Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Colours: Human Vision and Surroundings

To cite this article: Vera Montalbano and Daniela Marchini 2021 *J. Phys.: Conf. Ser.* **1929** 012012

Colours: Human Vision and Surroundings

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Abstract. We propose interdisciplinary teaching-learning sequences focusing on colours. How do we perceive colours? How do animals perceive it? How do some animals make unusual coloured liveries? The proposal was initially tested with high school students in a summer school, then it was discussed in a summer school for science teachers in order to enhance the interdisciplinary aspects. Finally, it was proposed and discussed in a training event for in-service science teachers. Involvement and motivation in the learning process were the main reactions expected and the forecasts were fully achieved.

1. Introduction
Interdisciplinary topics are usually more effective in teaching because they are able to arouse greater interest and motivate students [1-2]. Rarely, however, they are proposed in didactic practice especially when the skills of teachers of two different scientific subjects are needed.
The main difficulty lies in the fact that science teachers have had no experience of interdisciplinary learning paths [3] neither in their university studies nor in their initial training. For this reason, in the last years, we have been promoting the designing and implementation of interdisciplinary learning sequence involving teachers of different subjects.
Colour vision is a fascinating subject that lends itself to many interdisciplinary studies. Presenting the point of view of the physicist and that of the biologist enriches the understanding of the topic, while the four-handed presentation allows to focus the attention of the teachers on the conceptual knots of the two disciplines.
During the last decade, we realized several professional development programs for teachers in Physics and Mathematics in order to promote fundamental changes in their practice. Our activities were directed to teachers living in southern Tuscany (provinces of Arezzo, Grosseto, and Siena). Since 2016 a national summer school *Science in 4D* for qualified in-service science teachers was realized by choosing a relevant topic in science in which to develop new laboratories in an interdisciplinary way. The theme discussed in the summer school 2018 was the colour, starting from some laboratories developed and tested with students in a previous physics summer school (in figure 1 the participants to the physics summer school on colour are shown).
In the summer school *Science in 4D*, an interdisciplinary learning path was proposed by merging the key ideas of physics and biology on colour in order to better exploit the educational ideas developed in the laboratories and a better understanding of what colour is, how we perceive it, how it can be perceived

otherwise, how it is possible to observe in nature even very bright or changing colours also using homogeneous and sometimes black materials.
We present the final version of the teaching-learning path on colours like it is proposed to in-service teachers. It is articulated in three parts: human colour perception, animal perception and unusual liveries in animals.

Figure 1. Students and teachers during the physics summer school on colours, where we tested some activities.

All activities are performed and supported by the Italian National Plan for Science Degrees in order to foster student enrolment in basic sciences by promoting active laboratories and professional development of science teachers [4-5].

2. Human Colour Perception

The starting point is: what we need in order to see something? Usually students, and sometimes teachers too, forget that light is necessary for seeing. But the most part of materials in normal conditions does not emit light. The next step is to understand how light interacts with the organ of sight, i.e. the eyes. Anatomy and physiology of the eyes are revisited following the physical processes that govern the vision: eye as a *camera obscura*, absorption of photons that have not been transduced by the retina from melanin to reduce the background noise of vision, transduction of light energy into an electrochemical signal that can be transmitted from the optic nerve to the brain. The organs responsible for transduction are cones and rods that interact with the light in very different ways. The cones respond differently to the light of different wavelengths. Moreover, other singular aspects of the vision can be used for a deeper insights: colours that do not exist or how light intensity can affect the perception of colours.

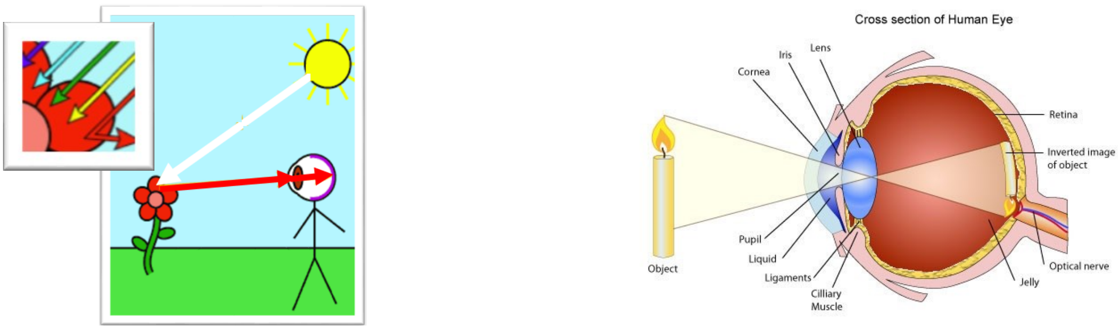

Figure 2. On the left, a very schematic drawing is shown how light interacts with materials, absorbing some frequencies and scattering others. On the right, the eye described as a dark room.

2.1 From light and matter to the human eye anatomy

The path begins with the light that interacts with matter, distinguishing the light sources from the materials that interact with the light and scatter it. The following step is to understand how the light interacts with the eye. First, it enters the eye that works like a *camera obscura,* i.e. a dark room, where the image is focused on the area most sensitive to light, namely the retina (see figure 2 where some materials proposed to teachers are shown).

Anatomy and physiology of the eye is introduced with the aim of understanding the relationship between the physical properties of light and the structures that make up the organ dedicated to vision (binocular vision, lens, photoreceptors, etc.).

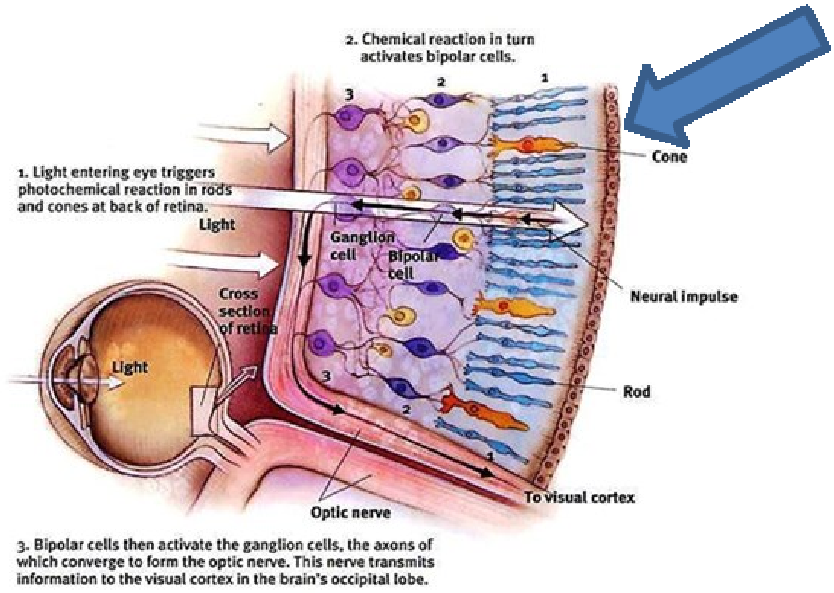

Figure 3. A figure from a textbook [6] where the direction of the light towards the photoreceptors is clear and the flux of the electrochemical signal after the transduction in the retina is indicated. The blue arrow indicates the choroid where the melanin is concentred.

2.2 Exploring photoreceptors: physics and biology

Usually, textbooks are not very clear about the direction from where the light arrives on the photoreceptors on the retina. Starting from a clear figure found in a textbook (shown in figure 3), it is possible to understand the role of melanin in the choroid, the vascular layer of the eye, containing connective tissues, and lying between the retina and the sclera. Melanin is a dark coloured pigment and

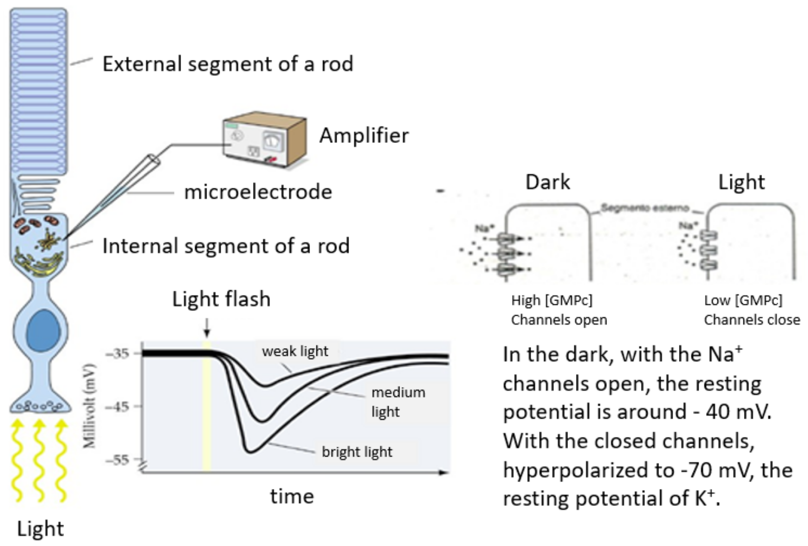

Figure 4. Photoreceptors transduction from a light pulse to an electro-chemical pulse: the rod reaction to light of different intensity [7].

helps the choroid limit uncontrolled reflection within the eye that would potentially result in the perception of blurry images.
In humans and most other primates, melanin occurs throughout the choroid. In albino humans, frequently melanin is absent and vision is low. The uncontrolled reflection of light from dark choroid produces the photographic red-eye effect on photos. absorption of photons that have not been absorbed by the retina from melanin to reduce the background noise of vision.

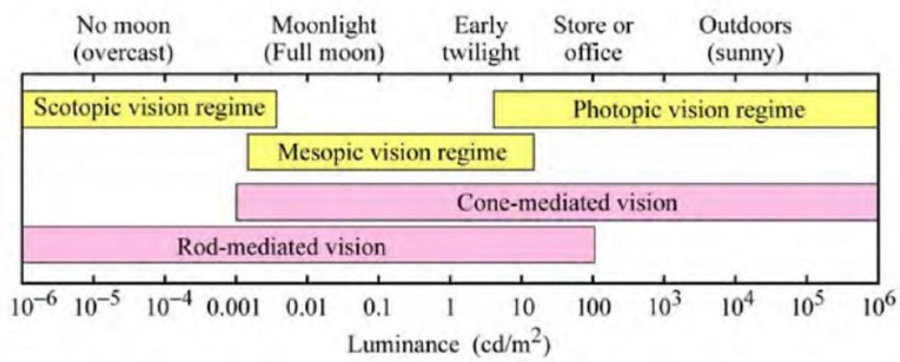

Figure 5. Sensitivity range for human visual system [8]. The Purkinje effect is the tendency for the peak luminance sensitivity of the eye to shift toward the blue end of the colour spectrum at low illumination levels as part of dark adaptation. Depending on the intensity of the light, day (photopic), night (scotopic) or mesoscopic vision will be active.

The key idea is the transduction of light energy into an electrochemical signal that can be transmitted from the optic nerve to the brain (see figure 4). The organs responsible for transduction are cones and rods that interact with the light in very different ways. The cones respond differently to the light of different wavelengths. The interpretation of the brain to the light stimulus sometimes leads to colours that do not exist (i.e. that do not have the correct relationship between energy and wavelength in a monochromatic wave, white and black are the most famous cases) or light intensity can affect the perception of colours (Purkinje effect, described in figure 5 and 6).

Figure 6. A flower in photopic, mesoscopic and scotopic vision [9].

Dark adaptation and sensor sensibility is an aspect that can be used for engaging students (see for example figure 7). The dark adaptation is important for explaining the pupil's changes and that the number of stars that it is possible to distinguish in a dark night depends on how long the eyes stay in the dark (figure 8).

Figure 7. The intensity of light plays a central role in the brain's choice of colour [10]. In this case, about 2/3 of people see the dress gold and white (or pale celeste) and 1/3 see it black and blue (the colours when fully illuminated).

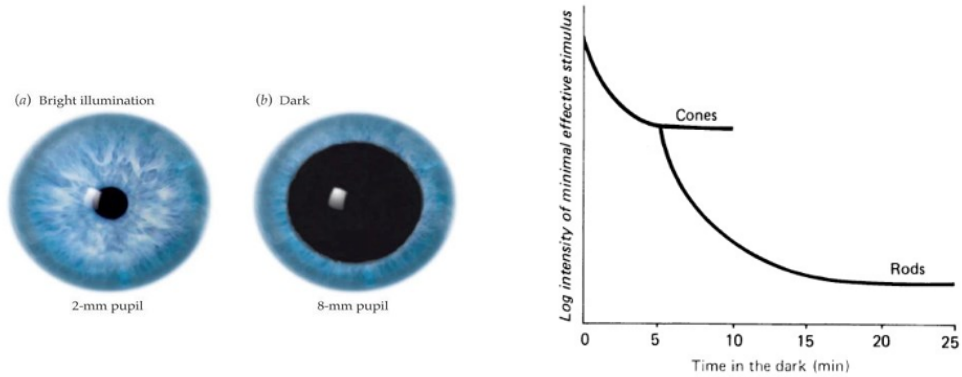

Figure 8. The intensity of light reaching the retina can be changed by adapting the pupil. On the left, it is shown the maximum and the minimum opening of the pupil [7]. On the right, the visual response of biosensors to darkness. Cones work at high light levels (during the day but also during driving at night in the headlamp spotlight); rods take over at twilight and night. Moreover, they need more time into darkness for recovering their initial state [7].

Finally, photoreceptors are compared to biosensor devices from a physical point of view (in figure 9 the materials prepared for discussing the comparison).

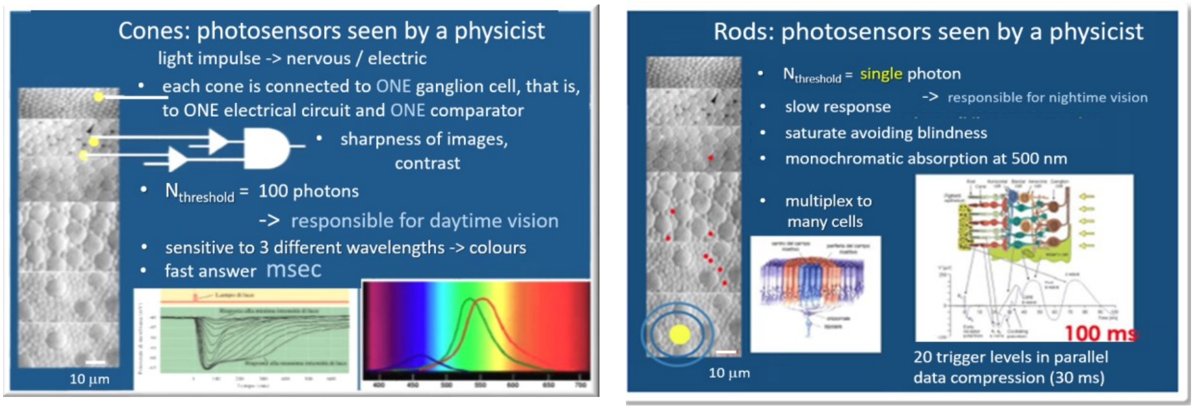

Figure 9. On the left, the summary of cones performance as biosensor device is shown. The same summary for rods is shown on the right [11].

3. Animal Perception

Animals perceive light and colors often differently from us. From the vision of the dog to that of the snake, from bees to birds, some species have a greater or lesser number of sensors with maximum sensitivity in visible light, while others perceive electromagnetic waves outside the visible wavelength region.

In the animal world, mammals have different visual characteristics that differ according to the skeletal conformation, life habits, and survival needs, becoming a specific attribute of each species. Humans have three types of cones in the retina and their vision is called trichromatic with a reduced presence of rods which implies a poor night vision; monkeys and primates generally also have a trichromatic vision even if they are sensitive to wavelengths slightly different from those of the humans. Many other mammals have only two types of cones, one sensitive to short waves (blue/purple light) and the other sensitive to medium waves (green/yellow light) so their vision is called dichromatic. The dichromatic vision does not, therefore, allow to distinguish red and green.

Figure 10. On the left, the warm look of snakes: an IR vision. On the right, how a bee sees flowers: UV vision compared with the human one .

Other animals evolved with a vision with photoreceptors in a larger or narrow frequency range, not necessarily in the visible one (the visible range is defined as the one perceived by humans of course).
The infrared vision of the snakes or the UV vision of the bees are some examples (see figure 10 for simulations selected by students), up to the mantis shrimp [12] with 13 different sensors ranging from infrared to UV which can also distinguish the polarized light (a summary of the mantis shrimp is given in figure 11). This part of the learning path arouses great interest and involvement of the students because it expands their knowledge on the animal world in a direction that makes a physical property of light, the wavelength, relevant. Usually, they study it in physics but get a few relevant examples of applications in everyday life.

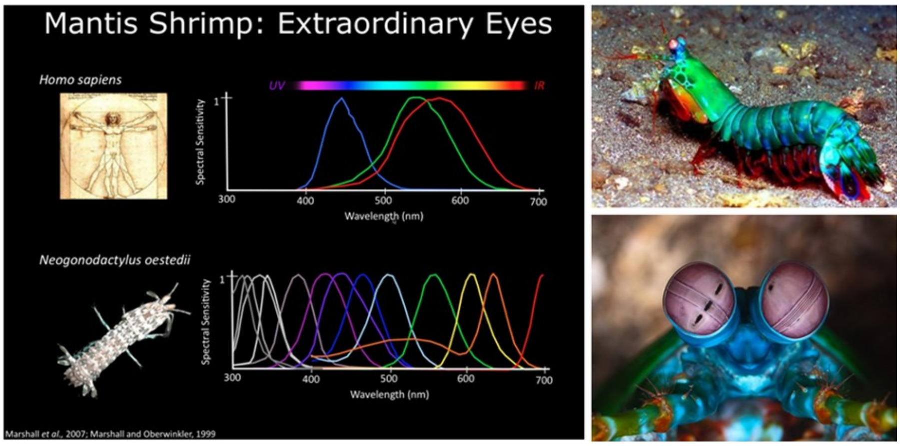

Figure 11. A comparison between human and mantis shrimp photoreceptors, communicated online by a newspaper [13].

4. Unusual Coloured Liveries

The colourful animal world that can be observed in nature can be realized in totally different ways. It ranges from cells (chromatophores) whose pigmented granules (which contain chromophores) can give rise to different colours with different concentrations, to non-pigmented structures containing melanin whose structure determines iridescent colours like in butterflies or peacocks. Also in this case anatomy, physiology, chemistry, and physics are necessary to understand how the colours of the liveries of living organisms are produced and sometimes how they change.

4.1 Chromatophores

The chromatophores are cells present in the dermis that contain numerous pigment granules. These granules can remain concentrated around the nucleus, resulting in a lighter or less uniform colouring, or expand into the cell giving darker or more uniform colour. This change in their disposition is activated in response to stimuli that ultimately change the position of the pigments. Chromatophores are present in amphibians, fish, reptiles, crustaceans, and cephalopods. In contrast, mammals and birds have melanocytes.

Figure 12. A colourful Blue Ram (*Mikrogeophagus ramirezi*) with all different chromatophores well visible.

The complex colours in fishes are due to the interplay of a range of pigment cells – yellow (xanthophores), red (erythrophores), white light (leucophores), and blue (cyanophores), like in the Blue Rams showed in figure 12. Melanophores produce black to brown colouration. Pigment cells expand and contract with animal behaviour, light levels, and the distribution of these cells changes as the fish age.

4.2 Interference more and more

The colour in the biological world is not only caused by the absorption of light by pigments, but also by other physical phenomena: interference, diffraction, and diffusion (scattering). In the latter case, we speak of structural colour since the interaction between light and microscopic structures is essential in the phenomenon. The peacock's plumage is the most famous example.

The first observation goes back to Newton who recognized in the iridescence something substantially analogous to the colouring of thin sheets.

The mechanisms that cause the structural colour of peacock feathers are the periodic microscopic structure of the melanin granules, which causes light interference and produces the resulting colour, and macroscopic structures, that play an essential role in distributing diffused light. Moreover, the absorption of the background light by the melanin pigment makes the colour due to interference very vivid. In fact, there are albino peacocks that, despite having the same microscopic and macroscopic structures in the feathers, are completely white due to the absence of melanin.

Butterflies, like the peacock, can have vivid colours due to a different structure acting as a diffraction grating in the wing, as shown in figure 13.

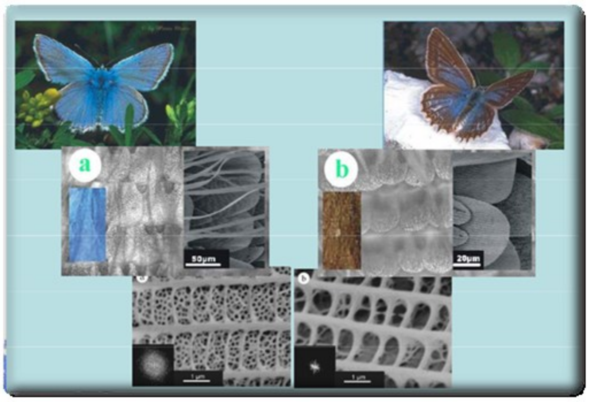

Figure 13. The blue and the brown butterflies have very different structures in their wings like show the scanning microscope pictures at the 1 μm scale.

The chameleon spectacularly changes colour, thanks to the tiny crystals of guanine contained in chromatophores called iridophores distributed in two layers. Only adult males have the upper layer of fully developed iridophores and use it not to camouflage themselves but to attract females or to intimidate rival males.

The colour changes because of a variation between the distances of the guanine nanocrystals that occurs due to a variation of the osmotic pressure (see [14] for a detailed study and spectacular images).

5. Conclusion

The learning path suggested many activities in physics lab, to better understand the underlying physics, ranging from interference to diffraction experiences, discovering the emission spectra for different light sources, continuous and discrete spectra from different materials, different behavior in light absorption and emission. The eye was modelled by a dark room that was realized with everyday materials, the same was done for a spectrometer and a diffraction grating. A thermal camera simulated the IR vision and students discovered how the world appears when enlightened by UV light. The wavelengths of the emission spectrum of an HG lamp were measured in the visible and in the UV region. The laboratories ranged from qualitative exploration to quantitative measurement and were tested with high school students (41 aged 16-18 y) in a summer school and the complete learning-teaching path was proposed in an interdisciplinary summer school for science teachers (18 participants).

Teachers discussed some aspects of the path, in particular, the need to change the sequence of topics in the physics and biology curricula. As with other in-service training opportunities, it is not clear whether and how many of the proposed innovations are then elaborated and tested in the classroom.

The interdisciplinary path proposed to teachers was highly appreciated in the summer school. Moreover, we were invited to propose it in a high school as a moment of cultural enhancement in service. Furthermore, it was included in a training course for science teaching. The first goal was to show everyone, teachers but also academics too, that a bridge in language, conceptual knots in different sciences, balance in complexity and interesting arguments can be found successfully.

The bridge to nanoscience was very effective in motivating students and teachers in the learning process because it is extremely rare at school to connect physical phenomena, often studied in books with few laboratory experiences usually very far from the real world, to the understanding of phenomena very close to student life, like vision and the animal world, and technologically advanced too. To achieve this goal, however, physics and biology teachers must work together in synergy. In this work, we have shown that this interdisciplinary path can be built using the disciplinary and didactic skills of a physicist and a biologist. A common language can found and meaningful topics for the knowledge of both disciplines can be melted, obtaining a stimulating path for students.

The feedback from students and teachers, evaluated informally through interviews and peer presentations of the participants, was very good but we must emphasize that the way for introducing paths like these in ordinary teaching is still very long.

6. References

[1] Alderman M K 2013 *Motivation for achievement: Possibilities for teaching and learning* (London: Routledge)

[2] Pugh K J, Linnenbrink-Garcia L, Koskey K L, Stewart V C and Manzey C 2010 Motivation, learning, and transformative experience: A study of deep engagement in science *Science Education* **94** 1–28

[3] Davies M and Devlin M 2010 Interdisciplinary higher education in *Interdisciplinary higher education: Perspectives and practicalities* ed M Davies *et al* (Bingley: Emerald Group Publishing Limited) pp 3–28

[4] Montalbano V 2012 Fostering Student Enrollment in Basic Sciences: the Case of Southern Tuscany *Proceedings of The 3rd International Multi-Conference on Complexity, Informatics and Cybernetics: IMCIC 2012* (Orlando: International Institute of Informatics and Systemics) pp 279–84

[5] Montalbano V *et al* 2019 The time in science: an interdisciplinary laboratorial approach *J. Phys.: Conf. Ser.* **1286** 012057

[6] Meyers D G 2006 *Psychology*, (New York: Worth Publishing Inc.). The image is a modified one from www.pinterest.co.uk/pin/376613587563073032/ based to the one in the textbook.

[7] Boccignone G 2011 From the eye to the brain: phototransduction in the retina, Lecture notes of the Course of Principles and Models of Perception (in Italian) unpublished.

[8] Perz M 2020 Flicker perception in the periphery (Master thesis) https://www.researchgate.net/publication/265155524_Flicker_perception_in_the_periphery
[9] en.wikipedia.org/wiki/Purkinje_effect
[10] https://www.corriere.it/foto-gallery/salute/neuroscienze/17_aprile_05/vestito-bianco-oro-o-blu-nero-risposta-tomentone-eb5cdae0-19d6-11e7-988d-d7c20f1197f1.shtml (in Italian) and https://pc-tablet.com/scientists-reveal-the-mystery-behind-the-whitegoldblackblue-dress/
[11] Cattai A 2015 Unveiling visible and invisible light (in Italian) communication to 101° Congresso Nazionale SIF, Roma, 21 - 25 settembre 2015, unpublished. Some material proposed to teachers was inspired by the second part of this presentation.
[12] Marshall J and Oberwinkler J 1999 Ultraviolet vision: The colourful world of the mantis shrimp *Nature* **401** 873–4
Marshall J, Cronin T W and Kleinlogel S 2007 Stomatopod eye structure and function: a review *Arthropod structure & development* **36** 420-448
Thoen H H, How M J, Chiou T H and Marshall J 2014 A different form of color vision in mantis shrimp *Science* **343** 411–3.
[13] http://lorologiaiomiope-national-geographic.blogautore.espresso.repubblica.it/2013/07/01/super-shrimp-il-super-mega-gamberetto-coi-superpoteri/ (in Italian)
[14] Teyssier J, Saenko S, van der Marel D and Milinkovitch M C 2015 Photonic crystals cause active colour change in chameleons *Nat Commun* **6** 6368 doi:10.1038/ncomms7368