Supplementary Information for

Cave spiders choose optimal environmental factors with respect to the generated entropy when laying their cocoon

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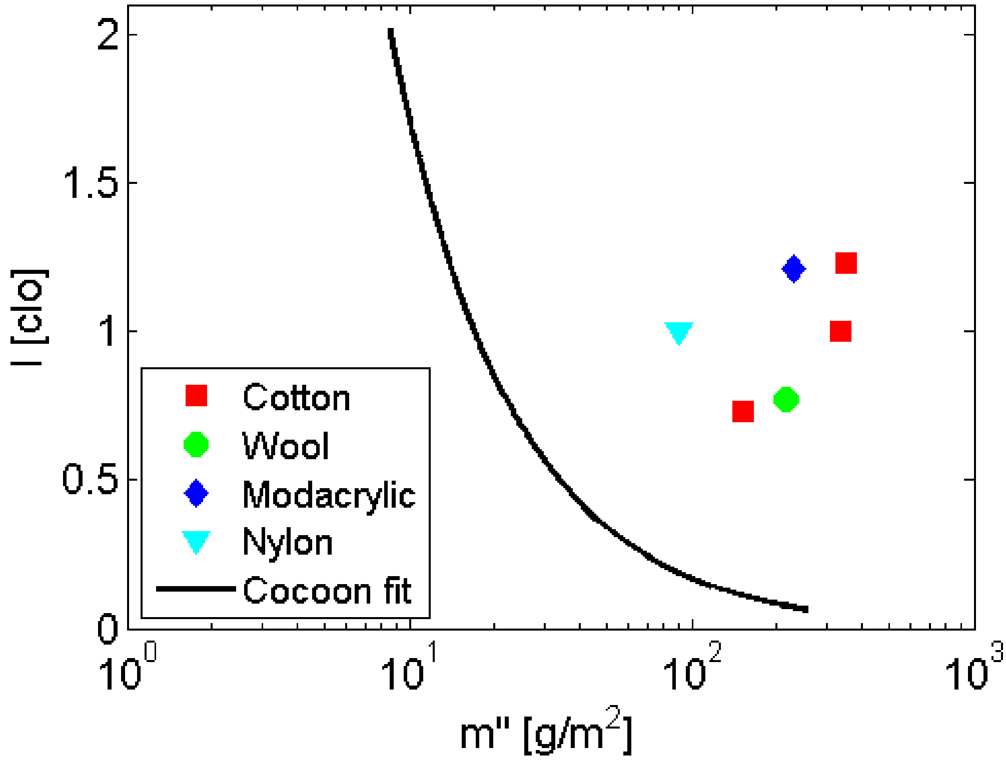
SUPPLEMENTARY FIGURES



Supplementary Figure 1. Thermal insulation properties of cocoons. The cocoon silk is characterized by good thermal insulation properties and ultra-low weight as compared to traditional textiles. Here, the cocoon silk insulating properties are compared to those of traditional textiles. The specific weight (i.e. the weight per unit of insulation surface area, [g/m2]) is denoted by m'', while thermal insulation properties are measured in [clo] (1 clo = 0.155 m2K/W). For defining that quantity, the inner or the outer surface should be chosen. However, owing to the complex structure made of silk wires, the inner surface of a cocoon remains not clearly defined. To overcome these difficulties, we report the continuous black curve denoting the locus of all points of the the cocoon thermal performances corresponding to a range of insulation surfaces from a minimum value strictly needed to surround the eggs up to the maximum value (i.e. area of the outer surface). The black curve presents a hyperbolic shape as the thermal insulation quality and specific weight are directly and inversely proportional to insulation surface area, respectively. Results show that cocoon silk might possibly significantly outperform the traditional textiles in terms of insulation properties (up to 2 times) and specific weight (up to 1 order of magnitude). In light of the above evidence, it is reasonable to expect that those unusual thermal insulation properties may be replicated in the near future using the latest and most advanced manufacturing techniques. To this end, complex structures similar to those shown in the Figure 1a-e could be mimicked by means of 3D printing as soon as the necessary resolution requirements are met.

SUPPLEMENTARY NOTES

Supplementary Note 1. Study sites. Balma Fumarella (cadastre number: 1597 Pi/TO) is a small limestone cave, with a planimetric development of 47 m and a vertical ascent of 16 m. The entrance measures 2 x 2.5 m. The first hall of the cave (approximately 2 x 3 x 20 m) is followed by a narrow passage and a second hall of approximately 1 x 2 x 10 m. In the inner part of the cave the mean annual temperature is around 11 °C (measured at ground level).

Cave di Marra (cadastre number: art. Pi/TO) is an abandoned mine of gneiss. The mine is basically a long tunnel of nearly 70 m, with a regular section of 4 x 5 m. The entrance connecting the tunnel to the outside is a quadrangular hole measuring 1.5 x 2 m. The mean annual temperature inside the tunnel is around 9 °C (measured at ground level).

Grotta del Bandito (cadastre number: 1002 Pi/CN) is a limestone cave, with a labyrinthine planimetric development of 336 m and a vertical ascent of 7 m. The main entrance of the cave measures around 1.5 x 2.5 m and is followed by a 35 m tunnel, with a section of 2.5 x 4 m. A minor entrance (1.5 x 1.5 m) is followed by a narrow tunnel of 10 m leading to a small chamber of approximately 4 x 3 x 10. The mean annual temperature inside the cave is around 10 °C (measured at ground level).

Supplementary Note 2. Model validation. In order to investigate the existence of a possible non-linear response between the presence/absence of cocoons and the explanatory variables, we applied a generalized additive mixed model (GAMM) that allowed us to fit a non-linear effect (smooth) of the covariates on the dependent variable. The model was fitted via the mgcv[1] R package (version 1.7-27) with the same structure derived from the previous model selection. The non-linear trend was rejected by plotting the smooth of the covariates against the observations, revealing a clear linear pattern and confirming the validity of the estimate values generated by the linear mixed model.

Supplementary Note 3. Laboratory experiments. A heater consisting of a compact and thermally stable electrical resistance (of value R) is inserted within the spider cocoon and supplied with a constant potential V. The thermal transmittance Tr can thus be calculated as follows:

$$Tr = \frac{\dot{Q}}{T_w - T_a} = \frac{\frac{V^2}{R}}{T_w - T_a}, \qquad (1)$$

where T_w and T_a are the temperature values recorded by a thermocouple in contact with the above heater and the air temperature, respectively.

Moreover, in our analysis, we also investigated the mass transfer and characteristic times governing the drying and wetting phenomena of the cocoon surface. Let us suppose that a cocoon (initially at a temperature T_w) is sprayed with water by a nozzle ensuring uniform wetting of the entire surface, and concurrently it is invested by an airflow at temperature T_a , velocity U_{air} and relative humidity φ .

In natural conditions, we expect that the cocoon surface experiences several partial wetting events during the time of egg presence. Here, for simplicity, we only considered a single complete wetting event, assuming this is representative of the several natural events.

The partial pressure of water vapor on the cocoon surface is the saturation pressure at T_w , $p_c = p_s(T_w)$, while the partial pressure of water vapor within the air stream is $p_a = \varphi p_s(T_a)$. Assuming $T_w > T_a$, this implies $p_c > p_a$. Thus, a vapor pressure difference is established at the cocoon boundary. Such a difference is responsible for the water mass transport from the cocoon to the air. However, the water transport is possible upon vaporization, and the heat h_{vap} necessary for this process must be extracted from the cocoon itself, which consequently cools down (adiabatic cooling).

In general, the total heat power $\dot{Q}_{tot}$ flowing from the cocoon to the air is the sum of the convective heat flux $\dot{Q}_c$, dictated by the temperature difference, and the latent heat flux $\dot{Q}_{lat}$, which is proportional to the vapor pressure difference:

$$\dot{Q}_{tot} = \dot{Q}_c + \dot{Q}_{lat} \qquad (2)$$

where $\dot{Q}_c = Tr\left(T_w - T_a\right)$ and $\dot{Q}_{lat} = h_{vap} K\left[p_s\left(T_w\right) - \varphi p_s\left(T_a\right)\right]$, being Tr and K the thermal and mass transport transmittance, respectively. During the first set of experiments, we only measured the thermal transmittance Tr, while the mass transport transmittance K was derived by invoking the Chilton-Colburn analogy[2].

In a second set of experiments, in order to determine the characteristic drying time, we focused on a fast wetting process of the cocoon followed by the subsequent drying due to forced airflow. In particular, the cocoon became wet by a spray nozzle, where water is constantly kept thermostatted at the ambient temperature T_a, and the cocoon itself is in thermal equilibrium with airflow before getting wet (see also the Fig. 2 in the main text). At this time, the heater is not powered and no heat sources are present in the cocoon, so that the temperature inside the cocoon suddenly decreases due to adiabatic cooling. Consequently, the temperature T_w decreases generating a temperature difference, and consequently a convective heat flux from the air to the cocoon. To summarize, a heat flux $\dot{Q}_c$ is observed from the air to the cocoon, while a latent (or vaporization) heat flux $\dot{Q}_{lat}$ goes from the cocoon to the air.

More specifically, the temperature T_w varies during time: starting from the initial value $T_w\left(t = 0\right) = T_a$, we firstly observe a sudden temperature decrease till a minimum value is reached (since T_a is constant, $\Delta T = T_a - \left(T_w\right)_{\min} = \Delta T_{\max}$), and subsequently an increase towards the initial value T_a.

We performed experiments exploring different value of the air velocity U_{air} . For each experiment, we calculate the drying constant time, defined as:

$$\tau = t_{tau} - t_{start} \tag{5}$$

where t_{start} indicates the time instant when the cocoon is sprayed, while t_{tau} is the characteristic time, such that $T_a - T_w(t = \tau) = (1 - 0.63)\Delta T_{\max}$.

Supplementary Note 4. Characterization of heat and mass transport transmittances.

During the first set of tests in the wind channel, the electrical assembly (heater and thermocouple described above. See also the Methods section in the main manuscript) is initially characterized without being surrounded by a cocoon (below referred to as naked setup). Subsequently, the above assembly is introduced within the cocoon, and the same characterization is performed.

The error bars in Figure 4a (main manuscript) represent the confidence interval at a level of 95%. Here, two kinds of measurement uncertainties are taken into account: type A uncertainties based on statistical analysis of measured quantities, and type B uncertainties determined by means of any other information (e.g. datasheets).

In this first set of experiments, measurements showed a good repeatability. Therefore, type B uncertainties were judged enough to construct the desired confidence interval. Equation (1) is used to compute Tr as a function of other measured quantities (V, T_a, T_w) and parameters (R), hence $Tr = Tr(V, T_a, T_w, R)$. The standard uncertainty σ_{Tr} for the quantity Tr can be computed by the following formula[3]

$$\sigma_{Tr} = \sqrt{\sum_{i=1}^{4} \sigma_{q_i} \frac{\partial Tr}{\partial q_i}} , \tag{6}$$

where σ_{q_i} is the standard uncertainty for the i-th independent quantity $q_i \in (V, T_a, T_w, R)$.

Supplementary Note 5. Dimensionless analysis. Since analytical solutions are not available for the majority of thermal fluid dynamics problems, it proves convenient to identify all relevant dimensionless quantities governing a system of interest, and ultimately obtain a correlation to relate those quantities.

Except for experiments at an airflow velocity of 0 m/s, here we deal with forced convective heat transfer on a body (naked heaters and cocoons). Hence, two dimensionless numbers are known to be relevant for such systems: the first one is the Reynolds number (Re), defined as:

$$Re = \frac{\rho_a U_{air} L_c}{\mu}, \qquad (7)$$

where ρ_a is the density of the fluid, U_{air} is the airflow velocity, L_c is a characteristic length and μ is the dynamic viscosity. The characteristic length is different for each type of flow. For naked configurations, L_c is chosen to be the height of the cylindrical heater, while in the presence of cocoons it is the square root of the external surface S_c of the cocoon $L_c = \sqrt{S_c}$.

The second relevant dimensionless quantity is the Nusselt number (Nu), defined as:

$$Nu = \frac{hL_c}{\lambda} = \frac{TrL_c}{S\lambda} \qquad (8)$$

where λ is the thermal conductivity of the fluid, L_c is a characteristic length (chosen as described above) and h is the convective heat transfer coefficient, obtained as the ratio between the transmittance Tr and the external surface S of the body.

Supplementary Note 6. Characterization of mass transport properties of *Meta menardi* cocoons and the influence of humidity. We considered that the surface through which the mass transfer occurs presents the same area as the one through which convective heat transfer happens. Such an assumption, combined with the Chilton-Colburn analogy between heat and mass transfer phenomena[2], allow us to state the following relationship:

$$Tr = Tr\left(U_{air}\right) = Tr_0 + Tr_1 U_{air}^{\alpha} \qquad (9)$$

which implies:

$$K = K\left(U_{air}\right) = K_0 + K_1 U_{air}^{\alpha}, \qquad (10)$$

hence:

$$\frac{K_0}{Tr_0} = \frac{K_1}{Tr_1} = \frac{T_a - T_{wb}}{h_{vap}\left[p_s\left(T_{wb}\right) - \varphi p_s\left(T_a\right)\right]}, \qquad (11)$$

where T_{wb} is the wet bulb temperature corresponding to the ambient relative humidity φ and ambient temperature T_a, as measured during our experiments. The quantities Tr_0, Tr_1 and α in (9) are chosen to best-fit the experimental data, while K_0 and K_1 are the corresponding parameters in the equation for the mass transport transmittance (10). Thus, based on the experiments in Figure 4a (main manuscript), the mass transport transmittance K is fully determined thanks to the latter equation (11), and results are reported in Figure 4c (main manuscript).

Moreover, the wetting experiments have been performed in order to estimate the characteristic drying time τ as a function of the airflow velocity U_{air}. Results are shown in Figure 4d (main manuscript).

The error bars in Figure 4d represent the confidence interval at a level of 95%. To construct a confidence interval in this case both type A and type B uncertainties should be taken into account, due to a poorer repeatability (compared to measurements in Figure 4a) of the experimental measurements of τ. Thus, for each airflow velocity value a significant number of experiments have been done, and then type A uncertainties $\sigma_{\tau,A}$ have been calculated using both t-student and chi-squared methods. Type B uncertainties have been calculated as in the case of Tr, where τ was regarded as a function of three independent quantities $(time, T_w, T_a)$, and the overall uncertainty is calculated as:

$$\sigma_{\tau} = \sqrt{\sigma_{\tau,A}^2 + \sigma_{\tau,B}^2} \quad (12)$$

SUPPLEMENTARY REFERENCES

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3. Kline, S. J. & McClintock, F. A. Describing uncertainties single-sample experiments. Mech. Eng. 75, 38 (1953).