BY **MIKE WOOD**

# Animal eyes – Part 3

IF YOU ARE A REGULAR READER of this column, you'll know that I have a fascination with the differing ways evolution has provided various members of the animal kingdom with 3D and color vision, and the associated customization that has occurred in some species. In previous columns I've looked at the eyes of predators and prey (*Protocol* Winter 2016) and octopus eyes (*Protocol* Summer 2017). This time I want to look at a very different creature, a spider. It's not the pupil shape that's the interesting feature this time, rather it's the structure of the eye. Parts of it are very familiar to those of us in entertainment lighting. In particular the jumping spider uses a colored filter to assist its color vision.

> **"... the vision acuity masters of the animal world ..."**

**Figure 1 – The jumping spider**

## The jumping spider

**Figure 1** shows an example of our subject, the jumping spider from the family Salticidae. These are the most common spider family, representing about 13% of all spiders, and occur everywhere in the world. What's particularly interesting about them from our point of view is that they are the vision acuity masters of the animal world. They have the highest spatial resolution vision in relation to their body size of any animal.

These spiders are active hunters, not web spinners, so good spatial awareness and 3D vision is particularly important. They hunt very like small cats, by using their vision and pouncing on their prey. Like a cat, and unlike any other spider, a salticid locates, tracks, stalks, chases down, and leaps on active prey, with all phases of these predatory sequences being under optical control. Using optical cues, salticids discriminate between mates and rivals, predators and prey, different types of prey, and features of non-living environment. Most of the species of salticids have relatively poor, bichromatic (two color) vision but there is at least one species with trichromatic (three color) vision like us. However, the mechanisms by which the jumping spider achieves this excellent vision is very different from our own eyes.

**Figure 2** shows a close up of the head of a jumping spider. Like many spiders, they have a lot of eyes, eight in the case of all jumping spiders, however the six eyes down the sides of the head are very limited in resolution and are primarily used to detect movement. It's the two large eyes at the front, the principal eyes, that are interesting.



Figure 2 – Jumping spider eyes

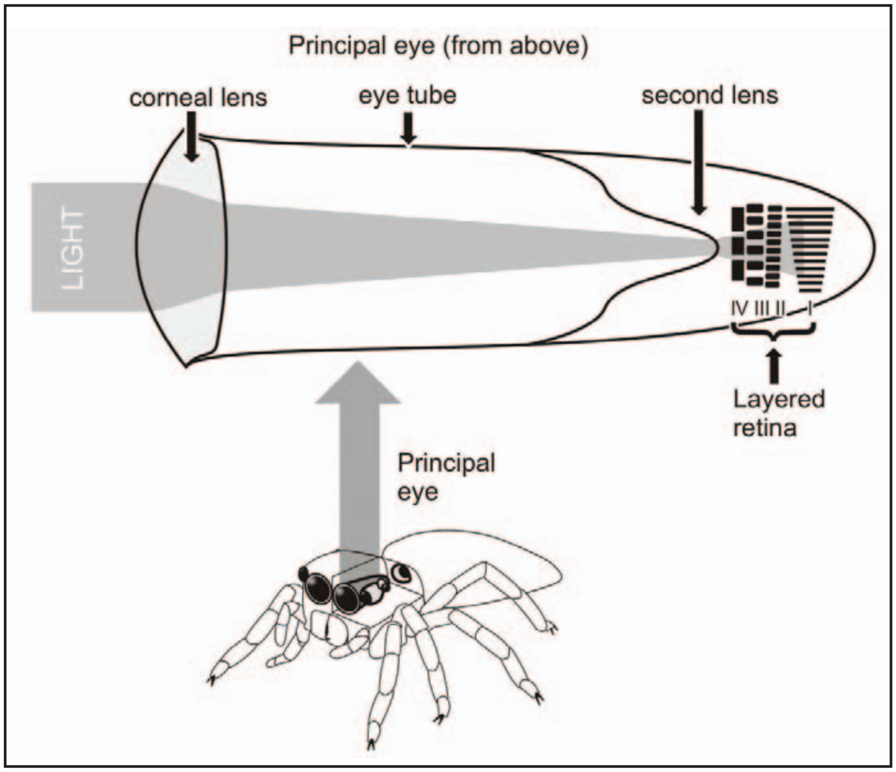




Figure 3 – Eye structure

## Depth perception

At first glance the structure looks very familiar, these eyes have a large lens to capture light and a retina with different photo receptors. However, these animals are tiny, with body widths of perhaps only a few millimeters, and those two eyes are very close together. How do they get any kind of reasonable depth perception? The two images would be almost identical making any normal binocular parallax effect extremely limited and certainly not providing the accuracy the spider needs to leap onto and grab a moving fruit fly. There must be something else going on.

A look at the cross section of the eye as shown in **Figure 3** shows the differences. Firstly, the eye is extremely long, not spherical like our eyes. It also has not one, but two lenses, positioned at either end of a tube so as to act like a telescope. This gives the spider a narrow field of view and accentuates the spatial acuity of its retina, which is very limited in size. Cells don't get smaller just because the animal does, so the spider has significantly fewer photoreceptors in its retina than we do. The lenses effectively give the jumping spider a pair of permanent binoculars to help offset that.

> **“. . . their courtship has to happen in bright light!”**

## References:

*Depth Perception from Image Defocus in a Jumping Spider*
Takashi Nagata, Mitsumasa Koyanagi, Hisao Tsukamoto, Shinjiro Saeki, Kunio Isono, Yoshinori Shichida, Fumio Tokunaga, Michiyo Kinoshita, Kentaro Arikawa, and Akihisa Terakita
*Science Magazine* Issue 6067, January 27, 2012

*'Eight-legged cats' and how they see – A review of recent research on jumping spiders*
Duane P. Harland, and Robert R. Jackson
*Cimbebasia 16*: 231 – 240, 2000

*Spectral filtering enables trichromatic vision in colorful jumping spiders*
Daniel B. Zurek, Thomas W. Cronin, Lisa A. Taylor, Kevin Byrne, Mara L.G. Sullivan, and Nathan I. Morehouse.
*Current Biology Magazine 25*, May 18, 2015

That telescopic vision only gets us part way and doesn't really help with depth perception as those two eyes are still very close together. It's the structure of the retina itself that provides the clue. Our eyes, like most animals, have a single layer of photoreceptors in the retina. The jumping spider, however, has multiple layers at different depths, one beneath the other.

As shown in **Figure 4**, the top layers are primarily sensitive to green and deep blue / UV light, while the bottom layers only to green.

Research done by Marie Herberstein at Macquarie University in Sydney, Australia suggests that the spider can use the different focus at different levels in the retina to improve its distance perception.

**Figure 5** shows what could be going on. When an object, a fruit fly perhaps, is close to the spider as shown in the upper half of **Figure 5**, the lens adjusts to focus the image on the top layers of the retina and form an image A. As the distance is small, the angles are quite sharp, and the light rays diverge rapidly, so the image that is then formed on the lower layers B is very blurry.

If, however, the fly is much further away as shown in the lower half of **Figure 5**, the angles are much shallower and although the image formed on the lower layers D is still a little blurry compared to the sharp image C, it's much less blurry than before. At the extreme, the rays from an object at infinite distance would be in focus on all layers at the same time.

Thus the jumping spider, by being sensitive to how blurred the image of an object is on the lower layers of its retina when that same object is sharply focused on the upper layers, gets valuable information on how far away the object is. The lower layers of the retina have a higher density of photoreceptors than the upper layers, which makes them better at judging how sharply focused an image is. All this, in addition to the binocular information it gets from two eyes, enables the jumping spider to accurately gauge its jump to catch its prey.

Duane Harland, a biologist who studies spider vision at AgResearch in Lincoln, New Zealand commented, "These results not only explain the usefulness of an out-of-focus retina, they also provide an exciting example of how half-centimeter-long animals with brains smaller than those of house flies still manage to gather and act on complex visual information. The next step will be figuring out how their eyes and brains actually compare those clear and fuzzy images to get a sense of distance."

## How about colors?

That's the end of the story for most jumping spiders. They just have the two types of color receptors, so their color vision is quite poor. They can distinguish blues and yellows, but their green receptors are broad

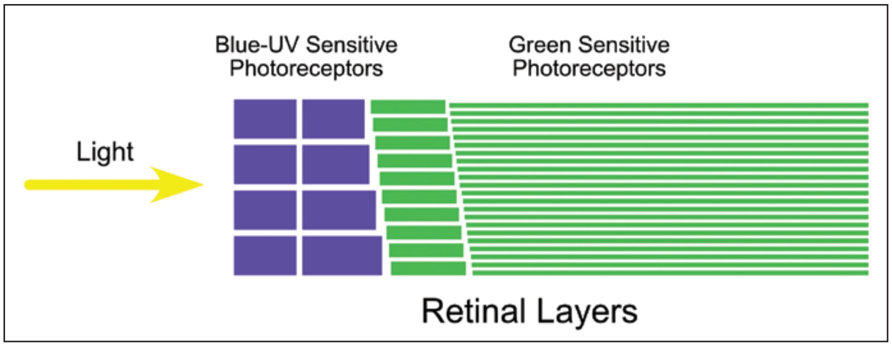


**Figure 4 – Retinal Layers**

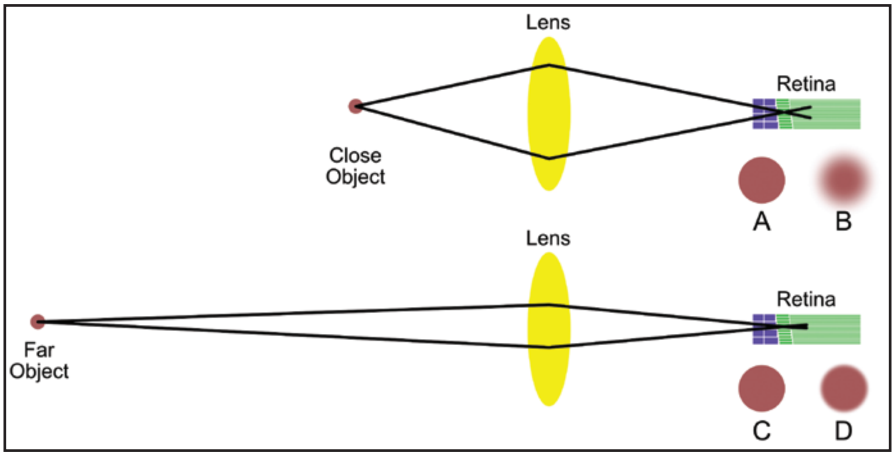


**Figure 5 – Focus difference on different retinal layers**

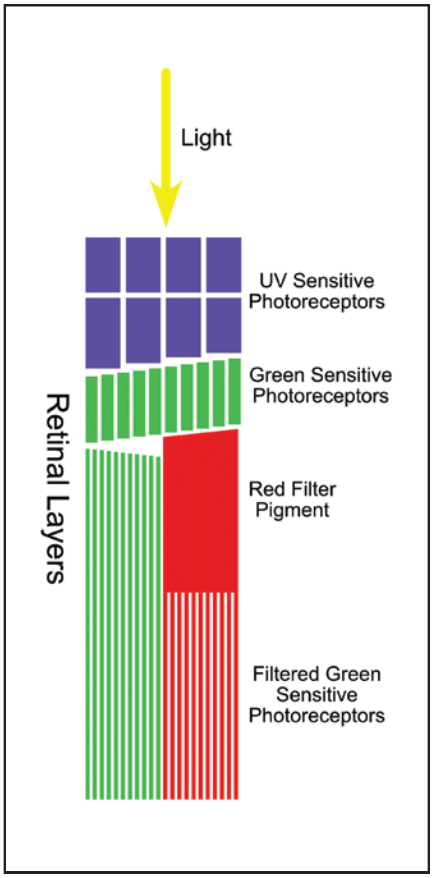


**Figure 6 – Retina layers with red filter**

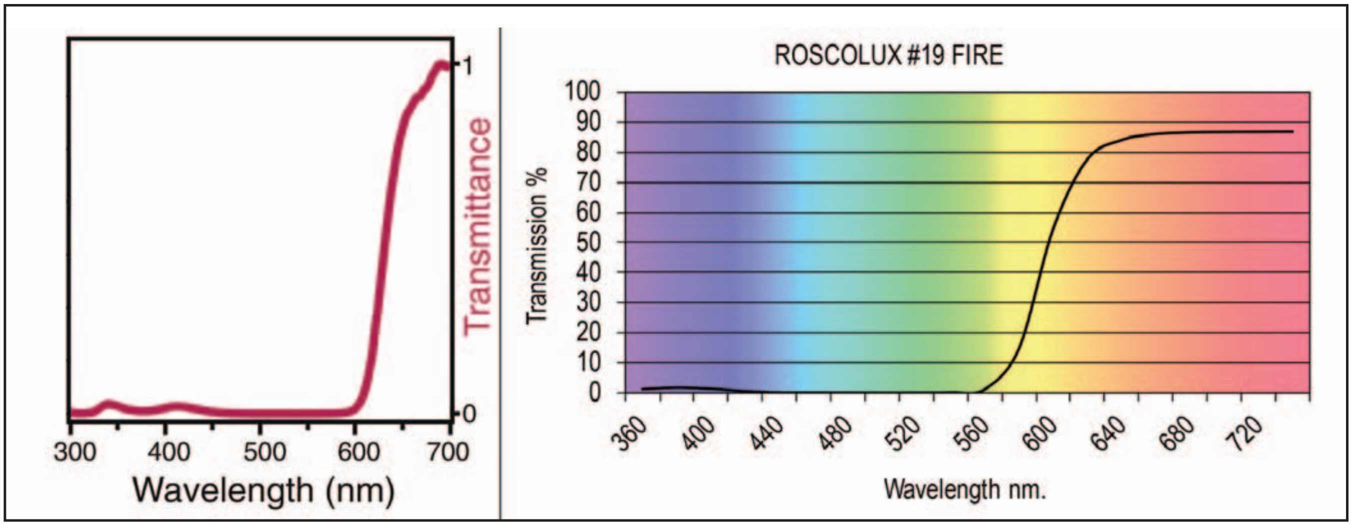


**Figure 7 – Red filter**

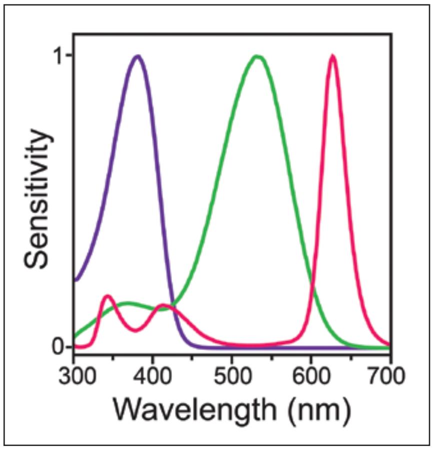


**Figure 8 – Trichromatic sensitivities**

band and pick up red light as well. They are thus red-green color blind. Some jumping spiders though are brightly colored and use reds and oranges in their courtship and mating displays. If they are red color blind, how do they distinguish those colors? Work done by the Morehouse lab at the University of Pittsburgh in 2015 suggests a mechanism. They discovered that some species of jumping spider, specifically the American Genus Habronattus, have another trick up their sleeve that allows them to achieve trichromatic vision and fix that red-green color blindness.

They don't have a third color of photoreceptor, instead they have a color filter that modifies the reception of a bank of existing green sensors. **Figure 6** shows the structure of the retina of the Habronattus Pyrrithrix jumping spider. It's very similar to that shown in **Figure 4**, but with the addition of a layer of red pigment which acts as a red filter for the photoreceptors underneath. These are still the same broadly green photoreceptors, but the addition of the red pigment above them modifies their effective response and changes them into red photoreceptors.

The pigment layer (**Figure 7**) has the spectral transmission of a deep red filter, very similar to that of Rosco #19, Fire Red. When that is overlaid with the response of the green photoreceptor you get a true three-color sensitivity (**Figure 8**).

Actually, the three colors of the jumping spider's vision are rather better separated than our own, and its short wavelength vision extends much further into the deep blue and UV. "In principle, they can see an even broader spectrum of colors than we can," says Nate Morehouse, an evolutionary biologist at the University of Pittsburgh in Pennsylvania and one of the study authors. This is because H. Pyrrithrix "are sensitive, not only to the spectrum of colors visible to us, but also to the UV."

Another unique feature of this filter system is its restriction to a small region of the retinal center, which results in a trichromatic area surrounded by an otherwise dichromatic retinal field. The end result is that the Habronattus jumping spiders have good color discrimination, at least in the center of their vision, and can distinguish reds, ambers, and yellows from greens and cyans. The problem with filters of course, is that they reduce light output, and the spider also suffers from this. Its red receptors drop off rapidly in dim light. This means that their courtship has to happen in bright light! ■

**Mike Wood** runs Mike Wood Consulting LLC, which provides consulting support to companies within the entertainment industry on product design, technology strategy, R&D, standards, and Intellectual Property. A 40-year veteran of the entertainment technology industry, Mike is a past President of ESTA and Co-Chair of the Technical Standards Council. Mike can be reached at mike@mikewoodconsulting.com.