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

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Summary. — Entoptic phenomena are visual artifacts arising from the interaction of light with the specific physical structure of the eye. Among the most famous ones, the phenomenon of Haidinger's brushes consists in the perception of a subtle bow tie in the presence of linearly polarized light, and it is originated by the peculiar spatial distribution of dichroic carotenoid molecules forming a sort of embedded radial polarizer in the macula. We have developed a compact versatile optical setup for the psychophysical analysis of the perceptual threshold of this entoptic effect. The tests on a group of 113 healthy individuals under conditions of maximum contrast (blue light) reveal the human capability to perceive an average polarization degree around 16%. The same analysis in white light suggests a polarization sensitivity around 55%. The developed prototype outlines a new platform to train the user in the perception of polarization and can help infer the physiological conditions of macular pigments in the fovea.

1. – Introduction

While the perception of polarization is diffused among many animal species for orientation, navigation, and biological signalling, human beings are commonly believed to be insensitive to this property of light [1]. In 1844, the Austrian physicist Wilhelm von Haidinger described for the first time the perception of a tiny yellowish bow tie observing the blue sky at 90° with respect to the sun, in the directions where the diffused light is maximally polarized [2]. The perceived pattern subtends a visual angle of 3° around the fixation point , and it is oriented perpendicularly to the polarization plane. Due to the adaptive mechanism negating fixed retinal images, the pattern vanishes in a few seconds, unless the eyes are rotated around the primary visual axis, *e.g.*, tilting the head side to side. Actually, the figure is not originated by an external object, but it is an entoptic

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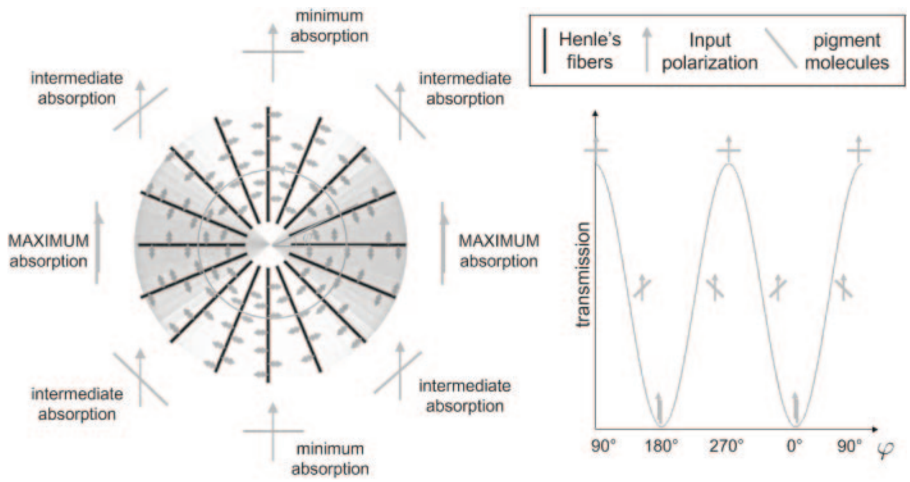

Fig. 1. – Scheme of the Henle's fibres radial configuration and distribution of the dichroic macular pigments in the fovea. The result is a radial polarizer for blue light: the transmitted intensity exhibits a periodic trend as a function of the azimuthal angle, depending on the direction of the input polarization plane with respect to the macular pigment orientation.

phenomenon, arising from the interaction of light with the anatomic structure of the human eye. In order to understand the formation of the so-called Haidinger's brushes, two key points must be considered. First of all, the strong dependence on the colour: the brushes are dark in blue light, while they disappear in green and red light, so that they form yellow in white light. Then, a similar pattern can be obtained by filtering linear polarization by using a radial polarizer. This seems to suggest the presence of a sort of radial polarizer for blue light inside our eye.

Indeed, during the ontogenesis of the fovea, the opposite migration of ganglion cells peripherally and cones towards the center results into a stretching and radial distribution of cones axons, the so-called Henle's fibres, which assume a radial configuration as the spokes of a wheel (fig. 1) [3]. This region of the eye is rich in antioxidant and protective macular pigments of dietary origin, such as lutein and zeaxanthin, having a high absorption for the blue light peaked at 458 nm [4]. Their long molecules induce a dichroic optical behaviour, absorbing more efficiently light which is polarized parallel to the long axis, *i.e.*, when the direction of the electric field is parallel to the molecule. Macular pigments are lipophilic and tend to orient perpendicularly to the lipidic membranes of the Henle's fibres, which are in turn arranged radially. The overall result is a radial polarizer for blue light in the fovea.

In case of linearly polarized light in input, the absorption is maximum when the polarization direction is parallel to the molecules and minimum when perpendicular, then the transmission will exhibit a periodic trend as a function of the azimuthal angle with a period of π (fig. 1). The density of macular pigments follows a distribution which decreases in the radial direction [5], limiting the pattern to a visual angle of about 3°. The combination of all those effects gives rise to the perception of dark brushes perpendicular to the polarization plane over a blue background (fig. 2(a)), while in white light the brushes are yellow due to the mixture of green and red which are basically unaffected by pigment absorption. Actually, the perceived contrast is lower, since a significant amount

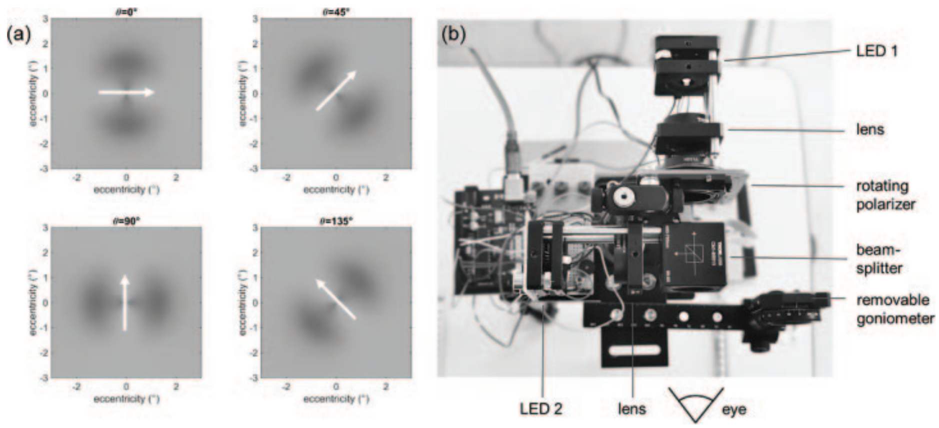

Fig. 2. – (a) Simulation of Haidinger's brushes perceived pattern in blue light: a faint dark bow tie appears, oriented perpendicularly to the polarization direction. (b) Picture and details of the assembled optical setup for the psychophysical tests: two LED sources are collimated by two converging lenses (focal length 3.5 cm) and combined using a 50:50 beam-splitter. One of the two sources is polarized with a linear polarizer mounted on a rotating goniometer.

of pigments are arranged randomly and there is a non-negligible absorption also when the electric field is parallel to the short axis of the molecules [6].

In this work, we present the development of a compact and versatile device which allows the user to perceive the formation of Haidinger's brushes under different conditions and conduct psychophysical tests to quantify his/her sensitivity to the polarization degree of light. In particular, the results of the tests are considered to provide a reliable estimate of the average perceptual thresholds in healthy individuals.

2. – Experimental setup and protocols

In order to obtain an estimate of the human sensitivity to the polarization degree of light, we designed and tested an optical setup to measure the perception of Haidinger's brushes [7]. As shown in fig. 2(b), two distinct LED sources are collimated and combined in the observer's eye using a 50:50 beam-splitter. One of the two arms is polarized using a linear polarizer (LPVISE100-A, Thorlabs) mounted on a rotator (ELL14K, Thorlabs), in order to keep the pattern perceivable by preventing neural adaptation. The colour and relative intensity of the two sources are controlled using a programmed ARDUINO board. A manual rotating goniometer, removable from the optical path, is also present for corneal retardance analyses.

We conducted a psychophysical analysis with two protocols in sequence. In fig. 3 we report the data for a subject referring to the first (a) and second (b) protocols. In the first stage (fig. 3(a)), the contribution of the polarized source is decreased by steps of 10% in polarization degree until the pattern is no longer perceived, while keeping constant the total intensity of the two sources. Then, the last perceived value is used as the starting point for the second protocol. In the second part (fig. 3(b)), the user is asked the rotation direction: if the answer is wrong, the polarization degree is increased by 2%, otherwise it is decreased by the same amount after two right answers in sequence. Finally, the average of the reversal points provides an estimate of the perceptual threshold. The

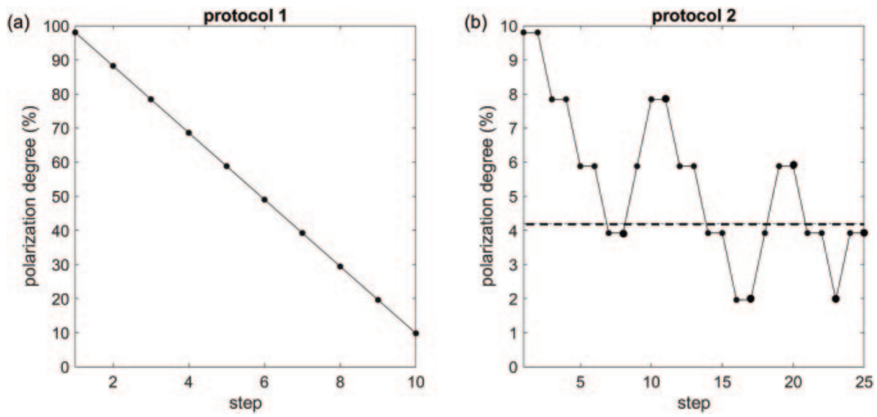

Fig. 3. – (a) Plot obtained from the analysis of the right eye of an examined subject during the first protocol in blue light. (b) Data of the same subject (right eye) during the second protocol (staircase method one-up two-down). The estimated threshold value ($4.2 \pm 0.9\%$, dashed line) is obtained from the average among the reversal points including also the last value.

system exhibits a good test-retest reliability for repeated measures in different days and under different illumination conditions. We decided to fix the number of total trials to 25 per eye, in order to find a good compromise between the number of reversals and total time of the test. A longer time would promote eye fatigue and the formation of afterimages.

3. – Results

The study was performed on a population of 113 healthy individuals, without any macular disease, with different sex (33.6% M, 66.4% W) and age (6–77, average 30). This is the largest analysis ever performed under high-contrast conditions. All the participants were recruited after explanation and informed consent. The research was carried out in accordance with the Declaration of Helsinki. In fig. 4(a) the distribution of the polarization threshold is reported for the best eye of each individual under test. The data set is not symmetric and well-fitted by a *log-normal* distribution. The results showed an unexpected high sensitivity of human beings to the polarization degree of light, with an average threshold around 16% (fig. 5(a)). Averages for blue light: best eye (15.8 ± 1.0)%, worst eye (21.0 ± 1.1)%, men (18.7 ± 3.1)%, women (16.1 ± 1.1)%. No significant correlation with sex, refractive errors, or age (Pearson's correlation coefficient $\rho = +0.16$) came to light from the tests. There can be a slight difference in the polarization threshold between the two eyes of the same subject, as shown in the distribution in fig. 4(b) showing the difference between the right-eye and left-eye thresholds. While the centroid of the Gaussian fit is compatible with zero ($\mu = 0.3 \pm 0.5$), its positive value, due to the slight asymmetry of the distribution, could suggest, on average, a better performance for the left eye. In particular, only for the 29% of the tested individuals we found a coincidence between best eye and pointing dominance. However, the right eye was always the first tested, then we could consider a learning effect, or maybe other types of dominance could be more significant in the perception of the phenomenon. In addition, a difference between the two eyes can be due to a different corneal retardance [8].

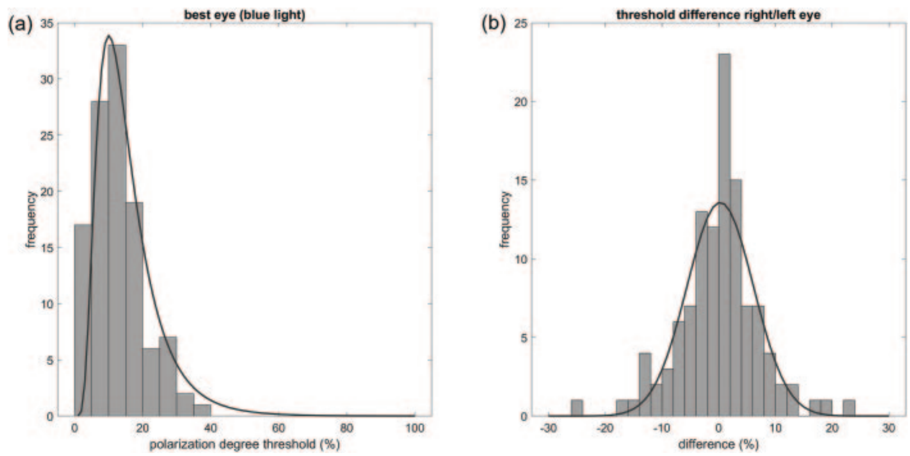

Fig. 4. – (a) Distribution of the polarization degree threshold for the best eye of the population under test. The data are well-fitted by a *log-normal* distribution. (b) Difference in polarization degree threshold between right and left eyes and normal fit.

Then, tests in white light were performed on a subset of 31 subjects of the previous population (age 11–69, men 45.2%) using only the first protocol, since the pattern becomes more challenging to perceive. Averages for white light: best eye (55.2 ± 2.4)%, worst eye (58.8 ± 2.5)%, men (51.9 ± 2.1)%, women (56.9 ± 2.6)%. Again, there was no significant correlation with sex, age ($\rho = +0.24$), or refractive errors. Around 48% showed the best performance when using their dominant eye. The constrast in white light is lower than in blue light, and the average best polarization threshold turned out to be around 55%, in good agreement with other studies [9] (fig. 5(b)).

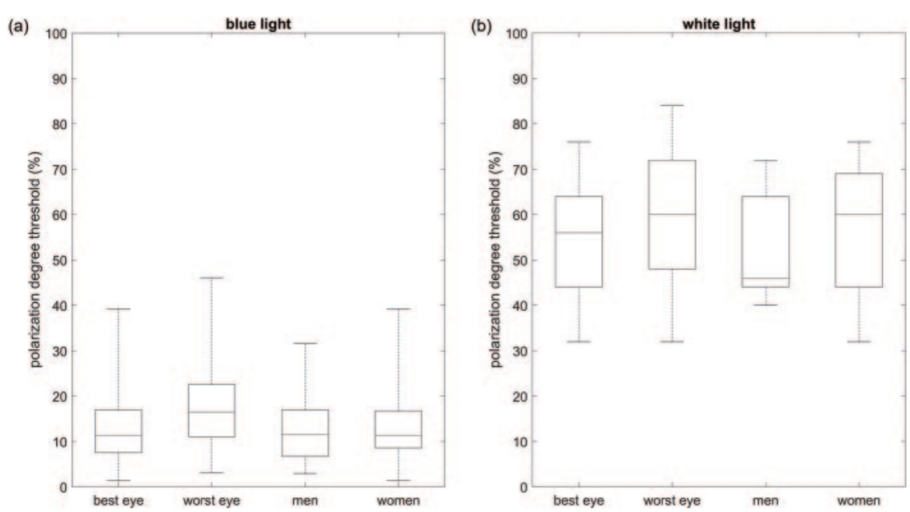

Fig. 5. – Box plots of polarization degree thresholds of the groups under test for analysis in blue light (a) and white light (b).

4. – Conclusions

To conclude, the human eye is sensitive to the polarization degree of light thanks to the perception of an entoptic phenomenon, the so-called Haidinger's brushes, which arises from the filtering action of linearly polarized light by the built-in radial polarizer for blue light embedded in the fovea. The developed setup allows training the user in the perception of the phenomenon and infer an estimate of the polarization degree threshold by performing a psychophysical test. Tests conducted on a population of healthy individuals revealed an average polarization degree threshold around 16% in blue light and around 55% in white light. While the effect is too subtle to enable additional visual capabilities, on the other hand it can provide information on the physiological conditions of the foveal region [10]. As a matter of fact, since a correct perception of the pattern is related to the distribution of macular pigments [11, 12], the setup can suggest a fast, economic, and non-invasive method for the indirect analysis of their density and conditions.

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