Faraday Discussions

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DISCUSSIONS

The role of structure: order *vs.* disorder in bio-photonic systems: general discussion

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Amanda Holt opened a general discussion of the paper by Hendrik Hölscher: Is the scaling law you observed gender independent?

Hendrik Hölscher replied: You are right, we should have discussed that. Unfortunately, we had no option (or knowledge) to distinguish male and female butterflies when we conducted the experiments several years ago. So, most likely the overall data contains a random mixture of male and female butterflies. However, as we do not observe any significant outliers, my first guess is that gender is not important, but it is definitely an issue to be considered in the future.

Yin Chang remarked: Thank you for the great talk. I think the scaling law is a very interesting observation, especially as it covers a broad range of butterflies crossing different areas and genera.

I was wondering if the scaling law is related to the body size (wing size) of the butterflies? If so, do functions such as self-cleaning also work for every different length-scale? A second question is: I want to know your opinions on the functions of this special design. Because the structures in living animals are also possibly an adaptation to multifunctions rather than a perfect adaptation for one function; have you maybe tried simulation with varied ridge geometry to see the optimized structure (sorry if there are already studies on this and for my limited knowledge of this field)?

Do you think it is possible that rather than being an optimized geometry for functions, the geometry is a result of cuticle self-assembly? These similar compositions grow following similar pathways and the structures scale up.

Hendrik Hölscher responded: Thank you for your interesting questions. Up to now we did not observe an influence of body size. In general, we observed larger distances for the ridges for larger butterflies. But that's not a simple linear relation. An interesting study on the scaling of butterfly scales *vs.* body size was published in ref. 21 of the paper.[1]

Regarding the length scales for (dry) self-cleaning we did some experiments and concluded that it works best if the distance of the ridges is smaller than the size of the dirt particles. Typical dirt particles that butterflies might experience include pollen which has a typical size of some 10 μm. Considering that the typical distance of ridges is a few μm, everything seems fine here.

I agree with you, regarding your second question. The observed scaling law is most likely an adaptation to multi-functionality. However, up to now we haven't conducted any simulation on this issue.

Finally, we also first thought that the scaling law is the result of some constraints like phylogenetic factors (please see ref. 13 of the paper for a discussion on that).[2] However, in the meantime we observed many butterfly scales which have a very arbitrary shape, *i.e.*, you can find bristles or even scales with fancy gyroid nanostructures. So, I would expect that nature could build butterfly scales with a wide range of designs. Consequently, I conclude that the scaling law is mainly a result of multi-functionality.

1 T. J. Simonsen and N. P. Kristensen, *J. Nat. Hist.*, 2003, **37**, 673–679.
2 D. Adriaens, *Proc. SPIE*, 2019, **10965**, 1096509.

Primoz Pirih commented: The studied species come from different branches of the butterfly tree – see *e.g.* the phylogeny by Heikkilä *et al.*[1] Have you looked at the distribution of the cell's morphological parameters across different groups? Perhaps there are subtle differences between different families? How about the lifestyle – for instance, *Aglais urticae* hibernates while some others do not. How about the related skippers (*Hesperiidae*) which have different flight dynamics? In some higher moth families, there are closely related diurnal and nocturnal species, and species that have a summer and a winter form. This would perhaps be worth exploring.

1 M. Heikkilä, L. Kaila, M. Mutanen, C. Peña and N. Wahlberg, *Proc. R. Soc. B*, 2012, **279**, 1093–1099.

Hendrik Hölscher answered: Thank you for your interest and your kind suggestions, we will have a closer look at that. Obviously, there is more to explore. Analyzing more species with advanced flight dynamics will be of high interest.

Andrew Parnell remarked: Please see the slides presenting some of our data; this pertains to height and ridge spacing for a number of butterfly species. We have overplotted some of our own data for a number of *Heliconius* butterflies onto the figure from your paper (DOI: 10.1039/d0fd00038h) and find that it does not follow your scaling law (Fig. 1). Our AFM data on the ridges has been verified using ultra small angle X-ray scattering (USAXS) (Fig. 2 and 3, Table 1). We see very consistent ridge spacing and in recent experiments we find that the ridge spacing is very tightly controlled (Fig. 4 and 5).

So the question is: did you perform a height histogram or take individual line profiles?

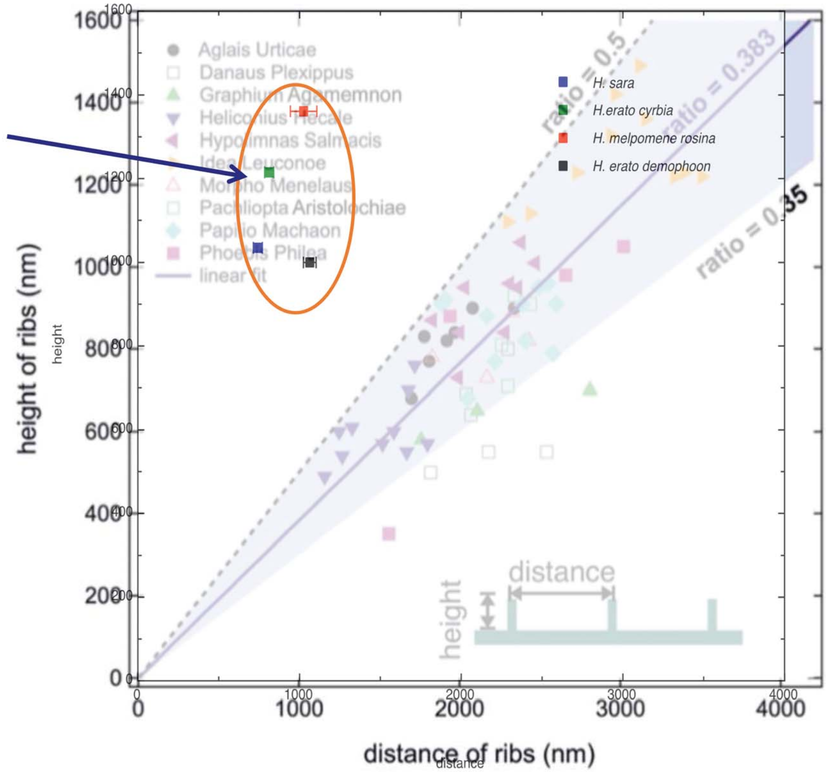

Fig. 1 If we overplot some of our own AFM data for *Heliconius* butterflies, we see that it lies away from the scaling law.

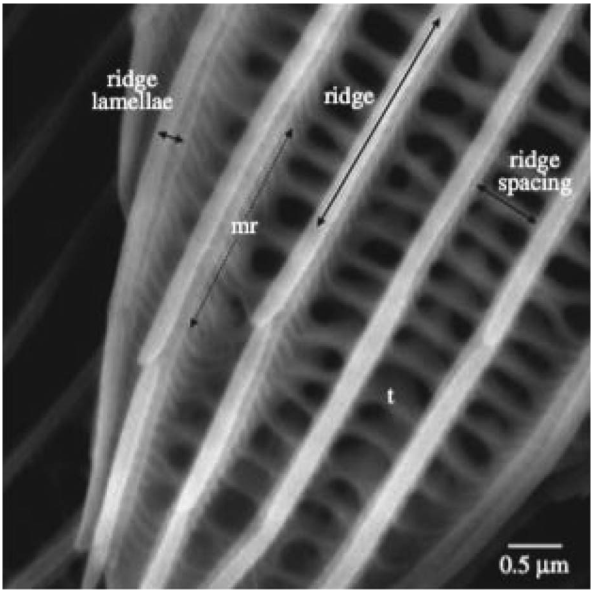

Fig. 2 The general structures seen on a *Heliconius* wing scale. Reproduced from ref. 1.

Table 1 Summary of reflectance parameters and ridge spacing measurements for all taxa

Species	Ridge spacing from AFM (nm)	Ridge spacing from SAXS (nm)	Wavelength of peak reflectance (nm)
H. erato cyrbia	887	812 ± 28	369 ± 8
H. erato demophoon	1149	1063 ± 39	~700
H. sara (Ecuador)	723	742 ± 28	497 ± 7
H. sara (Panama)	—	—	443 ± 3
H. eleuchia	1159	889 ± 73	455 ± 12
H. cydno	1143	929 ± 58	390 ± 2
H. melpomene cythera	1242	823 ± 22	362 ± 10
H. melpomene rosina	1253	1025 ± 82	~700

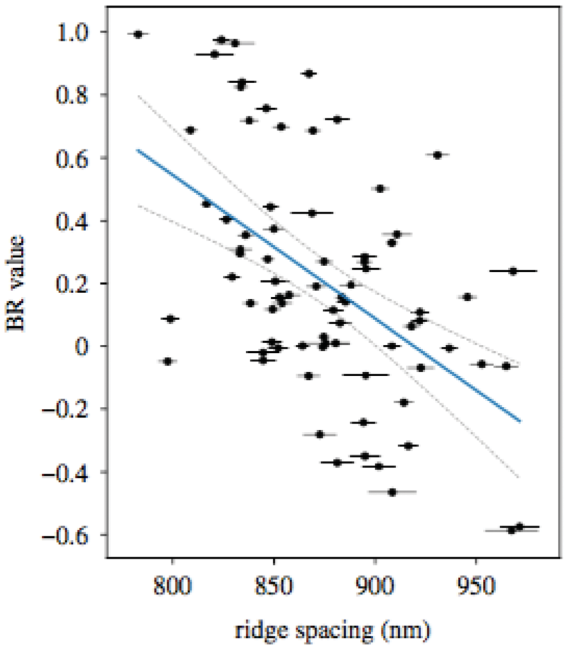

Fig. 3 For *Heliconius erato* crosses we observed an increase in longitudinal ridge spacing which correlated with a decrease in blue-red values. The cross-hairs show the standard error from the 33 to 133 SAXS point measurements for each individual. The blue line indicates the fitted linear regression, with the dotted lines showing the 95% confidence interval. Reproduced from ref. 2.

We verified that this breaks down for the same *Morpho* species you studied in your paper (DOI: 10.1039/d0fd00038h) (see Fig. 6). Can you be a little clearer on the data analysis you performed on the AFM images please?

What are we doing wrong in not being able to get our data to follow your scaling law?

1 A. J. Parnell, J. E. Bradford, E. V. Curran, A. L. Washington, G. Adams, M. N. Brien, S. L. Burg, C. Morochz, J. P. A. Fairclough, P. Vukusic, S. J. Martin, S. Doak and N. J. Nadeau, Wing scale ultrastructure underlying convergent and divergent iridescent colours in mimetic *Heliconius* butterflies, *J. R. Soc., Interface*, 2018, **15**, 20170948.

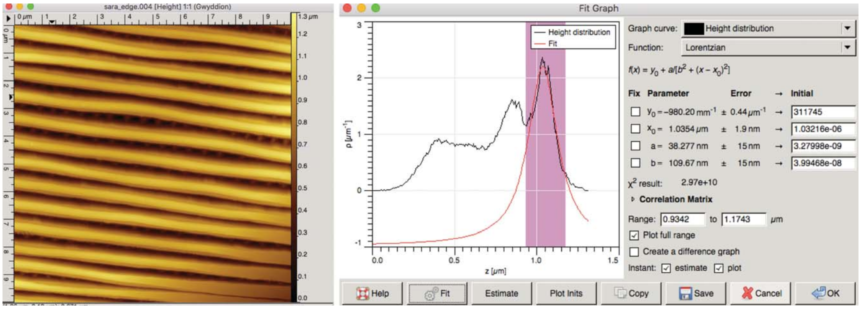

Fig. 4 Our AFM data for *Heliconius sara*, showing height histogram analysis; this is for the whole 10 μm × 10 μm scan area.

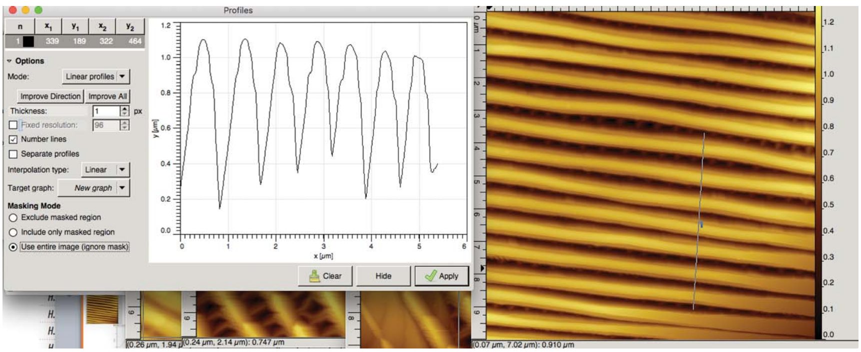

Fig. 5 Again our AFM data for *Heliconius sara*, showing height analysis; this shows an individual line cross section for the image.

2 M. N. Brien, J. Enciso-Romero, A. J. Parnell, P. A. Salazar, C. Morochz, D. Chalá, H. E. Bainbridge, T. Zinn, E. V. Curran and N. J. Nadeau, Phenotypic variation in *Heliconius erato* crosses shows that iridescent structural colour is sex-linked and controlled by multiple genes, *Interface Focus*, 2018, **9**, 20180047.
3 F. Liu, Y. Liu, L. Huang, X. Hu, B. Dong, W. Shi, Y. Xie and X. Ye, Replication of homologous optical and hydrophobic features by templating wings of butterflies *Morpho menelaus*, *Opt. Commun.*, 2011, **284**, 2376–2381.

Hendrik Hölscher responded: Thanks a lot for your interest. I highly endorse the fact that you looked right away at your own data. Actually, that's what we hoped for. I assume that there is much more data recorded by scientists in the last decades that could be used to test our hypothesis.

I discussed this with you directly after the conference and we concluded that your plots are most likely based on different geometrical analysis. In our case, we considered only cover-scales and defined the "height of the ridges" as the height distance between the top of the ridges and the upper edge of the ribs connecting them (please see Fig. 2(c) in our article, DOI: 10.1039/d0fd00038h). Actually, this definition does not work for all types of scales because the ribs are not present in every scale design. It is our conclusion that the scaling-law holds only for scales which have a so-called "generic" structure (see Fig. 32 in ref. 16 of the paper).[1]

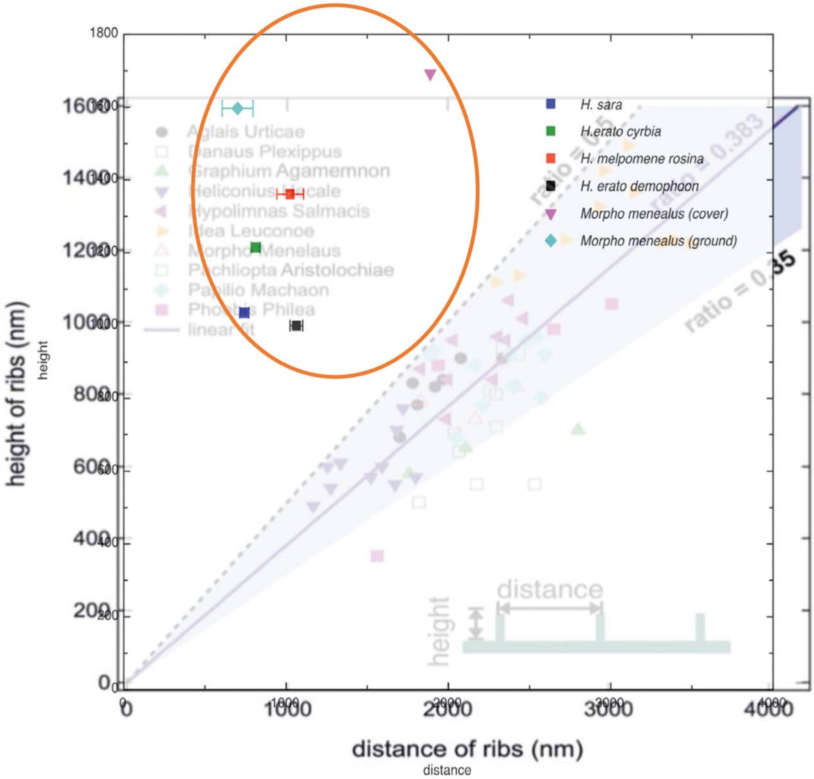

Fig. 6 The AFM data for *Morpho* butterflies also lies away from the scaling law. *Morpho menelaus* data from ref. 3.

1 H. Ghiradella, *Microscopic Anatomy of Invertebrates*, ed. F. W. Harrison and M. Locke, Wiley-Liss, Inc., 1998, vol. 11A: Insecta, pp. 257–287.

Mike Hardy commented: Thank you for your talk, Hendrik. Do you have any measures to minimise scale structure deformation during TEM analysis (Fig. 2c of the paper, DOI: 10.1039/d0fd00038h)? This problem is discussed briefly in the text (with epoxy resin use). I appreciate that your main characterisation modalities are AFM and SEM.

Hendrik Hölscher replied: Thank you for your interest. Colleagues at the University of Münster conducted the sample preparation for the TEM images presented in our paper (DOI: 10.1039/d0fd00038h) some years ago. We cannot fully exclude that some minimal scale structure deformation happened.

However, that's the reason why all the presented geometrical data was recorded by atomic force microscopy (and not by TEM). Here, we can exclude any significant deformation of the scales. With this approach, the samples can be imaged directly without specific sample preparation.

If TEM of butterfly scales with minimal damage by sample preparation is of interest to you, you might have a look at the paper by Siddique *et al.*[1] Here our colleagues from the University of Heidelberg describe briefly their approach to prepare TEM samples, which seems not to harm butterfly scales in an observable way.

1 R. H. Siddique, S. Vignolini, C. Bartels, I. Wacker and H. Hölscher, *Sci. Rep.*, 2016, **6**, 36204.

William Wardley asked: Are you looking at fabricating equivalent structures in polymers to test the various hypotheses you have for the function of the structure in the butterfly wing? Looking at the figures in the paper (DOI: 10.1039/d0fd00038h), I think either electron-beam lithography or two-photon polymerisation techniques ought to be able to build structures on a similar size scale and that those replicas of the structures would offer an excellent test-bed to explore your hypotheses regarding function.

Hendrik Hölscher answered: Thank you for your interesting question. Yes, we have already produced several artificial surfaces made from polymers using the so-called hot embossing (or nanoimprint) technique. Here, we analyzed the dry self-cleaning properties and got very convincing results (please see ref. 39 of the paper for details (sorry, only in German up to now)).[1] We plan to go on in that direction.

1 F. Vorholt, Bachelor thesis, Fachhochschule Münster, 2009.

Laura Ospina remarked: You mentioned a trade-off between visual signals and alternative functions like air self-cleaning. How does the top layer of scales affect the overall appearance? Do these scales contribute to generating the colour with the same nanostructures and periodicity as the bottom layer? Does the presence of these scales add to the overall disorder of the structure, therefore modifying the appearance?

Hendrik Hölscher responded: Yes, some butterflies developed coloring strategies where the interplay between cover- and ground-scales is important. See, for example, the coloring of the butterfly *Hypolimnas salmacis*, where blue color appears when the cover-scales lie on top of the ground-scales. The ground-scales alone are brownish while single cover-scales appear white (please see Fig. 1d in the paper by Siddique *et al.*).[1]

1 R. H. Siddique, S. Vignolini, C. Bartels, I. Wacker and H. Hölscher, *Sci. Rep.*, 2016, **6**, 36204.

Gea Theodora van de Kerkhof commented: The butterflies you studied come from all over the world. Did you find any connection between the height/spacing ratio and their natural environment? I could for example imagine that the climate in which the butterflies live is important if the ridges are used for thermoregulation (as mentioned as a possible function for the scales in the manuscript, DOI: 10.1039/d0fd00038h).

Hendrik Hölscher answered: Thank you for pointing that out. Actually, that's the reason why we examined butterflies from all over the world. We expected that the scaling-law might change depending on their environment. We first analyzed the scaling of the ridges for the "small tortoiseshell", which is native to Europe, before we subsequently analyzed butterflies from completely different environments like rain forests. Nonetheless, we did not observe any change in the scaling-law.

Primoz Pirih stated: I would like to bring to your attention a very recent study by Cheng-Chia Tsai *et al.* where they show that the wing is a physiologically active structure that works as part of an active cooling system and, quite interestingly, as a sensor for IR and visible radiation.[1] Perhaps you can comment on how the scale's cell dimension would be related to heating/cooling in these complex systems?

1 C.-C. Tsai, R. A. Childers, N. N. Shi, C. Ren, J. N. Pelaez, G. D. Bernard, N. E. Pierce and N. Yu, *Nat. Commun.*, 2020, **11**, 551.

Hendrik Hölscher responded: Thank you for guiding me to this interesting study. Up to now we have not analyzed the heating/cooling but we will look into it.

Christian Kuttner asked: Is the scaling law you mentioned also a relevant parameter for structural stability – perhaps in the context of stress dissipation?

Hendrik Hölscher replied: Thank you for pointing that out. We also thought about that. In principle, it might be that a ratio of 0.5 between the distance and height of the ridge is best for the stability of the scales. However, we finally concluded that this is not relevant because the scaling-law does not hold for several ground-scales and for many scales which do not have the "generic" structure (please see Fig. 32 in ref. 16 of the paper for the definition).[1]

1 H. Ghiradella, *Microscopic Anatomy of Invertebrates*, ed. F. W. Harrison and M. Locke, Wiley-Liss, Inc., 1998, vol. 11A: Insecta, pp. 257–287.

Anthony McDougal remarked: You discuss how the constraints for the scaling law may come from functional requirements of the scale. How do you think the constraints from functionality of the scale compare to constraints that may arise from scale development processes?

Hendrik Hölscher responded: Thank you for bringing that up. At first, we also thought that the scaling-law might be the result of scale development or other constraints like phylogenetic ones (please see ref. 13 of the paper for a discussion on that).[1] Actually, we cannot exclude that completely, but we observed that many butterfly scales have a more or less arbitrary shape, *i.e.*, you can find bristles or even scales with fancy gyroid nanostructures. Therefore, I assume that the scale development might result in very different designs if nature wants and that multifunctionality is the most likely reason for the observed scaling-law.

1 D. Adriaens, *Proc. SPIE*, 2019, **10965**, 1096509.

Sébastien R. Mouchet opened a general discussion of the paper by Lukas Schertel: In your paper (DOI: 10.1039/d0fd00024h, Fig. 2b), it seems that the reflectance at wavelengths longer than 700 nm is very high when the wax is intact (I am not sure whether the units of the *y*-axis are % or a.u.). Have you looked at the response in the (near-)IR? Could you comment on a possible role of the wax in thermal management?

Lukas Schertel responded: In specular reflection (Fig. 2b), the reflected intensity strongly increases for long wavelengths and we expect this also to continue in the NIR, but we could not measure at larger wavelengths. However, we do not think that this nanostructure plays any special role in thermal management as we would expect features to be on the micron-scale as the infrared atmospheric window is between 8 and 14 micrometres, significantly away from this reflection edge.

Amina Matt asked: In the FDTD modeling, when you show the disordered structure results, are they an average of multiple simulations? If yes, how many simulations are there and did you look into different amounts of disorder?

Lukas Schertel replied: The simulations shown in Fig. 4b of the paper (DOI: 10.1039/d0fd00024h) are the result of one run of an FDTD simulation. Their reproducibility, however, was tested and found to be 100%. The red "averaged" curve in Fig. 4c is the result of an average over 10 thicknesses between 0.5 μm and 2.3 μm. For studying the disorder in the platelet orientation, the platelets were tilted by an angle θ which was normally randomly distributed with mean 0° and standard deviation of 20°. We further studied the case of a rough surface (see Fig. 7a) as a second configuration of the disorder.

Alex Qiu enquired: Did you also investigate the effect of disorder in platelet or cuticle dimensions (in the model of a collection of platelets on a substrate)?

Lukas Schertel answered: Indeed, we studied the effect of the dimension of the wax platelets (Fig. 3 of the paper, DOI: 10.1039/d0fd00024h). We did not observe any increase in intensity for long wavelengths for the single platelets. We thus conclude that the golden shine is really originated from the disorder in the structural assembly of platelets. We also investigated the role of the thickness of the epidermal cell wall (Fig. S7b). The observed fringe pattern shows larger oscillations for smaller thickness, as expected for thin-film interference.

Anthony McDougal asked: What is the range of platelet angles used in your FDTD simulation of the leaf and multiple platelets (for example, as you show in Fig. 4b of the paper, DOI: 10.1039/d0fd00024h)?

Lukas Schertel responded: The platelets were tilted by an angle θ which was normally randomly distributed with mean 0° and standard deviation of 20°. The leaf was not tilted in the simulation. A plane incident wave at 0° was used in the simulations.

Sébastien R. Mouchet remarked: Do we know or have an idea of the chemical composition of wax in plants in general or on the leaves of *Tradescantia pallida*?

Lukas Schertel answered: We did not study the chemical composition of the wax platelets of *Tradescantia pallida*. However, there are several other studies on the chemical composition of wax in other *Tradescantia* species, such as *Tradescantia blossfeldiana L.*[1] A good introduction to the composition and structure of epicuticular waxes on leaves can further be found in ref. 2. In this study, the chemical composition is used to classify different types of waxes in plants.

1 E. N. Dubis, A. T. Dubis and J. W. Morzycki, *J. Mol. Struct.*, 1999, **511–512**, 173–179.
2 W. Barthlott, C. Neinhuis, D. Cutler, F. Ditsch, I. Meusel, I. Theisen and H. Wilhelmi, *Bot. J. Linn. Soc.*, 1998, **126**, 237–260.

Christian Kuttner addressed Lukas Schertel and Silvia Vignolini: Is it already understood how the wax layer is formed by the plant? Is the plant able to repair a damaged wax layer?

Lukas Schertel responded: We are not aware of any study discussing the growth and regeneration of wax platelets in *Tradescantia pallida*. On a short time scale (a few weeks) in standard growing conditions we have not observed that the plant is capable of repairing the layer. We refer to existing literature that studies the classification and formation of wax in other plant systems.[1,2]

1 W. Barthlott, C. Neinhuis, D. Cutler, F. Ditsch, I. Meusel, I. Theisen and H. Wilhelmi, *Bot. J. Linn. Soc.*, 1998, **126**, 237–260.
2 C. Buschhaus and R. Jetter, *Plant Physiology*, 2012, **160**, 1120–1129.

Silvia Vignolini replied: I think Lukas Schertel already answered also on my behalf! We are not aware of any study discussing the growth and regeneration of wax platelets in *Tradescantia pallida*. On a short time scale (a few weeks) in standard growing conditions we have not observed that the plant is capable of repairing the layer. We refer to existing literature that studies the classification and formation of wax in other plant systems.[1,2]

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2 C. Buschhaus and R. Jetter, *Plant Physiology*, 2012, **160**, 1120–1129.

Victoria Lloyd asked: is the golden reflection also present in the younger leaves? And if so how does it compare to the mature leaves? If you predict an anti-herbivory role for the colour, would you not also expect it to be important in younger leaves?

Lukas Schertel answered: Yes, we saw the wax platelets and a golden shine also in younger leaves and expect them to have the same function there (note that the function is not identified yet). However, we did not particularly study the effect of ageing in this case. We expect that the platelet density and size might vary with age (become larger and denser).

Esteban Bermudez Ureña commented: Are the wax platelets "soft" (malleable) or rather rigid? Can you for example transfer them without deforming them in case you wanted to study them separately?

Lukas Schertel replied: The platelets are soft. After rubbing the leaf with your fingers you could see on the microscope that the wax had smeared out, and rubbing it further removed the wax completely. We did not try to transfer them, other than to scrape the whole wax layer off and check the refractive index. For this last experiment, we just looked at the collective wax and didn't check if the platelets kept the same morphology. However, there have been studies where people managed to transfer the entire layer of wax platelets and keep them intact. This can be done by submerging the wax (on the leaf) in glycerol, and then freezing it with liquid nitrogen. While frozen the leaf can be removed and the wax stays behind in the glycerol (as described in ref. 1).

1 H. J. Ensikat, C. Neinhuis and W. Barthlott, *Int. J. Plant Sci.*, 2000, **161**, DOI: 10.1086/314234.

Amanda Holt asked: I am curious if you know what causes the feature at ~500 nm in the reflectance spectrum of both the plant and the FDTD simulations? And was absorption considered in the FDTD simulations? On a general note, how do we access the supplementary figures for your manuscript?

Lukas Schertel responded: We think that the remaining spectral feature that can be observed around 500 nm is associated with the fringe pattern that is visible before averaging the simulation data for various layer thicknesses. In the experiment, for a smaller incident angle (see Fig. S4 of the paper, DOI: 10.1039/d0fd00024h), more oscillations are visible and can be associated with a fringe pattern from thin-film interference. In the FDTD simulations, absorption was neglected as the studied layer was transparent in the experiments. The SI can be found online together with the manuscript: https://doi.org/10.1039/d0fd00024h.

Golnaz Isapour opened a general discussion of the paper by Diederik S. Wiersma: What is the mechanism of the elastomer's response to the color of the object?

Diederik Wiersma responded: The absorption spectrum of the object (which defines its colour) has to match the colour of the laser, or other kind of illumination source. If the light is absorbed, there will be local heating and the elastomer responds. So it is about matching the spectrum of the object with that of the illumination.

Note that this can be broadband (red/green/blue *etc.*), but in principle also very specific. If you take absorption spectra with (many) narrow spikes, and a light source that also has (many) spikes, you can match the spikes of the source with those of the object, creating an enormous amount of "matching/not matching" possibilities.

Christian Kuttner commented: In Fig. 6d of your contribution (DOI: 10.1039/d0fd00032a) it is shown that upon heat treatment, the substrate crumples and deforms. Can this be circumvented? I suppose the goal would be to limit the structural changes at the material surface/interface, right?

Diederik Wiersma answered: Thank you for this important point. We are indeed exploring how to do this. Much depends also on the sample geometry and anchoring points.

Laura Ospina remarked: How is it possible to combine the elastomer with the *Morpho* without dramatically altering the RI of the structure in the scale? What are the properties of the elastomer that allow it to embed in the Christmas tree-like structures of the butterfly while keeping the colour as vivid as in the intact wing?

Diederik Wiersma responded: In principle this seems possible. I do not know the detailed properties that the elastomer has to fulfil to make it work (and I am unsure if they are fully known), but my guess would be that the viscosity before creating the elastomer network should be low enough. I would also expect that much is related to the matching of hydrophobicity/hydrophilicity, but again these are just educated guesses.

Bianca Datta asked: Is this actuation powerful enough to move loads/cargo? How robust are these actuators?

Diederik Wiersma replied: They can grab a particle and release it, if you make sure that the "fingers" are not sticking. They can, in principle, also push a load forward although we never tried ourselves. The group of Wasylszyk looked at this if I remember correctly. The actuators are quite strong, but we have not yet done any quantitative measurements to give numbers.

Primoz Pirih said: In your presentation, you have shown a structure that worked as a kind of forceps upon light activation. Would it be possible to use the approach to micro-manipulate a living cell? How would this compare to *e.g.* the optical tweezers method?

Diederik Wiersma responded: Interesting question. I would say that one needs to look at the length scales involved (the gripper is about 100–200 micrometers, so this could be applied to cells that are on the large end of the scale). After that I would say that this is possible. Compared to optical tweezers, the intensities involved are much smaller and the degrees of freedom of a gripper – or in general a 3D structure that changes size and shape – are different, and maybe more, than those available with tweezers.

One should take care here in distinguishing the use of elastomers that respond to light *via* an intermediate heating step, and elastomers that respond to light directly without heating. The latter have the advantage that they can be run at constant temperature, which, I assume, could be important for the cell. Keep in mind that in that case the time response of the elastomer is typically slower (order of seconds or slightly better) than for elastomers with an intermediate heating step (order of milliseconds or slightly below).

An idea that comes to mind after thinking about your question is to attach a single cell to a gripper and study the effects due to stretching of the cell, or other forms of deformation. It would be interesting to look into this.

Álvaro Escobar enquired: Do you think this technology could be used for people who have lost muscle or mobility?

Diederik Wiersma answered: This is precisely what we are trying to explore, for instance to help the heart muscle.

Andrew Parnell asked: Can you evaluate the efficiency of this muscle, by evaluating the work done? How does this compare to the efficiency of biological muscles ?

Diederik Wiersma replied: This is an excellent point. We have not measured that so far. The difficulties are in the size. However, for the larger structures we are planning to look into this.

Mathias Kolle remarked: Really interesting implementation of an opto-mechanical converter. Are there implementations/designs that can respond with high sensitivity and response to changing light conditions? Changes in light conditions might arise simply from deformation of the actuators and a change in their light capture efficiency in a static field. Could one create opto-mechanical oscillators this way? On which timescale could such systems oscillate?

Diederik Wiersma responded: Yes this is possible (and a very nice concept in my view). The simplest version of this is a lever that makes a shadow on itself when it bends and hence goes into a bistable mode (and oscillates). This has been demonstrated. Much more complicated, but also very useful, would be something bistable that works at any illumination angle. So there are many interesting things to do regarding design. Response times are of the order of 1 ms, or better if you can live with a more modest excursion (down to say 0.1 ms, so actuation frequencies of 10 kHz). When thinking about design, more complex actions can also be looked into. An application could be a micro robot that walks with cw illumination. We also thought about microfluidics, making *e.g.* a pump that works with cw light.

Helen Clark commented: Is it possible to make structures that would grip something and hold it – and later react to a signal to let it go? I think that one challenge would be placement of the control mechanism. And the required spectral response function would have to be defined and implemented. Is there any current research ongoing that aims to address these challenges?

Diederik Wiersma answered: I think this is a good idea and it should be possible. One should take care of the fingers which should be made non-sticky (*e.g.* by adding rigid “nails”). By playing with the colours one can open and close in a controlled way. One can also close with one colour, and open with another, while nothing happens without light (this is important since it will allow one to keep the gripper closed even without illumination).

At the moment the topic is quite new and there is much to do. We are doing some things like this but cannot possibly do all the experiments ourselves.

Bianca Datta asked: Just to clarify, for the cell tests on liquid crystal elastomers, were they activated by electric field or light? If electric field was used, were there any issues with cell viability?

Diederik Wiersma responded: The cells are actuated by an electric pulse as though they were in a realistic context. The elastomer is actuated at the same time by light.

Thomas G. Parton commented: The elastomer conformation is controlled by changes in temperature. Have you been able to measure the local temperature increase, or temperature gradients, within the elastomers or at the elastomer boundary? My concern is that the temperature effect may make the elastomer less suitable for interfaces with biological systems.

Diederik Wiersma replied: We are using various types of elastomers, some of which require a temperature change and others do not. In the latter case the absorption of light provokes the shape change directly without heating. The disadvantage of this action mechanism is that it is typically slower, but the forces involved are similar.

Conflicts of Interest

There are no conflicts to declare.

