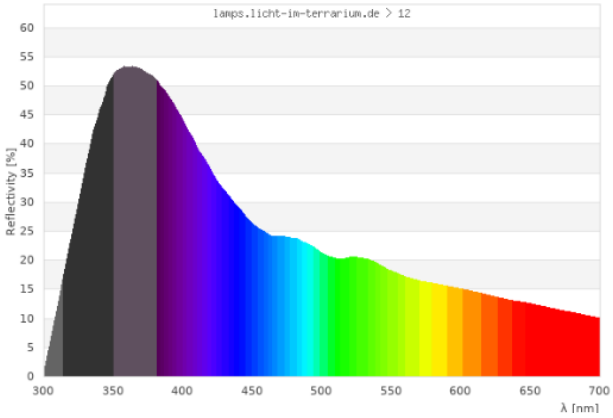
It has long been known that the blue patches on lizards are UVA reflective and that many reptiles, including most lizards, have retinal photoreceptors with four different peak sensitivities – red, green, blue, and UVA. I recently came across this paper [1], where the reflection spectrum of the blue patches is measured. Based on this and other data I want to visualize the impact of LED lighting on the colour perception. The paper is open access and contains a colour photo of the lizard.

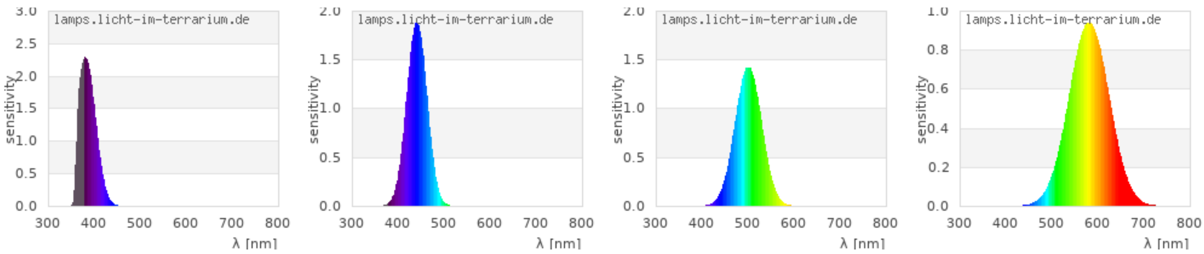
[1] Badiane, A., & Font, E. (2021). Information content of ultraviolet-reflecting colour patches and visual perception of body coloration in the tyrrhenian wall lizard podarcis tiliguerta. *Behavioral Ecology and Sociobiology*, *75*, DOI: 10.1007/s00265-021-03023-2.

More than 10 years ago I started a web database for lamp spectral measurements (http://lamps.licht-im-terrarium.de). This database, written in the programming language php, offers very convenient organization and evaluation of spectral measurements to me. Many of the calculations and figures in this document are based on the output of this database, so the graphs are sometimes a bit generic. Additionally, I use excel, matlab and python (especially for 3D plots).

The blue patches reflect light with a peak reflectivity around 360 nm:



To calculate the colour from the reflection spectrum the sensitivity of the photoreceptors needs to be known. In the database I use four very generic sensitivity curves that I chose to resemble a kind of average over many reptile species where the photoreceptor sensitivities have been studied:



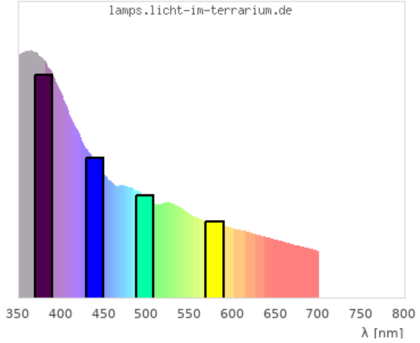
UV BLUE GREEN RED

The four photoreceptor responses are calculated as:

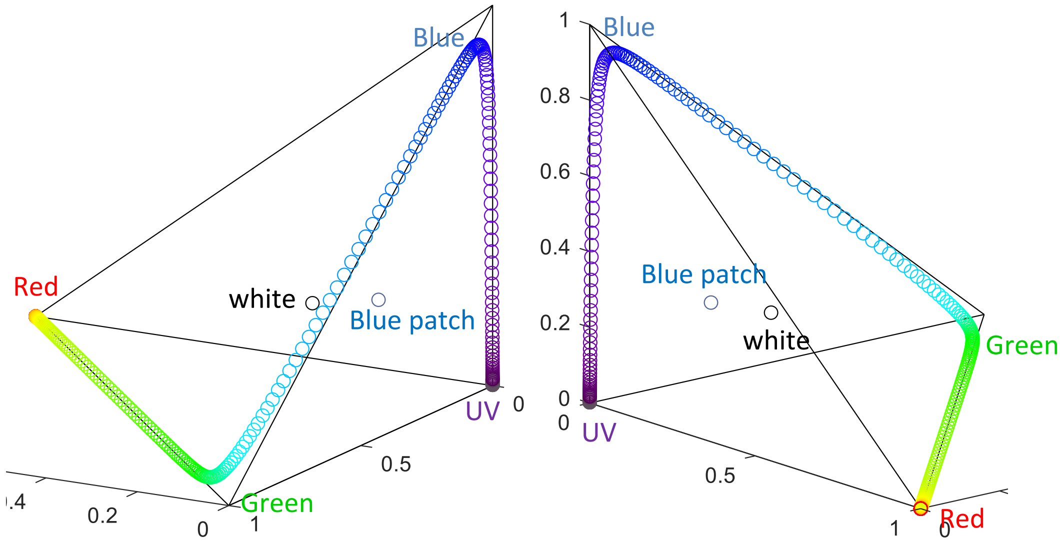
$$\text{Red Signal} = \int d\lambda \quad \text{Reflectivity}(\lambda) \cdot \text{Red Photoreceptor Sensitivity } (\lambda)$$
$$\text{Green Signal} = \int d\lambda \quad \text{Reflectivity}(\lambda) \cdot \text{Green Photoreceptor Sensitivity } (\lambda)$$
$$\text{Blue Signal} = \int d\lambda \quad \text{Reflectivity}(\lambda) \cdot \text{Blue Photoreceptor Sensitivity } (\lambda)$$
$$\text{UV Signal} = \int d\lambda \quad \text{Reflectivity}(\lambda) \cdot \text{UV Photoreceptor Sensitivity } (\lambda)$$

The Photoreceptor Sensitivities are normalized such, that for $\text{Reflectivity}(\lambda) = 1$ the four Signals are identical: Red Signal = Blue Signal = Green Signal = Red Signal. This is defined as "white".

For the blue patches, the signals to the four photoreceptors are: Red Signal = 0.7, Green Signal = 0.95, Blue Signal = 1.3 and UV Signal = 2.05.



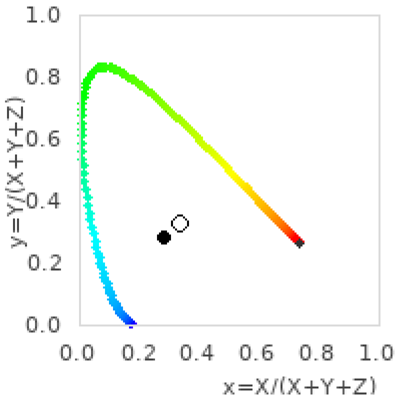
The standard procedure in colorimetry (the science of measuring colour) is to convert the 4 photoreceptor signals into a 3-dimensional coordinate in colour space. In this example the four signals add up to 0.7 + 0.95 + 1.3 + 2.05 = 5, so the rule is to divide them by 5 and use the first three as coordinates: (x,y,z) = [0.14,0.19,0.26]. This means that if only the red photoreceptor were to receive a signal, the coordinate would be at [1,0,0]. Likewise [0,1,0] is the green photoreceptor, [0,0,1] the blue photoreceptor and [0,0,0] the UV photoreceptor. To give more orientation in the colour space also the colour coordinates of all colours of the rainbow are shown:



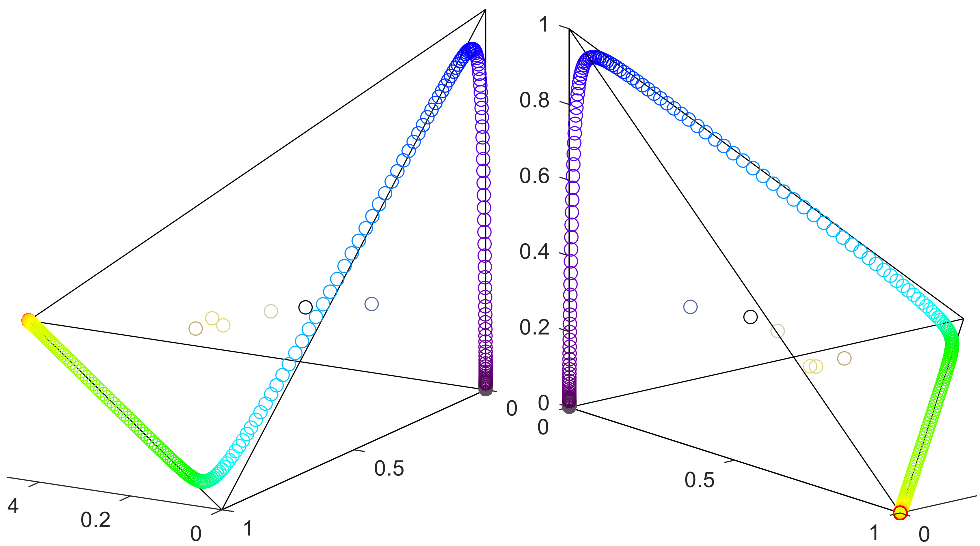
There are different conventions on how to shape the pyramid: Rectangular or equilateral, what corner to use for which colour, how to rotate the pyramid. I have chosen the mathematically easiest form.

The colour space allows to learn something about the appearance of colours even though we are not able to see these colours. The closer two colour coordinates are, the closer these colours looks. A mix of two colours always lies on the line connecting the two colours. All colours that are possible to be seen by a lizard lie within the pyramid. The colour pyramid tells us, that the colour of the “blue” patch to the lizard is a mix between UV and blue, far away from white.

For human colour vision the colour space is the famous CIE colour triangle (there also exist many other colour space representations). Here it can be seen that the blue colour is not a “bright” spectrally pure blue but actually lies close to the white point. To humans blue patches appear a bit greyish-blue.

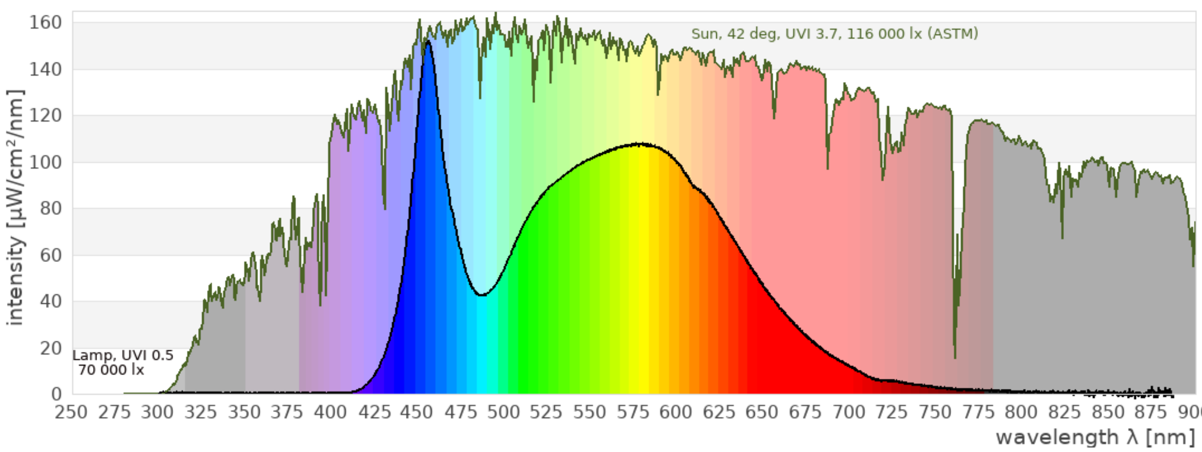


In this paper [1] also other coloured areas of the lizard where measured: The brownish dorsum and the white, yellow or orange throat:



Here it becomes clear, that even though the orange and yellow morph look quite different from a human perspective, the two colours are very close in the colour space of a tetrachromat reptile. And the “white throat” has more difference to the white point than in human colour space.

Now what interests me most, is what happens if these animals are not in their natural habitat but in human care. LED lights have become very high-quality light sources in the past years – from a human perspective. From a reptile’s perspective these light sources lack UVA radiation and thus are not able to render colours containing UV. I have chosen to base my calculation on this light LED light source, which is typical for many LED lamps with approximately 5000 Kelvin.

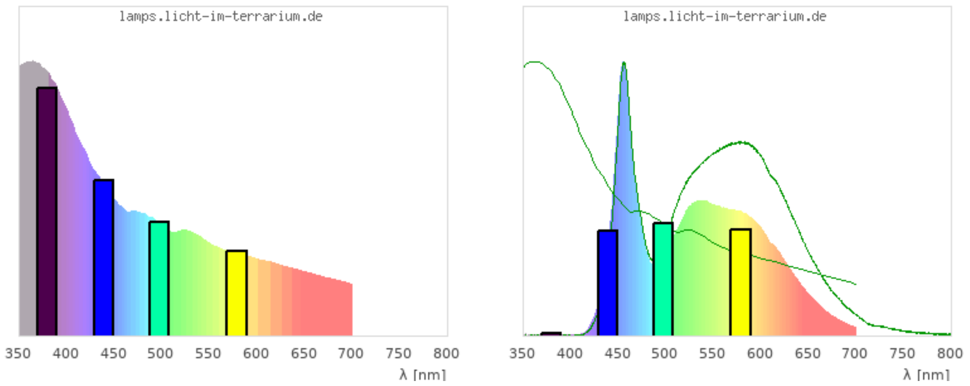


With a light source the calculation of the photoreceptor signals changes to:

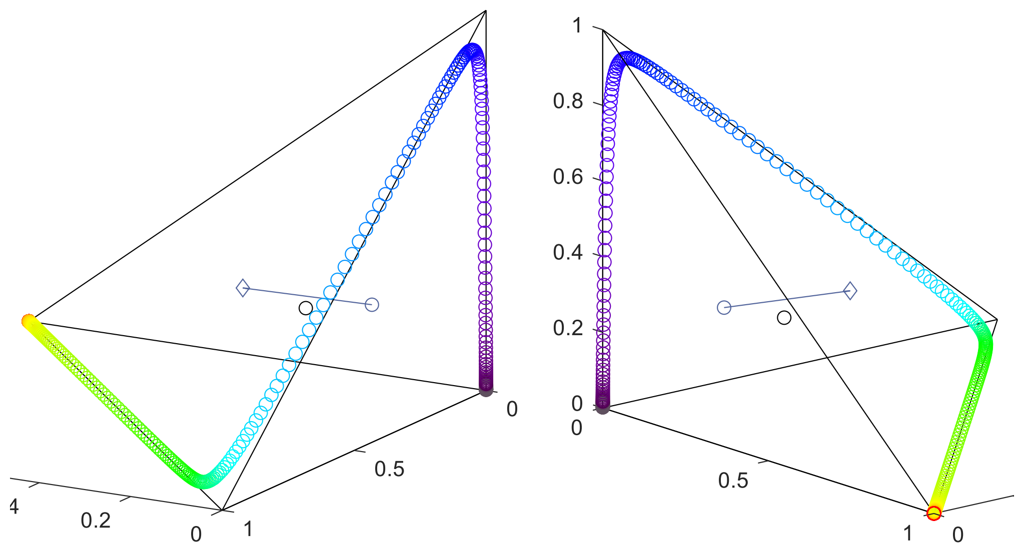
$$\text{Red Signal} = \int d\lambda \quad \text{Reflectivity}(\lambda) \cdot \text{Lightspectrum}(\lambda) \cdot \text{Red Photoreceptor Sensitivity } (\lambda)$$
$$\text{Green Signal} = \int d\lambda \quad \text{Reflectivity}(\lambda) \cdot \text{Lightspectrum}(\lambda) \cdot \text{Green Photoreceptor Sensitivity } (\lambda)$$
$$\text{Blue Signal} = \int d\lambda \quad \text{Reflectivity}(\lambda) \cdot \text{Lightspectrum}(\lambda) \cdot \text{Blue Photoreceptor Sensitivity } (\lambda)$$
$$\text{UV Signal} = \int d\lambda \quad \text{Reflectivity}(\lambda) \cdot \text{Lightspectrum}(\lambda) \cdot \text{UV Photoreceptor Sensitivity } (\lambda)$$

It would be necessary to re-normalize the Photoreceptor signals, so that for constant reflectivity (=white object) the four photoreceptor signals are equal again. This is the mathematical description of what is “white balance” in digital photography or “colour constancy” in vision. This is however not possible for a LED light source because the UV photoreceptor will receive no signal at all.

Doing this, the signal to the four photoreceptors from the blue patches changes from the left graph to the right graph:

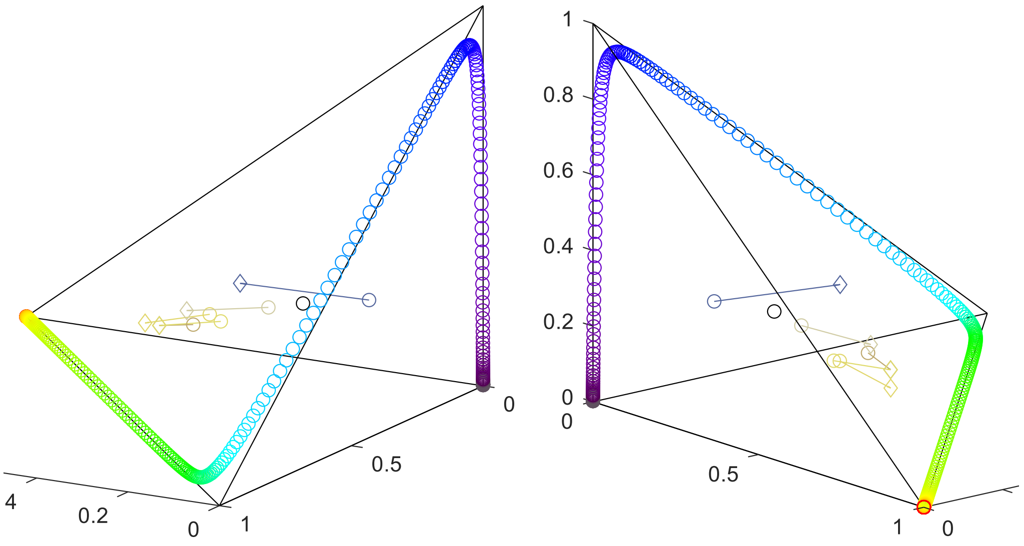


The impact on the photoreceptor signals is drastic. And such changes the colour coordinate from the circle shaped dot to the diamond shaped dot:



The colour changes to the opposite side of the white point. Colours on the opposite side of the white point are called complementary colours. For humans these are for example orange and blue, or red and cyan. What a drastic change in colour!

Also the other colours change:

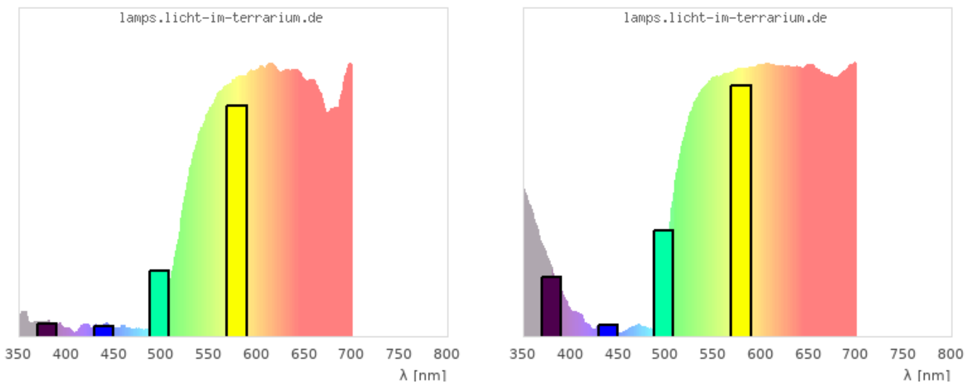


Another colour example comes from this paper [2], where flower colours were measured and evaluated in the colour space of honeybees.

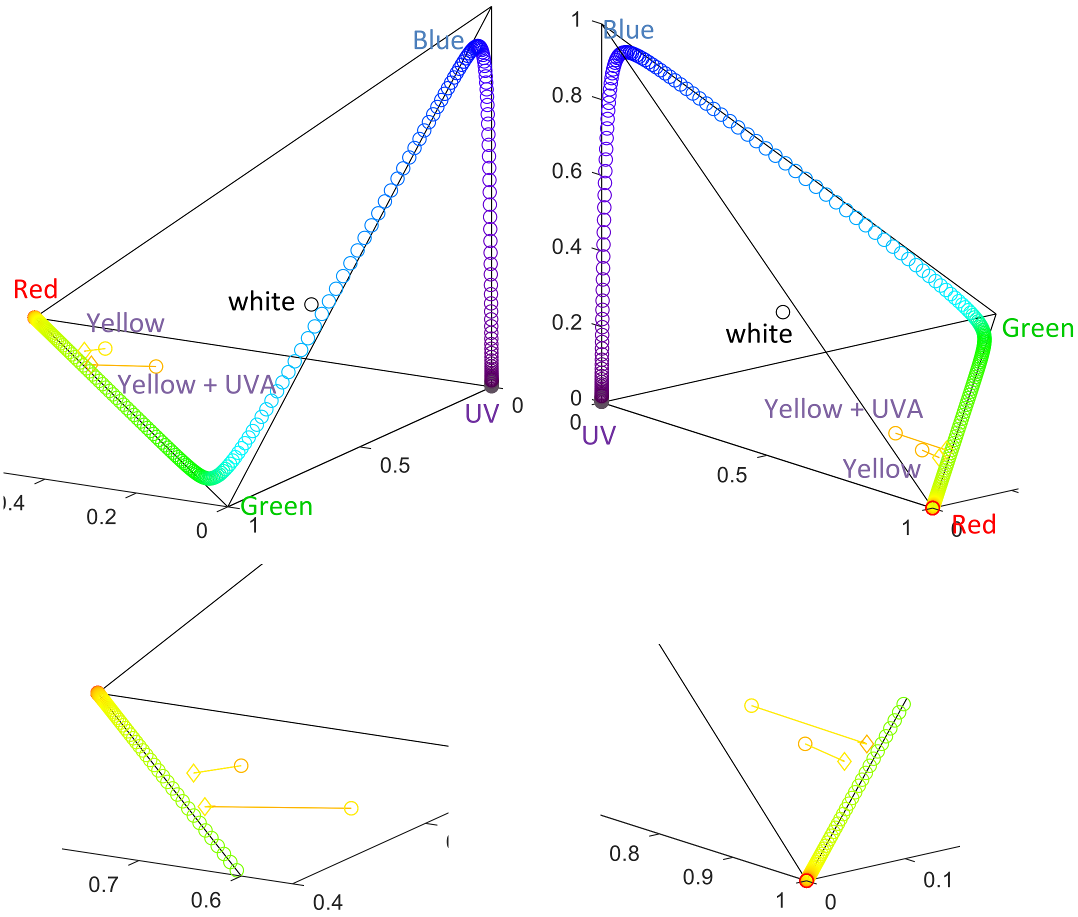
[2] L. Chita et al. (1994). Ultraviolet as a component of flower reflections, and the colour perception of Hymenoptera. Vision Research 34.11. 1489–1508.

There are many flowers that look homogeneously yellow to humans, but actually have two different colours. This is a photo that I have taken with a special UV camera and UV illumination of the flowers of the Jerusalem artichoke. It is purely yellow in its center and yellow with UVA at the outer parts.

The two reflection spectra together with their impact on the four photoreceptors are (left yellow only, right yellow + UVA):



In the colour pyramid the two colours lie close to each other because the UVA contribution is small. But when a LED light source is used, they become indistinguishable:



It is hard for humans to imagine what we do to reptile colour vision if we keep them under light sources that do not emit one colour. The mathematics of colorimetry helps to get a small insight.

[1] Badiane, A., & Font, E. (2021). Information content of ultraviolet-reflecting colour patches and visual perception of body coloration in the tyrrhenian wall lizard podarcis tiliguerta. *Behavioral Ecology and Sociobiology*, *75*, DOI: 10.1007/s00265-021-03023-2.

[2] L. Chita et al. (1994). Ultraviolet as a component of flower reflections, and the colour perception of Hymenoptera. Vision Research 34.11. 1489–1508.