A Different Form of Color Vision in Mantis Shrimp

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One of the most complex eyes in the animal kingdom can be found in species of stomatopod crustaceans (mantis shrimp), some of which have 12 different photoreceptor types, each sampling a narrow set of wavelengths ranging from deep ultraviolet to far red (500 to 720 nanometers) (1–3). Fundamentally, the complexity has presented a mystery (3–5). Why use 12 color channels when three or four are sufficient for fine color discrimination? Behavioral wavelength discrimination tests (Δλ functions) in stomatopods revealed a surprisingly poor performance, ruling out color vision that makes use of the conventional color-opponent coding system (6–8). Instead, our experiments suggest that stomatopods use a previously unknown color vision system based on temporal signaling combined with scanning eye movements, enabling a type of color recognition rather than discrimination.

Stomatopods are benthic marine crustaceans that are generally found in tropical and temperate waters. Their compound eyes possess a larger number of photoreceptor types than in any animal (between 16 and 21 different receptors in some species (1, 3, 9)), allowing them to discriminate color (5) as well as both linear and circular polarized light (3, 10). Such retinal complexity is unrivaled in the animal kingdom, although papillomidal butterflies may have up to eight spectral sensitivities (11). Theoretical approaches have predicted that between four and seven photoreceptor types are all that is needed to accurately encode the colors of the visible spectrum (12–14). The four-channel (tetrachromatic) solution that birds and reptiles use to sample a spectral range from 300 to 700 nm is optimally arranged to encode the known colors within this range. Where the spectrum examined loses the ultraviolet (UV) or red end, three photoreceptors suffice, and trichromacy is the solution that many animals exhibit (12).

Our question was therefore, why do the stomatopods use 12 different photoreceptors to encode color? Before the experiments described here, Marshall et al. (5) demonstrated that stomatopods are capable of simple color discriminations based on color-card tests, similar to those devised by Carl von Frisch for bees and now used widely for a number of animals (15). We hypothesized two alternative mechanisms for color information processing in stomatopods: (i) a multiple dichromatic color-opponent system (as described below), or (ii) the binning of colors into 12 separate channels, without any between-channel comparisons (4, 16).

Like butterflies, stomatopods have a variety of colorful body patterns, even using fluorescence to enhance color display (17). Furthermore, many of these species inhabit shallow coral reefs, one of the most colorful environments on Earth. The stomatopods’ colors are thought to be involved in particular complex communication systems, both between and within species (18), but little of this complexity requires a 12-dimensional color space to distinguish the colors available. Osorio et al. (19) speculated that stomatopods use their color sense to make reliable and quick judgments of color signals from conspecifics under changing light conditions, their steep-sided spectral sensitivities allowing particularly good color constancy. This would require comparison of the spectrally adjacent sharply tuned spectral sensitivities, and there is some anatomical evidence supporting this idea (6).

Stomatopod eyes are made up of a dorsal and ventral hemisphere, divided by a region of distinct