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Comparative Vision: Can Bacteria Really See?

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It has been known for some time that not only animals, but also some advanced unicellular algae possess imaging eyes. Now it seems that even tiny cyanobacteria have what it takes to qualify for the most basic definition of vision.

Naturally, we relate vision in other species to our own, human vision. Even though some species surpass us in specific aspects of vision such as acuity, colour vision, night vision or speed of vision, we are among the very best when it comes to visual performance on planet Earth. Nearly everything we do, including reading this text, relies on or is aided by vision. If we were to compile a list of human behaviours that use visual input, that list would become very long. Our internal representation of the external world is visually biased, and much of our huge brain is dedicated to processing visual information. Although we tend to have this high-end perspective on vision, it is interesting to look at the other end, and learn about the simplest forms of vision. A recent paper by Schuergers *et al.* [1] describes such a simple form of vision, in the least likely of places: a cyanobacterium.

Phototrophic cyanobacteria of the genus *Synechocystis* are spherical and only about 3 μm in diameter. They display positive phototaxis, by dragging themselves towards the light with pili that extend, adhere and retract at the side of the cell facing the light [2]. In the new study [1], the spherical *Synechocystis* cells are shown to act as lenses that pass sunlight (or light from LEDs) through the cell and bring it to a focus close to the cell membrane located opposite to the light source (Figure 1). The entire cell thus acts as a lens, and the cell membrane, which contains a number of different photoreceptor proteins, acts as a retina. Detection of strong light in one location on the plasma membrane causes the pili to pull at the opposite end of the cell, such that it moves towards the light.

Because this phototactic behavior uses information about the spatial distribution of ambient light, it must be classified as spatial vision, or just vision for short [3]. The resolution (acuity) is not great, about 20°, but completely adequate for phototaxis. The visual system has a minimum set of components, but even though the cell as a whole acts as a lens and the surrounding membrane as a retina, we cannot claim it has an eye, because these structures have other essential functions and are not primarily devoted to vision.

Sea urchins are interesting parallels. They express visual pigments (opsins) in their tube feet, which are distributed over the entire surface of the urchin [4]. Because the spines and the body shade the tube feet, they become sensitive mainly to light perpendicular to the surface. This makes the tube feet function a bit like the ommatidia of a compound eye, and the sea urchins use the visual image information for orientation towards dark objects [5]. Again, the basic criteria for vision are fulfilled, but just as with the cyanobacteria, there is no eye because the essential structures are not primarily devoted to vision.

The 'simplest' organisms with real eyes are warnowiid dinoflagellates. These are unicellular eukaryotic algae, which are 50–100 μm and thus much larger than the 3 μm *Synechocystis* cyanobacteria. Each warnowiid carries a single eye, or ocelloid, that is about 10 μm in size, with a focusing lens and a retinoid (retina) backed by dark screening pigment [6,7]. The light-sensitive layer of the retina is made up of modified and densely stacked thylakoid membranes originating from a chloroplast [7,8]. In this case, vision is the primary function of all the main components. There can be no mistake that this is an eye, but its biological role is as yet obscure. It is possible that warnowiids, which are partly

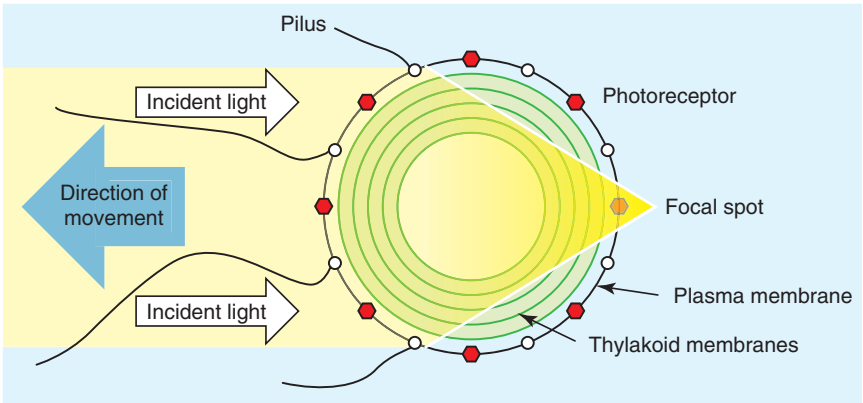

Figure 1. Vision and phototaxis in *Synechocystis*.
The spherical cell acts as a lens, focusing a bright spot on the plasma membrane at the side opposite the light source. The plasma membrane contains photoreceptor proteins that detect the concentrated light, and signal to inhibit (disassemble) nearby pili, or activate pili opposite the focal point. Active pili extend, attach and retract to pull the cell towards the light.

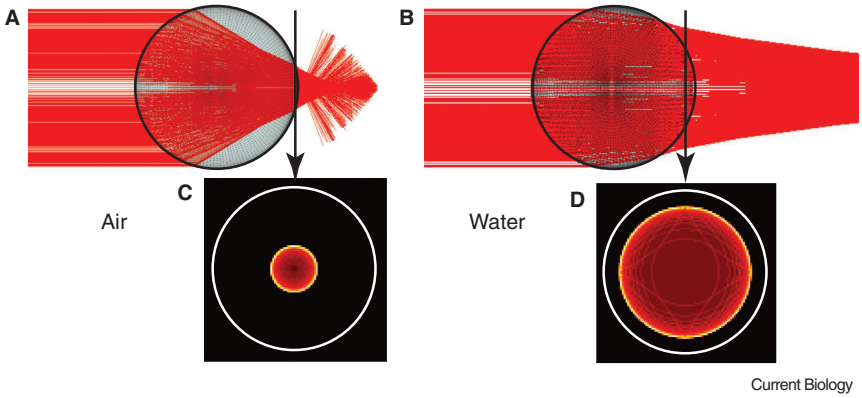

Figure 2. Light focusing by cells of *Synechocystis* in air and water.
The 3D ray-tracing models assume the cells have a homogeneous refractive index of 1.4. The short focus predicted with air around the cells (A) agrees with the experimental results and the 2D wave model presented by Schuergers *et al*. [1], but if we assume the cells are immersed in water (B), refraction is too weak to generate an intense focus on the cell membrane. Intensity plots (C,D) show the beam cross-section at the rear of the cell. The highly concentrated beam with the cell in air (C) is replaced by a very modest beam concentration when the external medium is assumed to be water (D). 3D ray-tracing provides a reasonable qualitative approximation despite the small size.

heterotrophic, use vision to guide assaults on other phytoplankton.

The existence of vision in dinoflagellates is spectacular, but it is more surprising to find vision in a prokaryote so small that a colony of them would fit inside the volume of a warnowiid lens. This small, 3 μm size could be problematic. One reason is that light cannot be concentrated to patches much smaller than its wavelength. Many prokaryotes are only a micrometer long, which happens to be about twice the wavelength of visible light. The 3 μm *Synechocystis* cells are thus only large enough to contain a very rudimentary image of the surrounding world. Therefore, they are able to succeed only by using the whole organism as an imaging device — any part of it would be too small. *Synechocystis* is clearly pushing the lower limit of what can be called vision, and if we are looking for an antipode to human visual excellence, we need look no further.

Photos and videos in Schuergers *et al.* [1] beautifully demonstrate how an image of a distant point source is focused close to the cell boundary opposite the light source. They also use wave optics analysis to confirm that this is an expected consequence of light being refracted in the spherical cell. As convincing as this may seem, there are reasons to question the results. The methods state that all experiments were made with *Synechocystis* moving on an agarose substrate, and the optical wave analysis reveal that they assumed a refractive index of about 1.0 outside the cells. In other words, both the experiments and the modelling were made with the cells in air.

But agarose surfaces in culturing dishes are not the natural habitat of *Synechocystis*. According to the literature [9], the *Synechocystis* strain used (PCC 6803) inhabits freshwater lakes. Substituting water for air means that the refractive index around the cells increases from 1.0 to 1.33, and thus comes close to 1.4, which is realistically assumed for the cells. The focusing power of the spherical cells arises entirely from the difference in refractive index between inside and outside. With water outside, this difference drops to less than one-fifth compared to having air outside. This implies a more than five times longer focal length when the cell is immersed in water, and the concentration of light on the rear cell membrane becomes dramatically reduced (see simple modelling in Figure 2). The basic mechanism suggested for allowing phototaxis in *Synechocystis* [1] requires that light is substantially concentrated by focusing at the rear membrane. Schuergers *et al.* [1] estimate the focus to be just below 0.5 μm wide, but in water it would become 2.25 μm at the rear of the cell (Figure 2), and the increase in light intensity a mere 1.8 times compared to almost 40 times with air outside the cell (accurate figures would require a 3D wave analysis).

With this weak focusing in water it is questionable if the phototaxis mechanism would work in the natural aquatic habitat of *Synechocystis*. But the biologically relevant and robustly demonstrated mechanism in air tells us it probably will work also in water. It seems more unlikely that a biologically relevant mechanism would evolve if it only works under artificial conditions. Before this issue is finally resolved, the otherwise beautiful experiments presented by Schuergers *et al.* [1] would have to be repeated with cells immersed in an aqueous medium.

A factor that severely limits the sensitivity of vision in *Synechocystis* is that the light receptors are believed to be located in the outer plasma membrane. A single layer of membrane has a limited capacity for housing receptor proteins. The small number of proteins packed in a single bilayer would only be capable of absorbing a fraction of a percent of the incident light [3]. For this reason, the photoreceptor cells in all animal eyes contain massive stacks of membrane [3], allowing absorption of 70% or more of the incident light. Without stacked membranes the sensitivity is not sufficient for spatial vision even in bright daylight. The problem is the statistical noise from random photon arrivals that can be overcome only by collecting enough photons per integration time. But for *Synechocysteis*, one cure is probably a very long integration time. The response lag seems to be at least 10–20 seconds as judged from the time-lapse videos in Schuergers *et al.* [1]. Another cure for low sensitivity is the fact that the object of interest to *Synechocystis* is the sun, which is about five orders of magnitude brighter than any other object seen on Earth. This of course implies that *Synechocystis* will only be able to respond to bright light sources such as the sun in shallow water, and not see any of the structures that form the visual world of humans and other animals.

Despite its limitations and simplicity, vision in *Synechocystis* offers a powerful reminder that animal vision is not an entirely unique evolutionary product. *Synechocystis* is believed to use a light receptor formed by a membrane protein with two transmembrane regions binding

a linear tetrapyrole chromophore [10,11]. This is unrelated to the seven-transmembrane bacteriorhodopsins implicated in dinoflagellate vision [12] as well as to the G-protein coupled receptors of animal vision [13]. Both photoreception and vision thus have multiple origins. It is interesting to speculate on which organism was first to evolve vision. Maybe bacteria used vision long before any animals saw the light.

REFERENCES

1. Schuergers, N., Lenn, T., Kampmann, R., Meissner, M.V., Esteves, T., Temerinac-Ott, M., Korvink, J.G., Lowe, A.R., Mullineaux, C.W., and Wilde, A. (2016). Cyanobacteria use micro-optics to sense light direction. eLife *5*, e12620.

2. Schuergers, N., Nürnberg, D.J., Wallner, T., Mullineaux, C.W., and Wilde, A. (2015). PilB localization correlates with the direction of twitching motility in the cyanobacterium *Synechocystis* sp. PCC 6803. Microbiology *161*, 960–966.

3. Nilsson, D.-E. (2013). Eye evolution and its functional basis. Vis. Neurosci. *30*, 5–20.

4. Ullrich-Lüter, E.M., Dupont, S., Arboleda, E., Hausen, H., and Arnone, M.A. (2011). Unique system of photoreceptors in sea urchin tube feet. Proc. Natl. Acad. Sci. USA *108*, 8367–8372.

5. Yerramilli, D., and Johnsen, S. (2010). Spatial vision in the purple sea urchin *Strongylocentrotus purpuratus* (Echinoidea). J. Exp. Biol. *213*, 249–255.

6. Francis, D. (1967). On the eyespot of the dinoflagellate, *Nematodinium*. J. Exp. Biol. *47*, 495–501.

7. Greuet, C. (1987). Complex organelles. In The Biology of Dinoflagellates, *Vol. xxii*, F.J.R. Taylor, ed. (Oxford: Blackwell Scientific Publications), pp. 119–142.

8. Gavelis, G.S., Hayakawa, S., White, R.A., III, Gojobori, T., Suttle, C.A., Keeling, P.J., and Leander, B.S. (2015). Eye-like ocelloids are built from different endosymbiotically acquired components. Nature *523*, 204–207.

9. Stanier, R.Y., Kunisawa, R., Mandel, M., and Cohen-Bazire, G. (1971). Purification and properties of unicellular blue-green algae (order Chroococcales). Bacteriol. Rev. *35*, 171–205.

10. Yoshihara, S., Katayama, M., Geng, X., and Ikeuchi, M. (2004). Cyanobacterial phytochrome-like PixJ1 holoprotein shows novel reversible photoconversion between blue- and green-absorbing forms. Plant Cell Physiol. *45*, 1729–1737.

11. Yoshihara, S., Shimada, T., Matsuoka, D., Zikihara, K., Kohchi, T., and Tokutomi, S. (2006). Reconstitution of blue–green reversible photoconversion of a cyanobacterial photoreceptor, PixJ1, in phycocyanobilin-producing Escherichia coli. Biochemistry *45*, 3775–3784.

12. Hayakawa, S., Takaku, Y., Hwang, J.S., Horiguchi, T., Suga, H., Gehring, W., Ikeo, K., and Gojobori, T. (2015). Function and evolutionary origin of unicellular camera-type eye structure. PLoS One *10*, e0118415.

13. Porter, M.L., Blasic, J.R., Bok, M.J., Cameron, E.G., Pringle, T., Cronin, T.W., and Robinson, P.R. (2012). Shedding new light on opsin evolution. Proc. Biol. Sci. *279*, 3–14.

Oriented Division: Using T-Junctions to Determine Direction

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Cell shape has long been thought to be the main cue for spindle positioning in mitotic cells, but new evidence suggests that, in the context of an epithelium, tricellular junctions encode positional information that helps orient mitotic spindles.

How do animal cells orient their axis of division? This is a fundamental problem that has interested biologists since the nineteenth century, when Hertwig and others noted that large embryonic cells divided perpendicular to an imposed long cell axis when deformed [1,2]. As a result, the two daughter cells generated by division have a more isotropic shape than their mother. Later, it was discovered that the division plane in animal cells is determined by the position of overlapping antiparallel astral microtubules [3] and the central part of the metaphase spindle [4]. What then positions the spindle? By perturbing mitotic cell shape it is possible to explore the geometric cues governing spindle positioning [5]. Using this type of approach, in 2011 Minc *et al.* [6] carried out a systematic analysis of the relationship between cell shape and spindle positioning in single sea urchin zygotes confined in microfabricated chambers. With the aid of a computational model, their analysis suggested that the mitotic spindle is aligned along the axis of symmetry and centered by pulling forces acting on astral microtubules, which scale with microtubule length.

Although the experiments described above all sought to explore the role of metaphase cell shape in spindle orientation, most animal cells assume a rigid spherical shape as they enter mitosis. This is the case for isolated cells in culture, which undergo rounding through the partial disassembly of cell–substrate adhesions, leaving the cell tethered to the substrate by thin ‘retraction fibers’, and for cells in a crowded tissue entering mitosis, which round as a result of increasing cortical rigidity and osmotic swelling [7,8]. Remarkably, however, despite being

