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Spectral Tuning in Biology

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Abstract: Spectral tuning is a diverse topic, both with regard to mechanism and with regard to biological significance. We have touched upon a related topic already when dealing with quantum dots in Chapter 5. In organisms, spectral tuning can be achieved both by chemical means (choice of pigment) and by physical means. The latter aspect is treated towards the end of the chapter in a section on structural color. As for the functional aspect, spectral tuning has significance for photosynthesis, vision, bioluminescence, and coloration both for protection and signalling in various contexts.

9.1. Introduction

The justification for a book about photobiology rests partly on combination of various specialities for interdisciplinary comparisons. One topic suitable for comparisons is "spectral tuning." By this we mean the principles for how spectra of pigments, and factors that can modify their spectral responses, are adjusted to the needs of the organisms that produce them. A number of examples will be found in this chapter.

To pigments, substances that produce color by absorbing light of some wavelengths and reflecting or transmitting the rest, we must add a second class of color mechanism, *structural* colors. These are produced by the interaction of light with the detailed architecture of the material or structure on which it falls. We will begin with a discussion of biological pigments and then move on to biological structural colors. Finally, we will discuss some additional mechanisms by which organisms control their spectral presentation to the world.

Spectral tuning is relevant for vision (not only for color vision), photosynthesis, bioluminescence, flower colors, and adaptive coloration of animals, and especially for animals that move around among green plants, to increase contrast of edges. These processes are not independent. Flower colors are adapted to the vision of pollinators and as a contrast to photosynthetic pigments. Bioluminescence and vision have evolved together. Phytochrome has evolved to discriminate between direct daylight and light modified by chlorophyll absorption. The basis is the spectrum of the sun. To begin with, let us see what the relation is between

the spectrum of the most important of all pigments, chlorophyll *a*, and the spectrum of the sun.

9.2. Why Are Plants Green?

Many people have discussed the spectrum of chlorophyll in relation to daylight. Some have come to the conclusion that they do not match well, as absorption "in the middle of the spectrum," i.e., the green band, is weak. A common idea is that an ideal pigment for photosynthetic energy conversion ought to be either black, absorbing all available radiation, or absorb most efficiently at the "peak" of daylight.

But what is the "peak" wavelength for daylight? The maximum of the daylight spectrum depends on how we plot it. For the present purpose, to simplify comparisons and calculations, we may represent the daylight spectrum by that of a 6000 K blackbody radiator, and thus apply Planck's radiation law (Chapter 1). We can then calculate that if we plot the spectrum as energy per uniform wavelength interval the maximum is at 480 nm. But if we instead plot it as photons per uniform wavelength interval, the maximum is at 600 nm, and if we, following the habits of physicists, plot the spectrum as energy per uniform frequency interval, or photons per uniform frequency interval, the peak will be seen at frequencies corresponding to 800 nm and 1200 nm, respectively.

Thus the "maximum of the daylight spectrum" is an ambiguous concept, and we have to find another way of optimizing our pigment. As for the idea that an ideal pigment should absorb everything, we should remember that the better a substance absorbs, the better it emits, and the transformation of radiant energy into other energy forms is just the balance between absorption and re-radiation. That total absorption is not an ideal is even more apparent in the case of color vision. Vertebrate cones, which are cells receiving light signals for color vision, are shorter than the rods involved in "noncolor night vision" (scotopic vision), and therefore absorb a smaller portion of the light and discriminate between wavelength bands better than they would if they were as long as rods.

Photosynthesis depends on photochemistry, and photochemistry works particle to particle, photon to molecule. The useful energy storage can be regarded as the product of the number of reacting photons and the free energy that each converted photon contributes. Björn (1976) following this principle comes to the conclusion that the long-wave absorption band of a pigment giving maximum energy conversion in direct sunlight should be rather narrow and have a maximum at 707 nm. Furthermore the pigment should be highly fluorescent (when not quenched by photochemistry). The maximum chemical potential difference that can be created by a one-step system is $\mu_o = kT\ \ln[\Phi r^2/4R^2)] + hv_o(1 - T/T_S) - b^2[h^2/(2k)]T(1/T^2 - 1/T_s^2)$, where k = Boltzmann's constant, Φ Planck's constant, T ambient temperature, T_S the temperature of the radiating surface of the Sun, μ the fluorescence yield, r the radius of the Sun, R the Earth-Sun distance, v_o