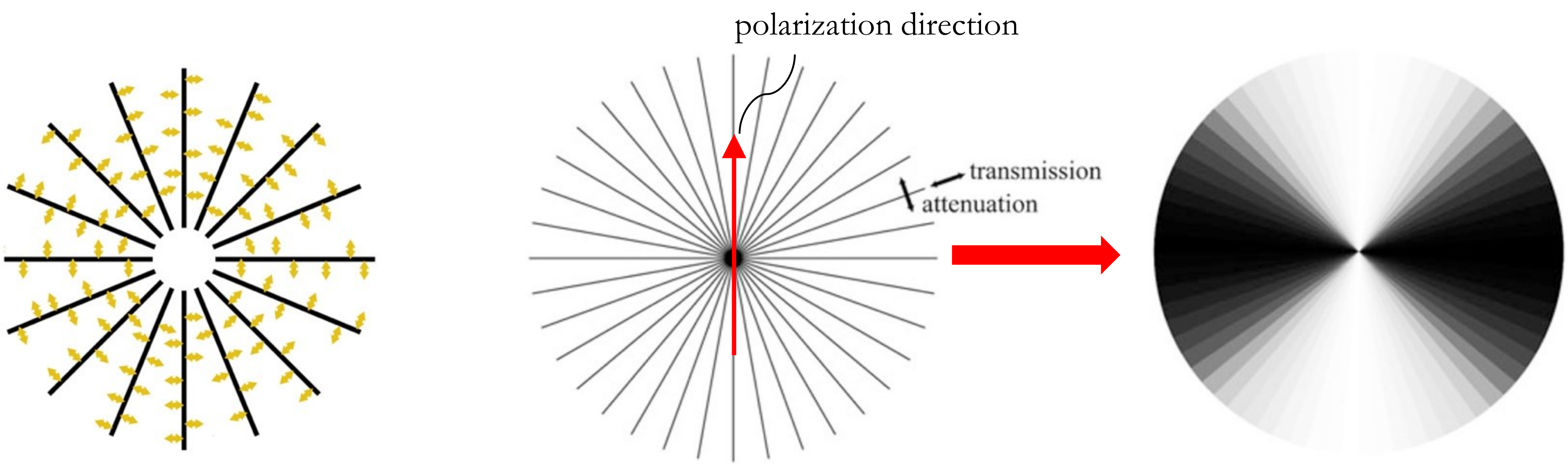
Fundamental protective and preventive function: absorption of short wavelengths (70% of 400-500 nm) to prevent photochemical damage and reduce scattering (improved acuity), strong antioxidant behaviour. Dietary origin.

An integrated radial polarizer



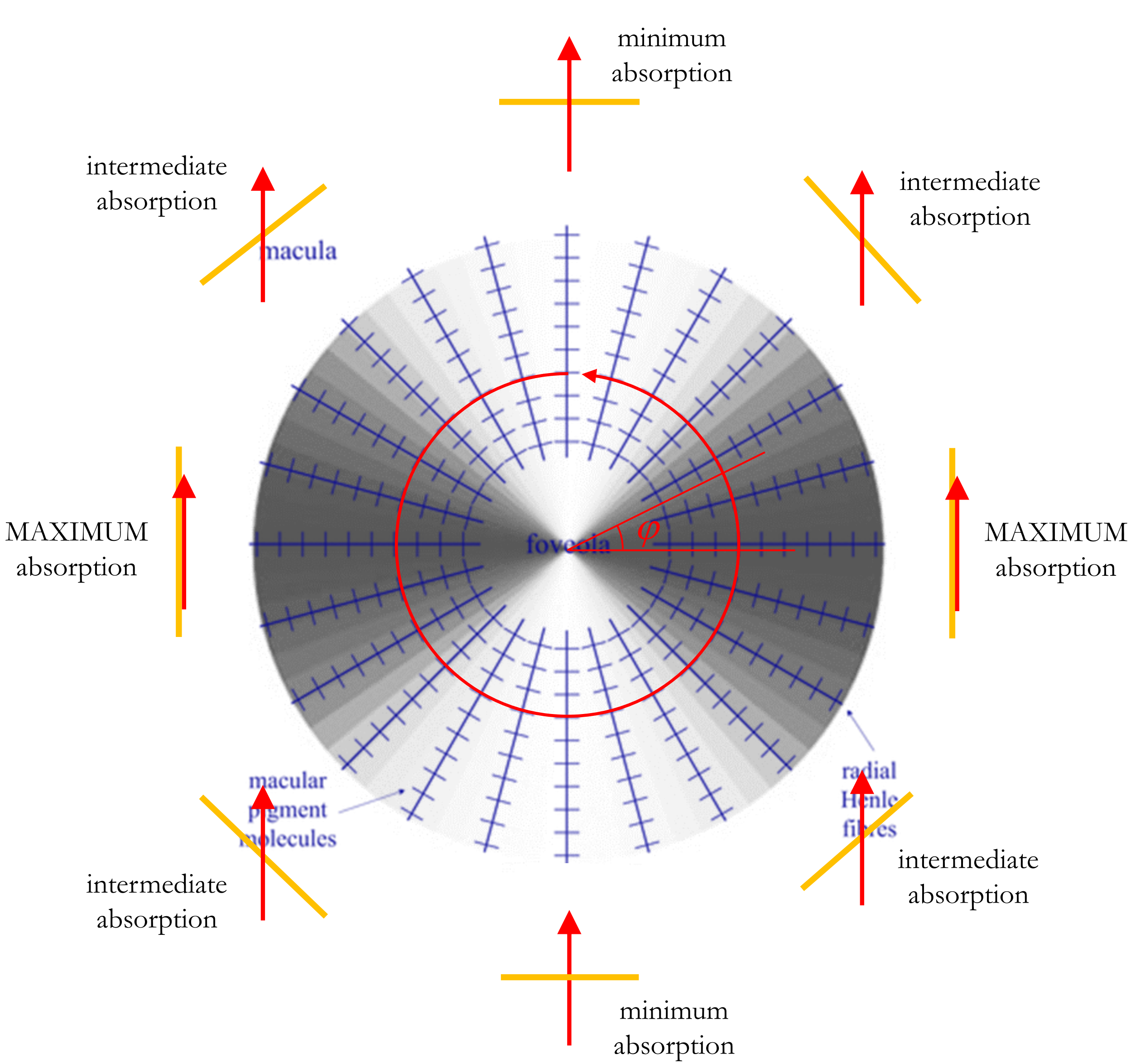
The pigments, mostly trapped inside the lipidic membranes of Henle's fibres are lipophilic and tend to orient perpendicularly to them, which are in turn arranged radially.

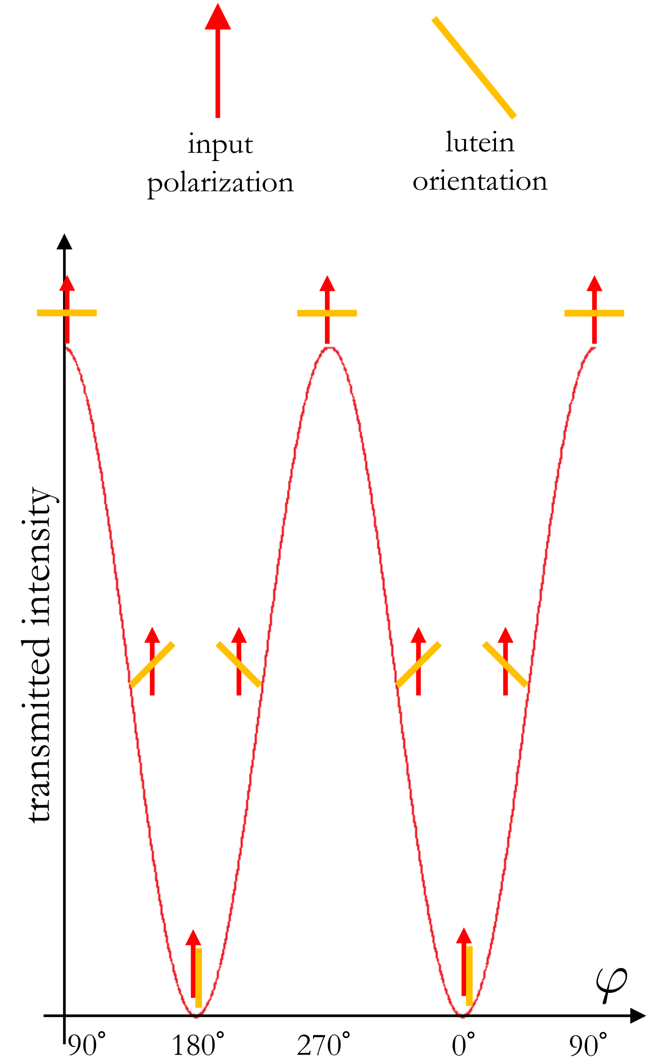
The result is a radial polarizer for blue light in the fovea!



transmitted pattern

The foveal radial polarizer





$$I \propto \cos^2 \left(\varphi + 90°\right)$$

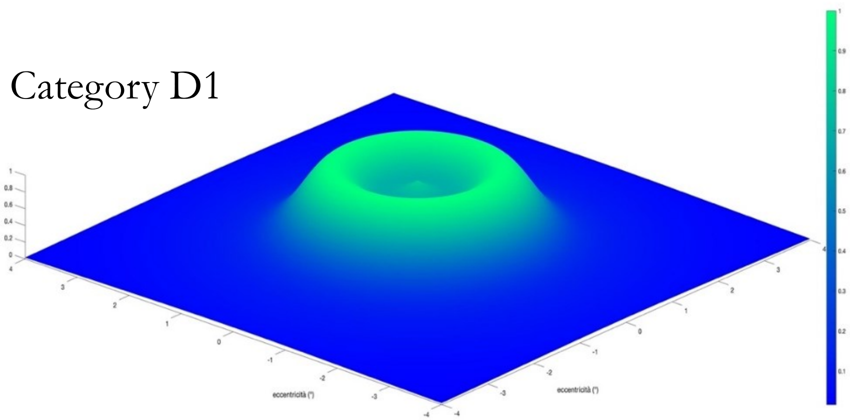
Macular pigment density function

The density function describes the optical density and 2D distribution of macular pigments in the macula. The parameters can vary significantly in different subjects, however in most individuals the density of the pigments decreases as a function of the distance from the center of the macula. Several categories can be identified.

Model of Berendschot and van Norren

$$\rho(r) = A_1 10^{-\rho_1 r} + A_2 10^{-\rho_2 (r - x_2)^2}$$

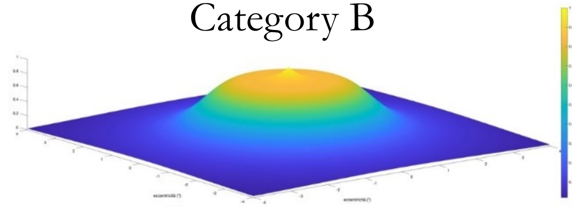
Category D1



	Parameters[a]	Value Range[a]	Category Values[b]				
			B	C	D	D1	E
A_1	Amplitude of the exponential component	0.28 ± 0.13 (reflectance)	0.25	0.3	0.3	0.25	0.2
A_2	Amplitude of the Gaussian component	0.13 ± 0.07 (reflectance)	0.1	0.045	0.15	0.2	0.12
ρ_1	Peakedness of the exponential component	0.38 ± 0.24°	0.3	0.5	0.15	0.3	0.22
ρ_2	Peakedness of the Gaussian component	1.2 ± 1.1 deg^2	0.6	0.1	1.2	1.2	0.3
x_2	*x*-axis eccentricity at which the Gaussian distribution peaks	0.70 ± 0.66°	1.3	0.7	1.3	1.3	1.2
x, *y*	Cartesian coordinates of eccentricity relative to centre of macula/radial diattenuator						

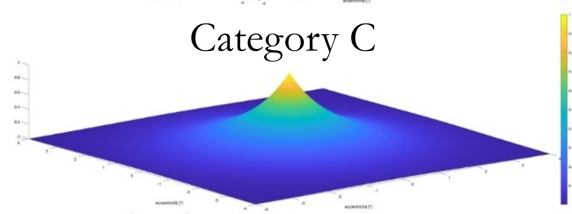
G. P. Mission, *et al.*, *JOSA* 35(6) 946-952 (2018)

Category B



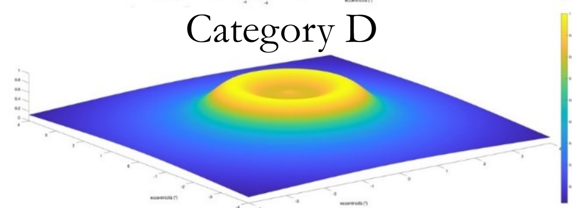
22%

Category C



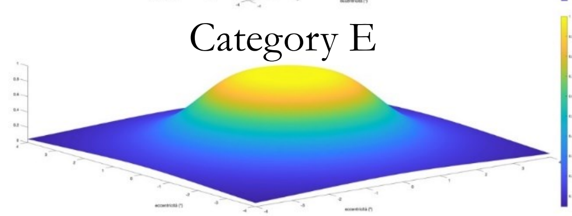
28%

Category D



17%

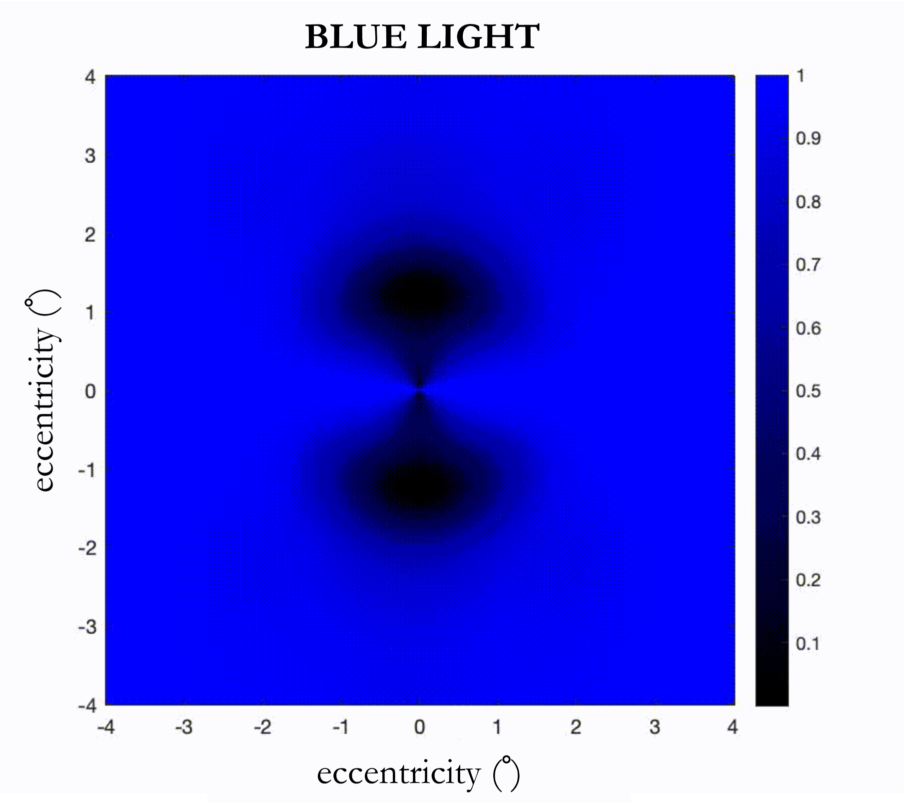
Category E



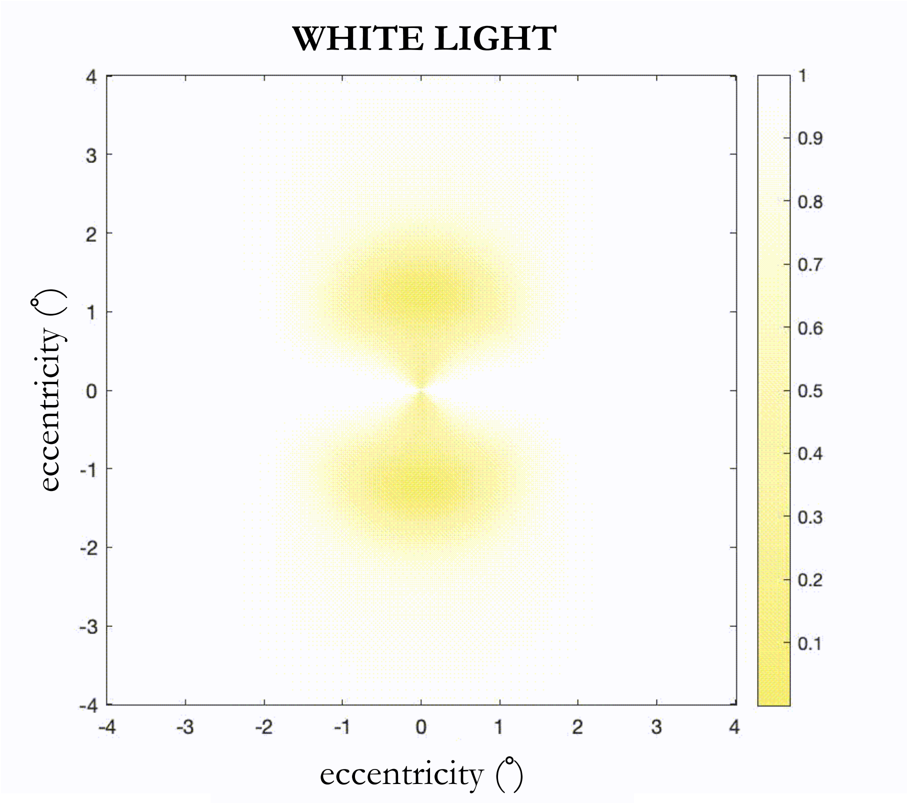
12%

Haidinger's brushes

The combination of all those effects gives rise to Haidinger's brushes formation:

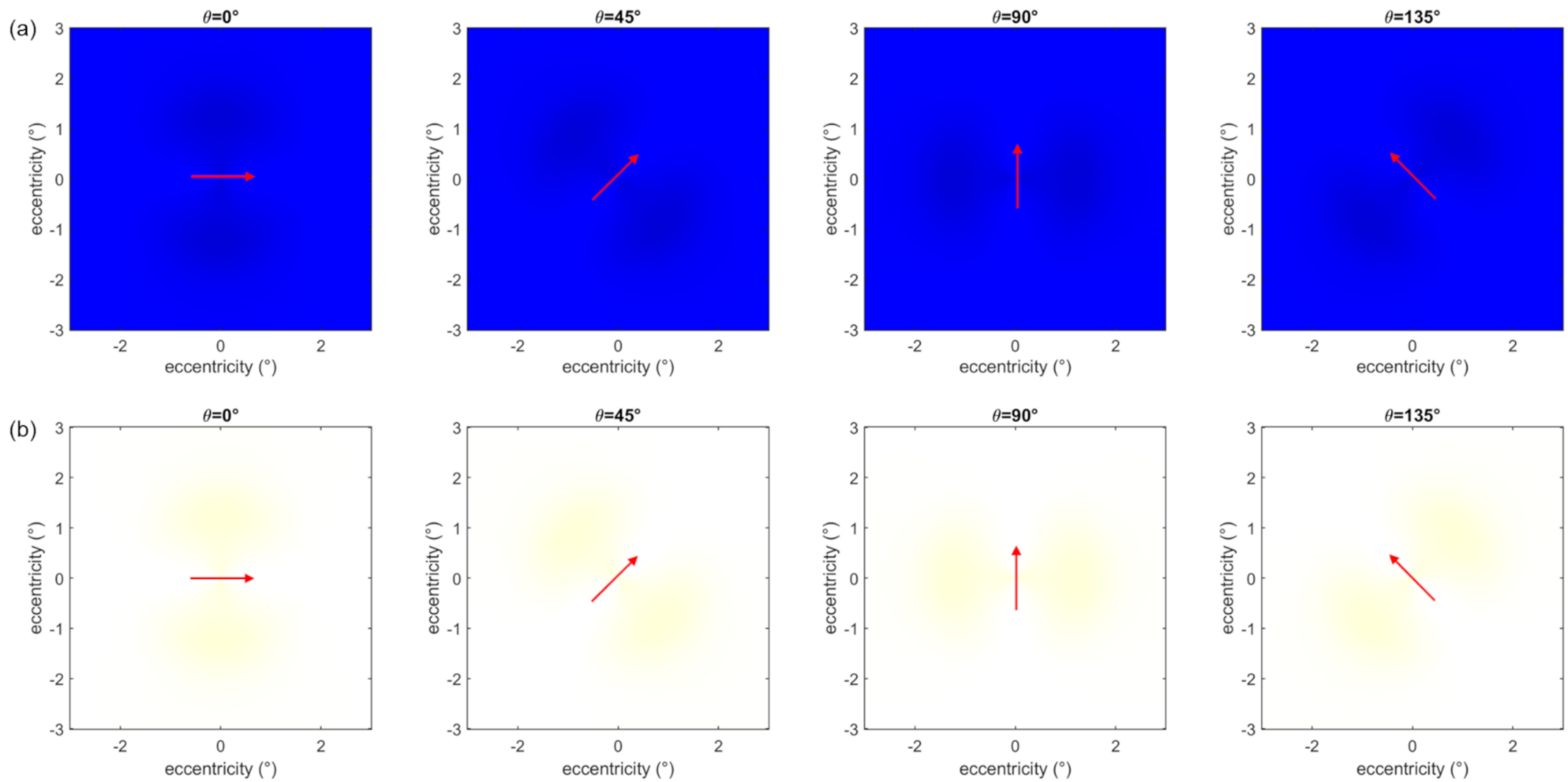


dark brushes over a blue background



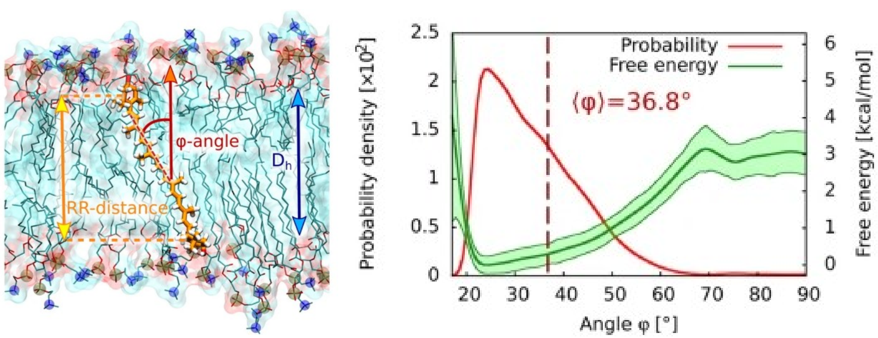
yellow (green+red) brushes
over a white background

More realistic simulations



The perceived constrast is lower since:

- a fraction of lutein molecules is randomly arranged
- peaked distribution of orientation around 25°
- non-negligible absorption also along the short axis



W. Grudzinski, *et al.*, *Sci. Rep.* 7, 9619 (2017)

Psychophysical study on HB perception

Psychophysical test to find out a normal value of perception threshold in a population of subjects not affected by macular diseases.

Research in the framework of the thesis of Dr. Jacopo Mottes: '*Haidinger's brushes: design and test of a setup for the phychophysical analysis of an entoptic effect*', degree in Optics and Optometry, A.A. 2020-21. Supervisors: G. Ruffato, D. Ortolan

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Haidinger's brushes: Psychophysical analysis of an entoptic phenomenon

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VisionOttica Award
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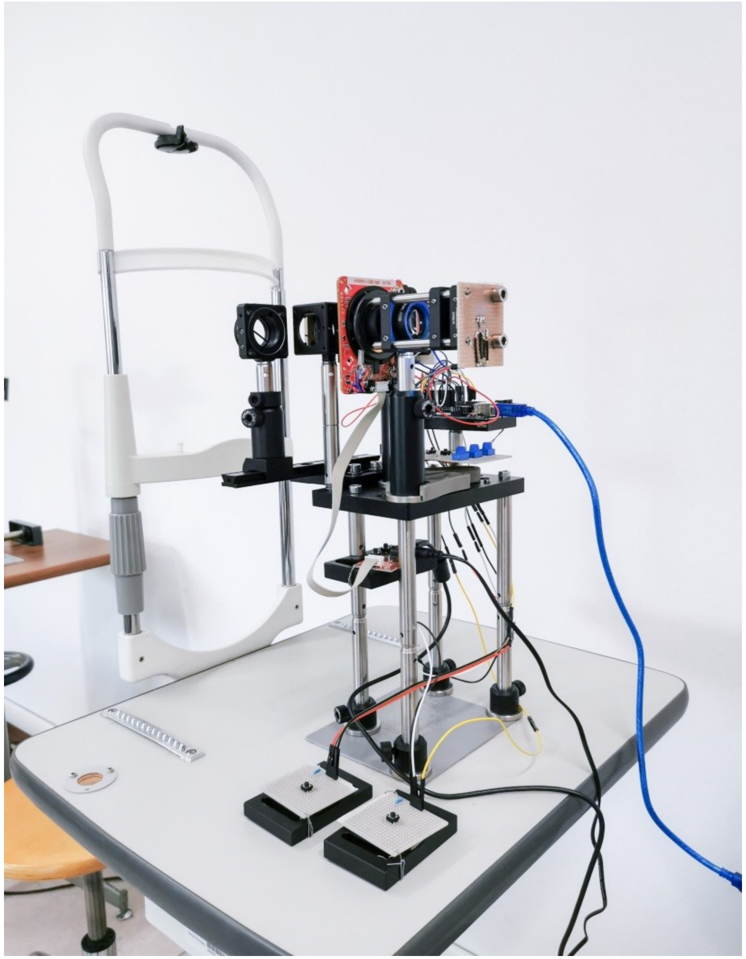
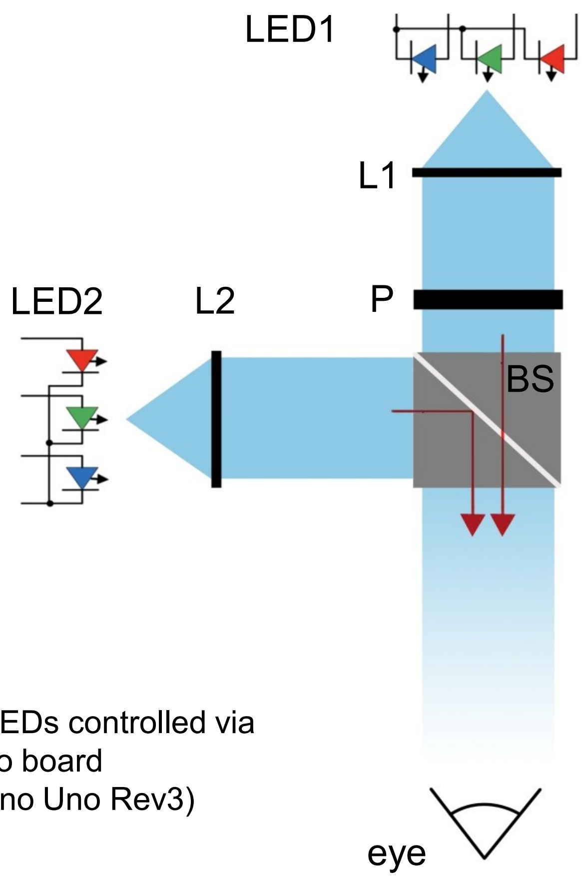
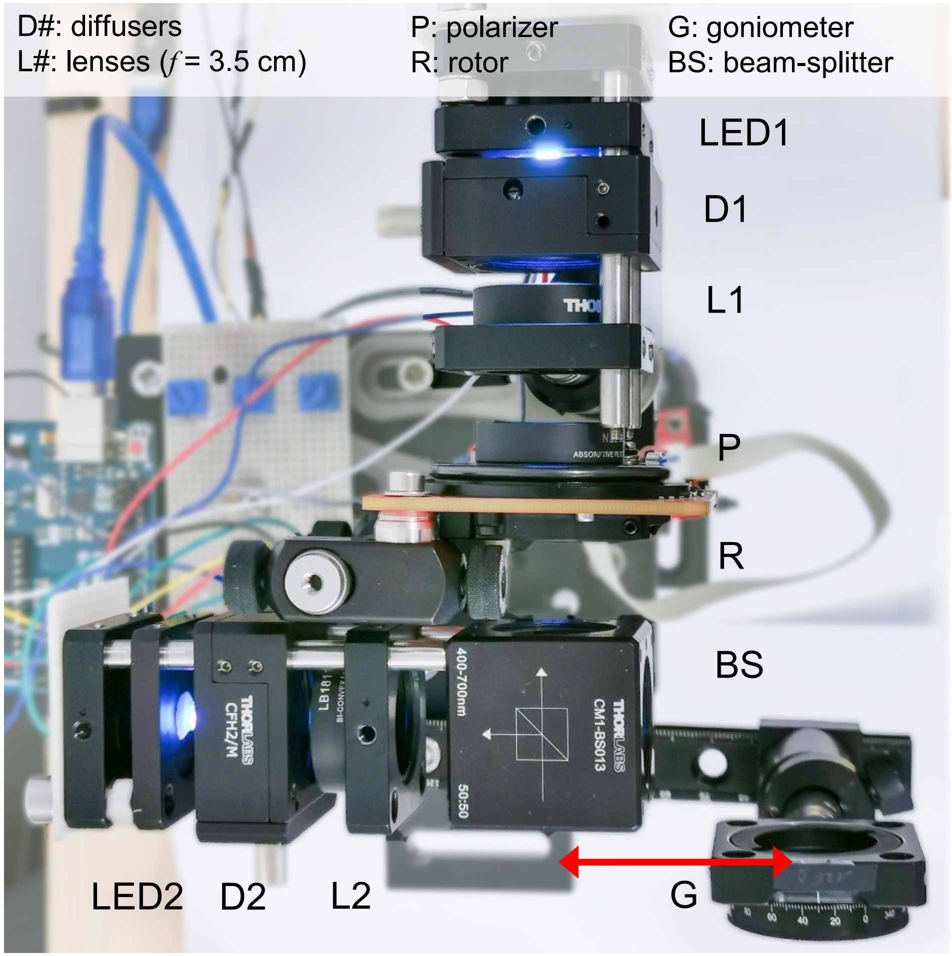


A setup to measure HB perception

Università degli Studi di Padova



RGB LEDs controlled via Arduino board (Genuino Uno Rev3)

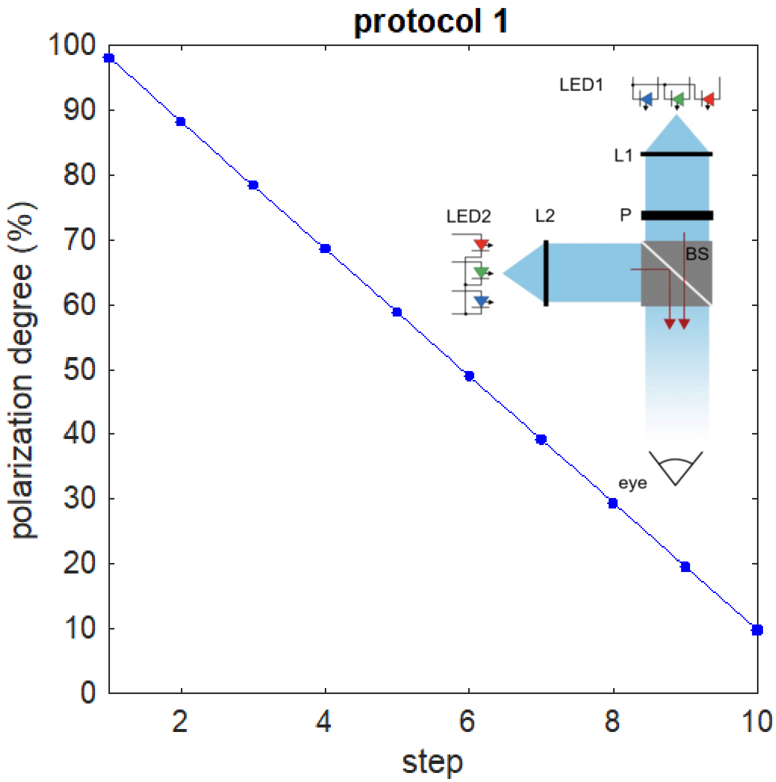


- Combination of two computer-controlled (Arduino board) RGB LEDs, with and without polarizer, to produce different degrees of polarization.
- Rotating polarizer to elude neural adaptation and keep the pattern perceivable.

Psychophysical test

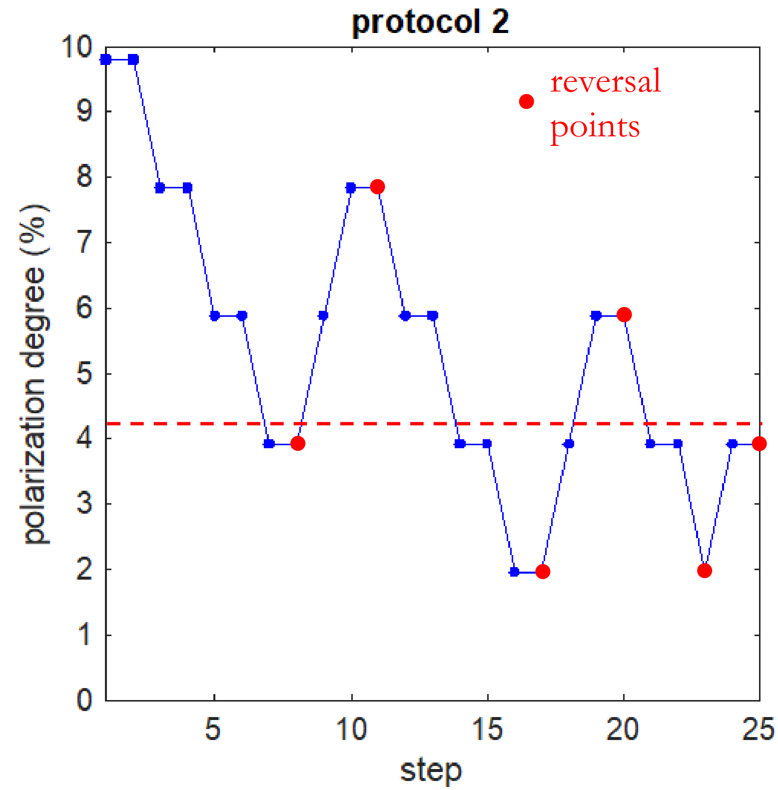
Test in blue light. 2 protocols in sequence, one eye at once:

descending method of limits



The polarization degree decreases at steps of 10% until the HB pattern is no longer perceivable

staircase one-up two-down



The user is asked the rotation direction: +2% when wrong answer, two right answers to trigger a reversal (-2%)

Tests in blue light

Università degli Studi di Padova

Population of 113 healthy individuals:

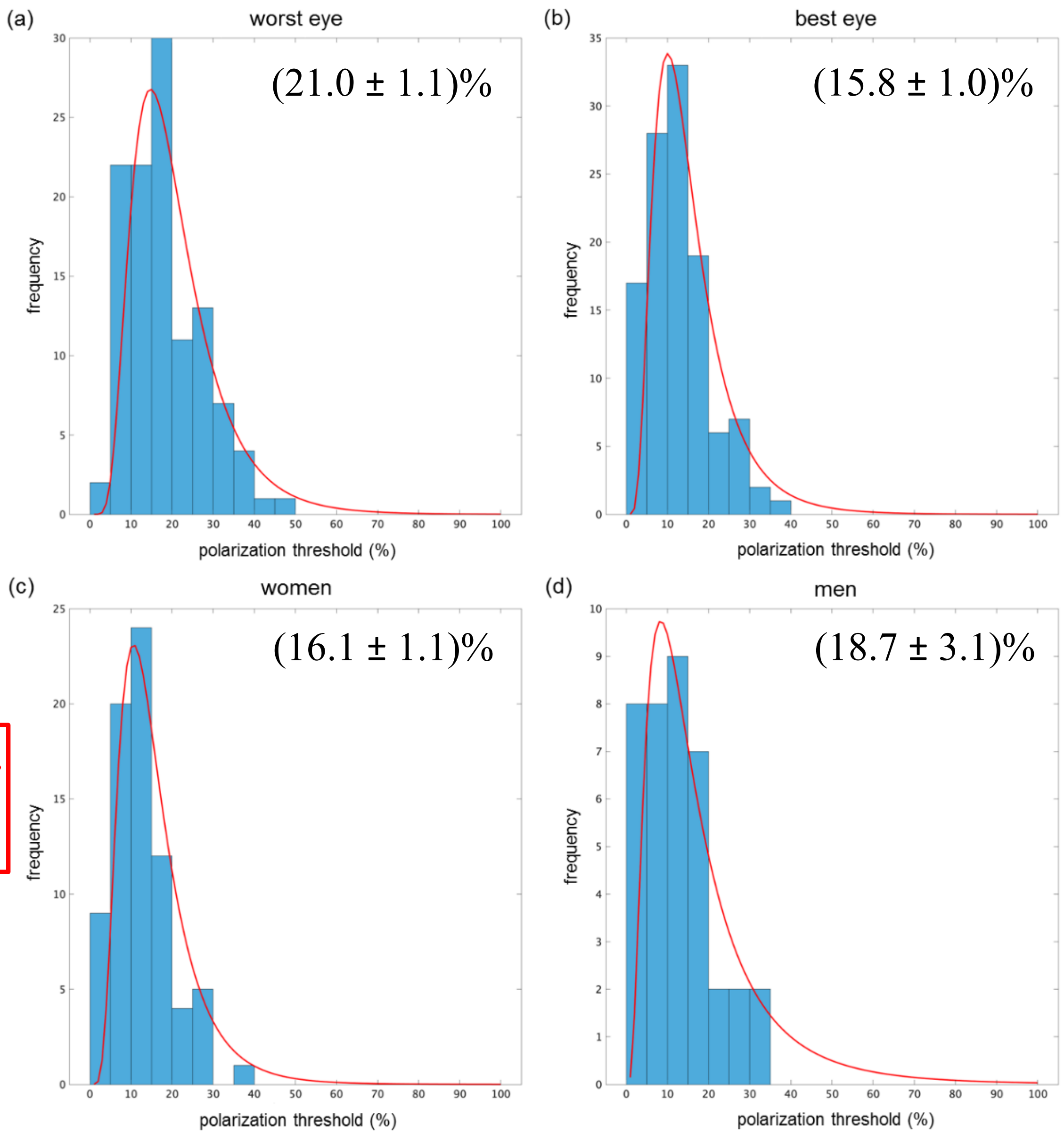
- age 6 -77 years old (average 30)
- 33.6% men, 67.4% women
- no macular diseases

Fits with a *log-normal* curve:

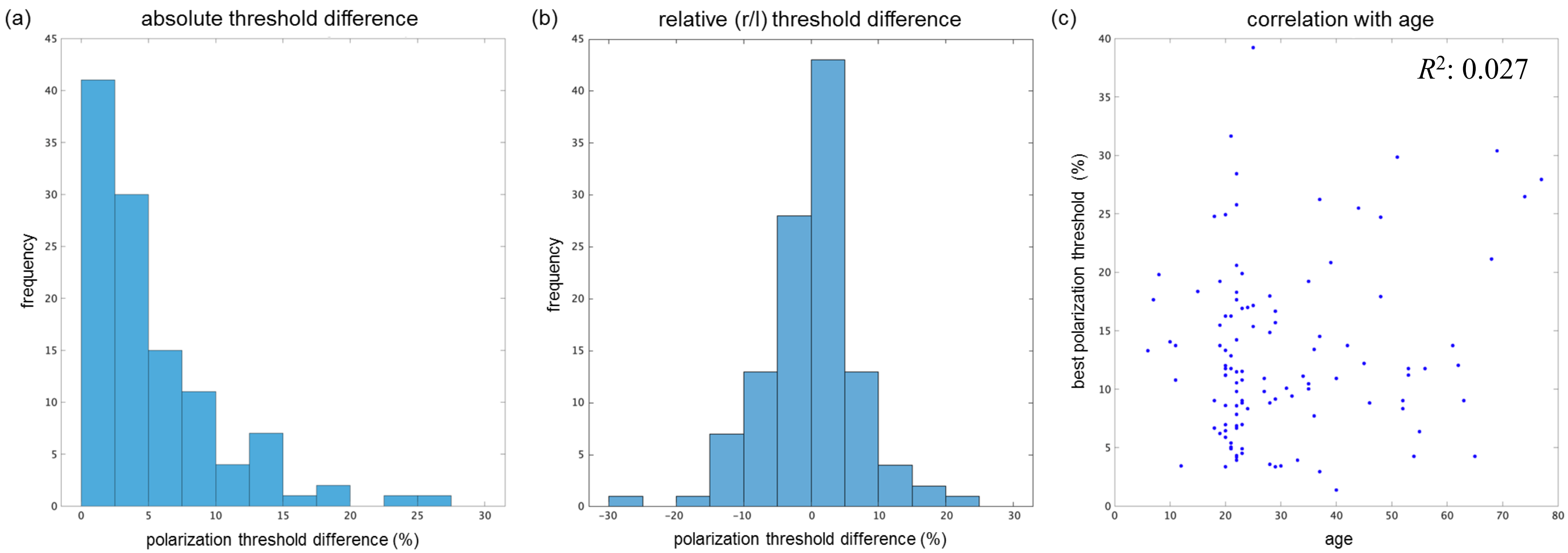
$$f(x)=\frac{1}{\sqrt{2\pi}\sigma x}e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}}$$

Polarization degree threshold for the best eye: (15.8 ± 1.0)%

J. Mottes, D. Ortolan, and G. Ruffato, *Haidinger's brush: psychophysical analysis of an entoptic effect*, *Vision Research* **199**, 108076 (2022)

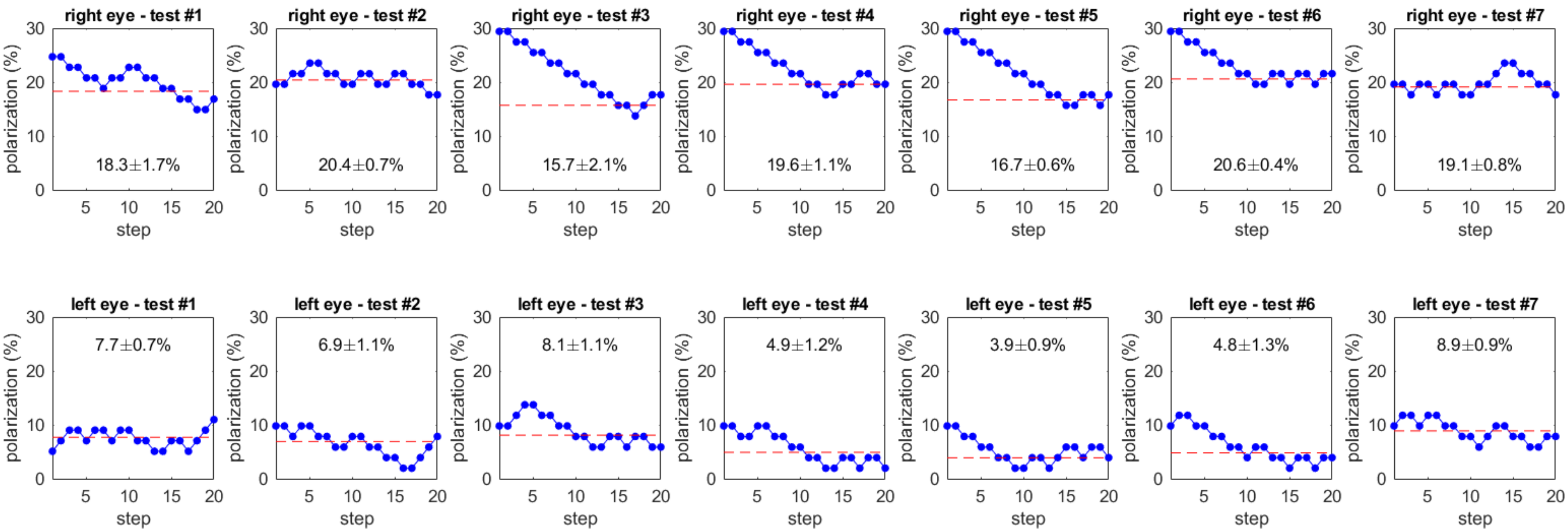


Tests in blue light



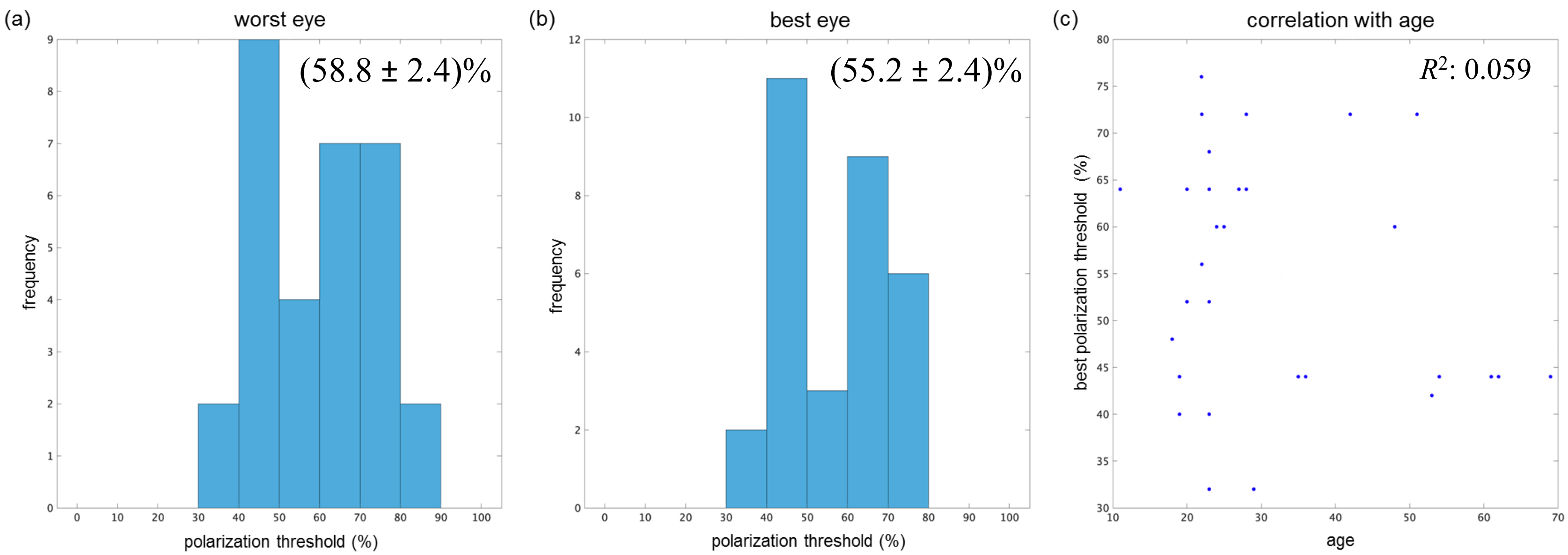
- No correlation with sex, age, or refractive errors
- Difference between the two eyes, but learning effect to be considered (right eye first)
- Only 29% of the tested individuals reported the best performance with the dominant eye (right eye for 69%) (other types of dominance should be considered)

Test-retest reliability



- Good test-retest reliability
- 25 trials per test: reasonable compromise between average number of reversals and total time of the test to prevent afterimages and eye fatigue

Tests in white light

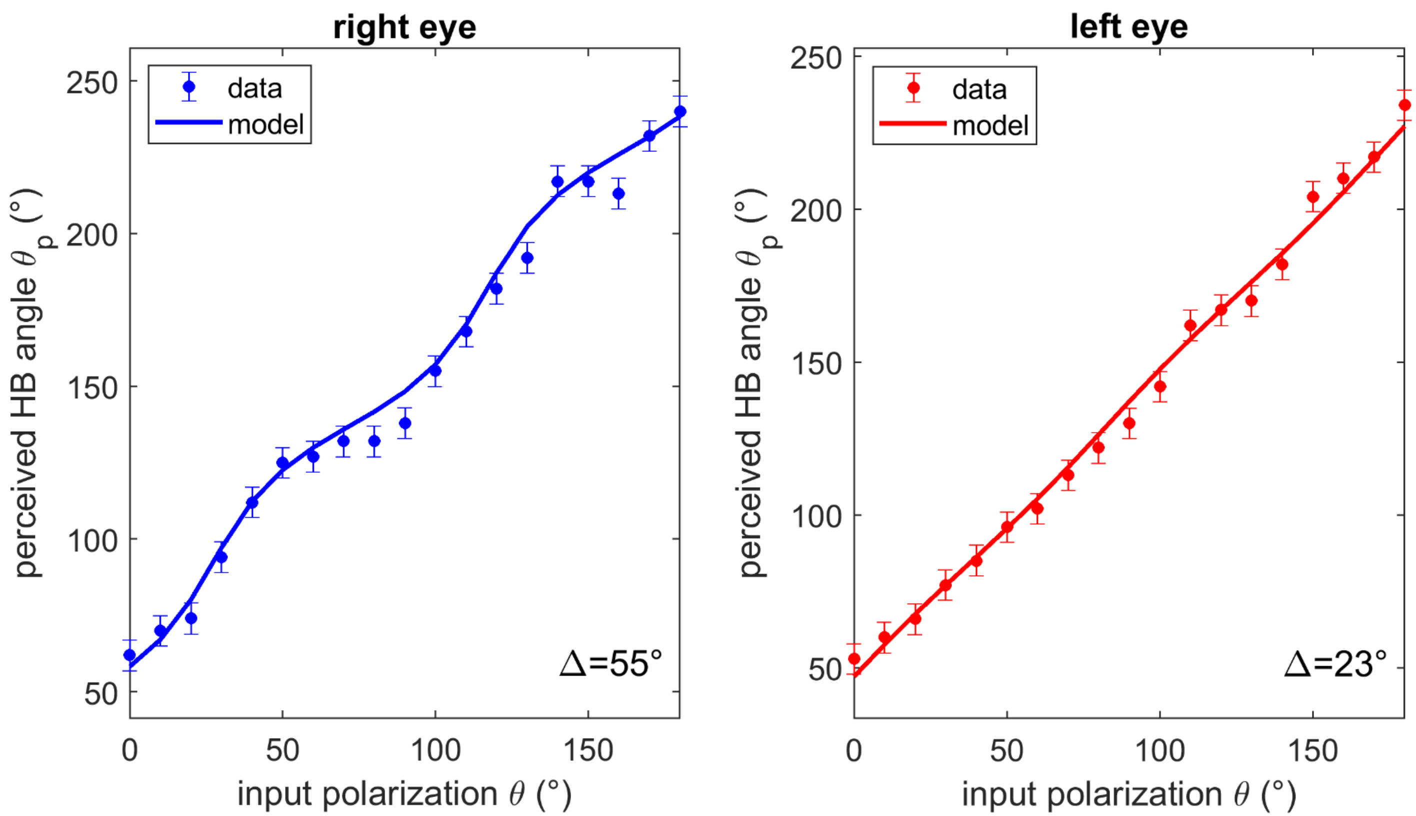


- Subset of the previous population: 31 subjects from 11 to 69 years old (average age of 32), 45.2% men, 54.8% women
- Average thresholds: **best eye (55.2 ± 2.4)%**, worst eye (58.8 ± 2.5)%
- No correlation with sex (M: 51.9±2.1%, W: 56.9±2.6%), age, or refractive errors
- Difference between the two eyes lower than 12%
- Only 48% of the tested individuals recorded the best performance with the dominant eye

Effect of corneal birefringence

Corneal birefringence introduces a deviation of the perceived polarization angle with respect to the input one:

$$\theta_p = \frac{1}{2}\arccos\left(\frac{\cos\left(2\left(\theta+\theta_0\right)\right)}{\sqrt{1-\sin^2(\Delta)\sin^2\left(2\left(\theta+\theta_0\right)\right)}}\right)-\theta_0$$



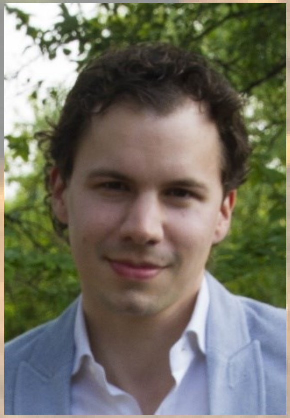
The retardation value can be different for the two eyes.

Rothmayer M, *et al*. *Appl. Opt*. **46**, 7244-7251 (2007)

Conclusions and perspectives

- The human visual system can perceive the degree of polarization of light with a low average threshold: 16% in blue light (maximum contrast) in healthy individuals. 55% in white light.
- HB is an entopic phenomenon arising from the filtering of linearly-polarized light by the radial dichroism of Henle's fibres in the fovea
- The dichroich behaviour and spatial arrangement of macular pigments play a key role in the phenomenon
- The developed setup can provide quantitative estimations of the perception of the phenomenon (polarization degree threshold) and of the corneal birefringence
- HB suggests a fast, economic, and non-invasive method for the early diagnosis of macular degeneration and other macular diseases or visual anomalies
- Next step: analysis on patients affected by macular degeneration, lens opacity, etc. to prove the expected correlation with a higher threshold in polarization-degree perception
- The setup is now one of the experimental activities at the Physics Laboratory of the degree in Optics and Optometry at the University of Padova

Thanks for your kind attention!



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