An unexpected light

With the completion of early drafts of the human and other genomes, and the development of proteomics, some have concluded that the discrete characterization of disease, the identification of susceptible individuals, and the custom design of drugs are all at hand. Botanical extensions of these fields of knowledge, they imagine, will allow painless manipulation of the diet to provide more anti-oxidant, increased vitamin A and safer fats. Whatever you think, the issues are complex and many prophesies will prove false. Even so, the information acquired is resolving unexpected issues, notably in the field of development, where views about the evolution of form and function are changing as surprises are produced.

For many years, the eye seemed to present a problem for classical accounts of the process of evolution as selection by fitness. Such a complex structure could not have developed without a large number of genetic steps, and the incremental advantage conferred by each of these was not always obvious. Photoreception, of course, can be useful to an organism in several ways. Simple monitoring of the level of ambient light allows regulation of biological rhythms. Perception of a sudden change in incident light may signal the arrival of a predator and give time for the animal to initiate protective actions. But it was in the context of the development of a highly specialized image-forming organ that a number of authors pointed out the apparent lack of advantage of having just part of an eye. The surprising number of widely different evolutionary solutions—from the compound eyes of arthropods to the single-lens structures of cephalopods and vertebrates—suggests that this analysis must be mistaken.

There is great variation in the structures that species have evolved for photoreception. For example, the eye of the Cubomedusae jellyfish has an epidermal cornea, a lens and a multilayered retina with around 11 000 cells linked together in a neural net, whereas Bilateria flatworms have simple pigment-cup ocelli that lack lenses but have the ends of their retinal cells pointing away from the light. At first sight, this variation might suggest evolutionary divergence, but recent findings suggest quite the opposite. The photoreceptors in the eyes of insects, crustaceans, octopods and fish, for example, all express rhodopsin genes homologous to those of mammals, and the mechanism of activation of the G-protein second-messenger system by receptor cells is identical.

There is further evidence of developmental linkage at the G-protein level. In the frog, lightsensitive pigment cells in the skin and iris, as well as hypothalamic neurones involved in the control of circadian rhythms, express a chromophore—melanopsin. The impact of a photon on melanopsin induces conformational changes in a seven-membrane G-coupled receptor that is subsequently regenerated in neighbouring cells. Invertebrate photoreceptor cells behave similarly, except that the properties of a different G protein allow the chromophore to be regenerated and available within the same cell. This feature reflects the dispersed nature of photoreceptors in invertebrates—the specialized cell-packed structures that allow functional specialization in eyes do not exist. Invertebrate-type opsins may have survived in vertebrate skin to provide light sensitivity in tissues remote from the eye, but light-dependent intracellular pigment redistribution may also have evolved for thermoregulation and photoprotection. Arnheiter thinks that pigment cells may have been the evolutionary precursors of photoreceptor cells, since the role of pigment cells in eyes is to act as a screen blocking access of light to one side of a receptor cell to endow it with directional sensitivity. Although photoreception has developed along a number of evolutionary pathways, it seems probable that the starting point was always a rhodopsin-expressing pigment cell in the skin.

The developmental sequence of the vertebrate eye includes specification of the anterior neural plate, evagination of the optic vesicles from the forebrain, and cellular differentiation of the lens and...
retina. The transcription-regulating Pax-6 gene plays a major role in this process, and its sequence is highly conserved in both vertebrates and invertebrates. Murine and human Pax-6 are identical over the complete 422 amino acids and the Zebrafish gene is identical for 97% of the sequence at amino acid level. Similar genes are found in the rat, chick and axolotol. The first invertebrate Pax-6 homologue to be identified was in Drosophila and is called eyeless. This gene shares 94% sequence identity in the paired domain and 90% in the homeodomain with mammalian Pax-6 gene, and homologues are also found in sea urchins, cephalopods and nematodes.

The human, mouse and Drosophila Pax-6 genes are expressed in a closely comparable manner as the central nervous system develops. Mutations in the Pax gene family (aniridia, small eye and eyeless) produce eye defects or loss of eyes, just as ectopic expression of these genes produces supernumerary eye structures. The Drosophila gene eyes absent has a human homologue, the Eya1 gene, and mutations here produce ocular defects in man.

In the lower chordates—animals that have a notochord but no vertebrae—there are two sensory organs: a photosensitive ocellus and a gravity-sensing otolith organ. They arise from two precursor cells, either of which may give rise to either organ, depending on position. Glardon et al. have examined the Pax-6 gene homologue in the ascidian Phallusia mammillata and found a high degree of amino acid identity with the vertebrate gene in both the paired domain (87%) and the homeodomain (95%). It is expressed in the Phallusia embryo in cells immediately anterior to the developing sensory organs.

So it seems that whatever structure an animal ends up with as a light-detecting mechanism, its development started with a rhodopsin-containing pigment cell and continued under the control of Pax-6. Not at all what the investigators were expecting to find when they set out to solve quite different problems.

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References