Comparing bird and human soaring strategies

Supplementary Information

1 Materials and methods

The GPS device. In order to have data about the fine details of the flight patterns of birds and gliders we decided to implement a very light GPS device with the highest spatial and temporal resolution possible. Since GPS devices equipped with radio transmitters are relatively heavy (a bird of about 700 grams cannot fly freely enough with a load larger than 50 grams, *e.g.,* 7% of its weight) we opted for chips which store the data obtained from their interaction with the satellites in their memory. Thus, we had to work with tame birds to have the possibility to download the GPS log files after the flights. These birds were moving freely most of the time and usually came home only for night. One important condition we wanted to meet was that the GPS had to have sufficient memory to store the data logged during a whole day with 1 s rate. As the GPS devices available on the market do not comply with these conditions, we developed a miniature GPS device especially for this research. A similar GPS device had been constructed for the Homing Pigeon project [10-11 in the main text].

The three major ingredients of a GPS device are the receiver, the antenna and an accumulator. We have chosen an ultra light receiver with an integrated patch antenna from Fastrax Ltd [1]. The board was capable of logging 24,500 log points (latitude, longitude and altitude coordinates and time). The size of the board was 4.8 x 4.5 cm, weighting only 17 g. It allowed us to set the logging time to one second. This logging function was restricted to the time when the bird was moving. A new point was stored in every second if the distance from the previous log point was longer than 1 m and in every minute only if the distance was smaller.

Very lightweight lithium polymer accumulators (520 mAh, 11.3 g) were used as power supply. We covered the device with heat shrink tubing, making the GPS compact and protected from a possible injury (attack of other birds, etc.). When it was completed the device was weighing 34 g (Fig.1). The spatial resolution of the GPS in the "absolute" coordinates we obtained were below 1 m, and for the "relative" coordinates (used for determining the velocity of objects) were less than 0.1 m (both according to our tests and estimates available on the Internet). The error of the time measurement gives 20 ns deviation.

A

B

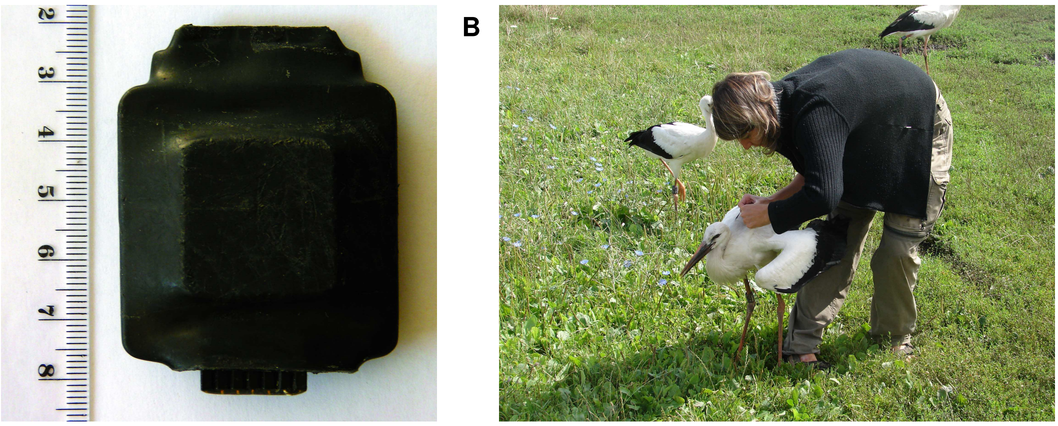

Figure 1: Attachment (B) of the GPS device (A).

Collecting data about flights of tame birds. We fitted one falcon with the ribbon used to hold the GPS device. This ribbon was left on the bird until the end of the project. The bird had to be narcotized when the ribbon was fitted. This was necessary in order not to shock the falcon with the fitting process and to preserve the tameness of the bird. The attachment point to fix the GPS device was on the back of the bird, where the ribbons cross each other (Fig. 1B in the main text). This point was developed in order to make the putting on and getting off of the GPS easy. We used two GPS devices, therefore it was sufficient to contact the bird once a day and just change the GPS on the back of the bird. Every morning the falconer took off the actual GPS unit and fitted the bird with the other one while the bird was eating meat roped onto a stick. After this the log file was downloaded from the GPS and the accumulator was charged up, so the GPS was ready to be used on the next day. For safety reasons we also used a radio device. This lightweight, high power radio transmitter was attached on top of the GPS unit. With this radio transmitter it is possible to find the falcon by radio telemetry in case it does not return to its base [2].

In the White stork project two young storks that fell out of their nest were transported to the Budapest Zoo at the beginning of July 2006. They were approximately 2 weeks old. As in the falcon project, it was necessary to train them not to be afraid of the people who will later change the GPS device on their back. After one week one of us (Zs.Á.) moved with the birds to the Repatriation Park for one and a half month. Another stork, approximately two weeks older, got into the project here, as it seemed to be possible that this bird still can be tamed. We fed them usually with fresh wet chickens every morning and evening.

The putting on, exchange and downloading procedure was the same as in the case of the falcon project.

In the White stork project, we were faced with the possibility that the storks would leave for good (migration) before we can collect data enough for a decent statistical analysis. And, indeed, this is what happened, all three storks provided only a limited (few flights, with limited number of thermalling) data before they left the basis completely. This is the reason why we used their data only for the determiation of the circling radius and period time.

Collecting flight data from pilots. These days, the only way of verifying a task at a cross country flying competition is submitting a GPS track log. At competitions pilots start from one place (usually a cylinder around a given point defined by GPS coordinates) and have to fly along a route determined by turning points. The objective is to reach goal as soon as possible or if it is impossible (*e.g.,* the weather is not good enough to complete the task) to fly as far as you can along the route. A different type of competitions is online contests where pilots fly individually and upload their GPS track logs to the web page of the contest. This way flights performed at different places and dates can be compared by a pre-defined algorithm evaluating (amongst others) the length and average speed of the flight.

Paragliders typically use the "rule of thumb" that in a whether with better thermals it is more optimal to choose a faster gliding speed. Most of the contestants are aware of the MacCready theory, but their equipments usually do not have a MacCready function, because with decreasing gliding power the relevance of the theory decreases. Most importantly, however, our paraglider data are for the flights of two world champions who are expected to either use a MacCready speed ring, or have the instinct and the experience to apply the prediction of the theory to a great extent.

Application of the MacCready theory. We apply the MacCready theory making use of the following argument. The goal of the gliders is to make a given distance L_{AB} (using both thermalling and gliding and not loosing height in average) during a time as short as possible (see Fig.2). Thus, they intend to minimize the quantity:

$$min\Big[\frac{L_{AB}}{v_{xy}} - \frac{L_{AB}}{v_{xy}}\frac{v_z}{v_{climb}}\Big]$$

where $v_{xy} = x$ is the horizontal velocity during gliding, $v_z = p(x)$ is the vertical velocity during gliding, which is given by the the polar curve, v_{climb} is the thermal climb rate in the thermal at position

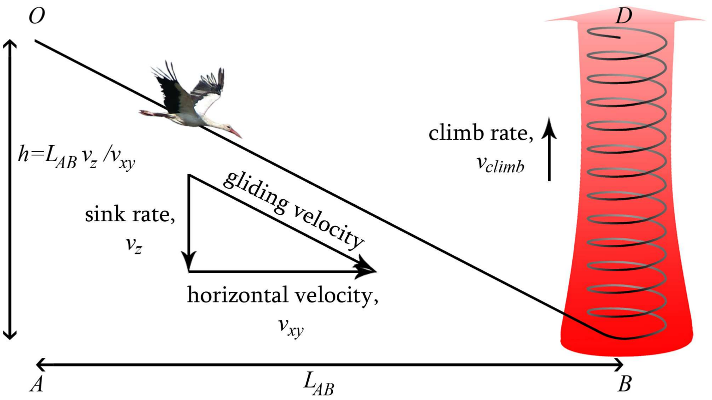

Figure 2: **MacCready theory.** The glider start gliding from position O at the top of the previous thermal. The horizontal distance to the next thermal lift is L_{AB}. According to the choosen gliding velocity, it reaches the next thermal at higher or lower altitude. From this position the horizontal distance to the top of the thermal can be taken with the v_{climb} climbing velocity.

B (see Fig.2). The two terms are the required times from A to B and for making the elevation L_{BD}. L_{AB} drops out, as a simple constant multiplier. Thus, we want to minimize

$$min\left[\frac{1}{x} - \frac{p(x)}{xv_{climb}}\right]$$

we do this by making the derivative equal to 0

$$\frac{d}{dx}\left(\frac{1}{x} - \frac{p(x)}{xv_{climb}}\right) = 0$$

From here

$$\frac{p'(x)}{v_{climb}} = \frac{p(x) - v_{climb}}{xv_{climb}}$$

or

$$\frac{p(x) - v_{climb}}{x} = \frac{dp(x)}{dx}$$

This equation is equivalent to the statement that the optimal gliding horizontal velocity $v_{xy} = x$ can be obtained by drawing a line from the v_{climb} point (along the y axis) tangent to the $p(x)$ polar curve and reading the corresponding v_{xy} value.

The minimization of the time of the whole flight is equivalent to maximization of the average horizontal speed, the so-called cross-country speed.

Typically, this theory is used by sail-plane pilots and hang gliders, because the polar curve of their aircraft is flatter, so a larger speed difference corresponds to the same climb rate difference than for paragliders. Instruments have been developed for the sail-plane and hang glider pilots to calculate the horizontal speed to a realized expected thermal climb rate, so the task is to estimate the next climb rate.

Polar curve of the Peregrine falcon, the paraglider and the hang glider planes. We used polar curves measured in wind tunnel experiments. In Table 1 the falcon data is reproduced from Ref. 9. in the main text, while in the case of the gliders we give data provided by the manufacturers. In addition, in the case of the falcon we used a function that was fitted to our real flight GPS data between thermals, which also include the parts, when the falcon is flapping its wings (see the second row of Table 2, marked with $*$, and Fig. 3).

Table 1: Data points of the polar curves.

Peregrine falcon	$v_{xy}(m/s)$	6.57	8.02	9.27	10.22	11.26	12.30	13.96	15.52
	$v_z(m/s)$	-1.13	-1.03	-1.03	-1.13	-1.22	-1.34	-1.91	-2.41
Paraglider	$v_{xy}(m/s)$	8.84	10.25	10.53	11.08	12.42	13.75	16.45	
	$v_z(m/s)$	-1.01	-1.15	-1.20	-1.29	-1.58	-1.93	-2.69	
Hang glider	$v_{xy}(m/s)$	9.83	13.45	18.10	23.27	27.93			
	$v_z(m/s)$	-0.70	-0.76	-1.24	-2.22	-3.49			

Table 2: Fitted parameters of the polar curves.

	Function	a	b	c
Peregrine falcon	$p(x) = a/x + bx^3 + cx^{-3}$	-4.1	-0.00056	-100
$*$	$p(x) = ax^2 + bx + c$	-0.014	0.2	-1.58
Paraglider	$p(x) = ax^2 + bx + c$	-0.015	0.16	-1.2
Hang glider	$p(x) = ax^2 + bx + c$	-0.0095	0.2	-1.7

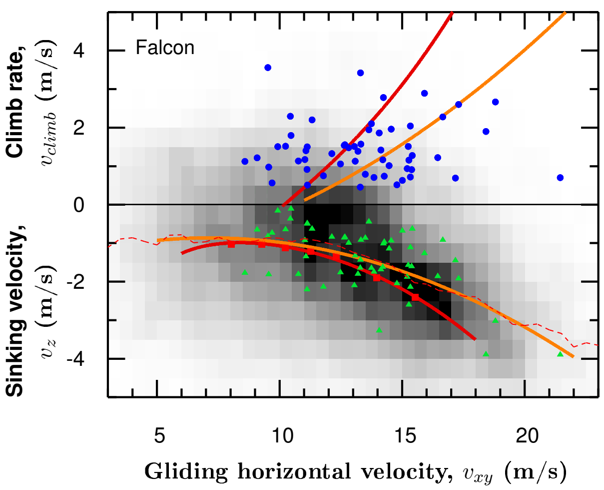

Figure 3: **Climbing rates for individual thermals and the subsequent horizontal speeds.** The climbing rates and the corresponding horizontal velocities are shown with filled blue circles and green triangles, respectively. The points are scattered because it is rather the average than the individual values of the climbing rates are considered by both birds and humans when selecting the right horizontal speed. The distribution of the observed gliding speeds is shown with grey scale in the background. Red dots indicate the measured polar curve in dark red for falcons (Ref. 9 in the main text). We find that due to flapping periods, for the falcons we are prompted to use an effective polar curve (orange) which takes into the account that the gliding (straight) parts of a falcon's trajectory contain intervals of lifting periods (due to occasional flapping flight). The red dashed line shows the measured averaged sinking function.

To check the assumption that birds and humans are trying to fly cross country during the flight sequences, here we give some related details in Table 3. During most of the competitions of paragliders the task is to make a trajectory which ends at the starting point. However, this trajectory is typically (just as in the case of the flights we considered) is divided into well defined parts between distant points which have to be reached by the paragliders. The falcon also returns home every night, however, it makes several flights of varying length over a day (and takes rests between them, as it is indicated by our GPS logging data). Looking at the trajectories, it is typical that the falcon is trying to make large distances during individual flights. In particular, when returning home at evening, the falcon follows a more or less linear trajectory while "stopping" for thermalling periods to gain height without investing much effort.

Table 3: Duration and spatial extension of 10 typical flights.

Peregrine falcon	T (min)	58	11	9	88	97	76	7	56	51	47
	s (km)	40	8	4	64	63	55	4	41	41	34
	d_{se} (km)	5	2	1	1	1	2	1	15	15	1
Paraglider	T (min)	329	360	280	471	132	307	303	153	49	53
	s (km)	212	256	295	334	113	317	321	154	40	41
	d_{se} (km)	86	195	0	5	6	0	1	3	3	4
Hang glider	T (min)	321	323	275	201	266	241	280	223	286	327
	s (km)	289	320	281	212	284	266	338	243	344	378
	d_{se} (km)	3	3	3	3	139	3	3	15	300	3

T: Flight time; s: Length of the trajectory; d_{se}: Start to end distance.

Elimination of the wind effect. To determine the circling radius during thermalling, we eliminated the effect of the wind. Fig.4A shows the calculation of the local wind velocity from the drifting of a thermal (Fig.4B).

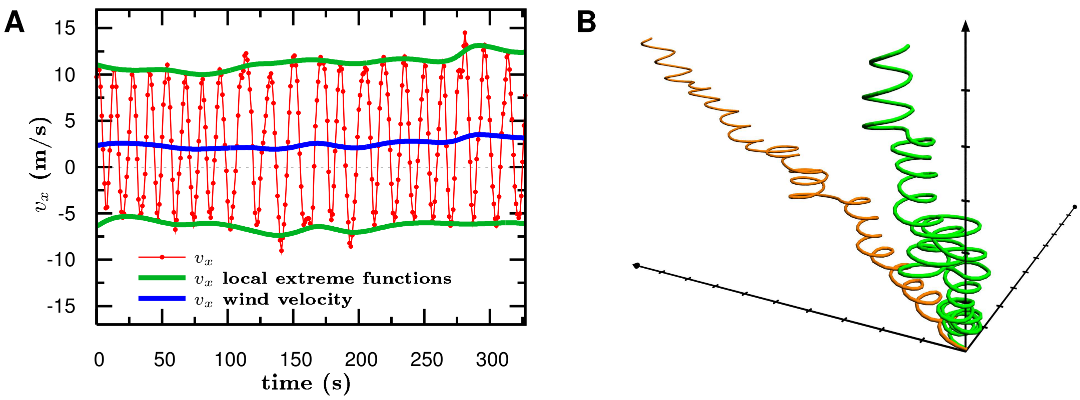

Figure 4: **Elimination the effect of the wind.** Red line denotes the x component of the falcon's velocity. Green lines denote the local maximum and minimum velocity functions. The x component of the calculated wind velocity function is indicated by the blue line (A). The original thermal as drifting with the wind (red) and the same thermal after the effect of the wind was eliminated (green) (B).

Period distribution. The period of the circling in thermals was calculated from the time difference between the neighboring local maximum (minimum) peaks of the velocity components (see Fig.4A). The distribution function from these time differences was calculated (Fig.5). The local period can also be allocated by wavelet transformation. The wavelet spectrum of the thermalling and gliding parts of the flight is very different (Fig.7). But it gives false results where the flyer changes the circling direction of thermalling.

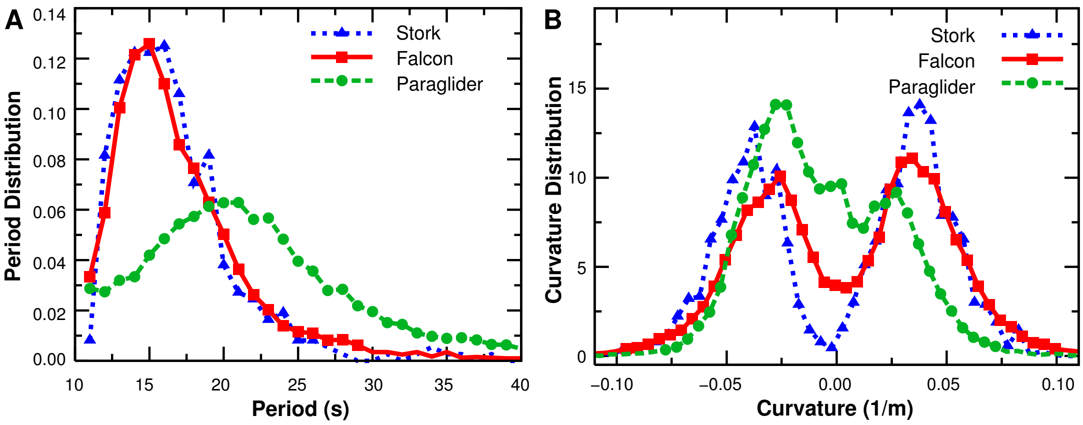

Figure 5: **Period and curvature distribution.** Triangles, squares and circles denote the period (A) and curvature (B) distribution of the White stork, the Peregrine falcon and paragliders respectively.

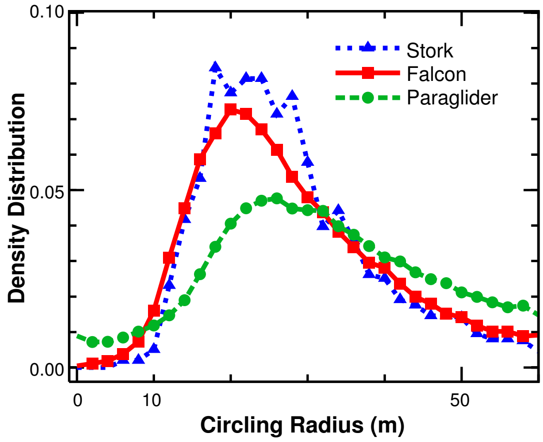

Figure 6: **Circling radius distribution.** Triangles, squares and circles denote the the circling radius distribution (PDF) of the White stork, the Peregrine falcon and paragliders respectively. Here we present the absolute values for the radius (see Fig.5B).

Curvature distribution. We have also calculated the curvature distribution (Fig. 5B), from the wind eliminated thermalling parts of the track. To the curvature distribution function Gaussian function fits properly.

The geodetic coordinates provided by the GPS were converted into X, Y, and Z coordinates using the Flat Earth model (see, *e.g.,* [3]). The data were smoothed by a Gaussian filter ($\sigma = 1$) and the Cubic B-Spline method (see, *e.g.,* [4]) was used for fitting curves onto the points obtained with 1 s sampling rate. In this way we obtained trajectories having continuous first and second derivatives and going through the measured data points. The local curvature of the track was obtained by calculating the derivatives of the functions, of $x(t), y(t), z(t)$ denoting the two horizontal and the vertical coordinates of a trajectory. The local curvature of the track projected onto the horizontal plane is given by the textbook expression:

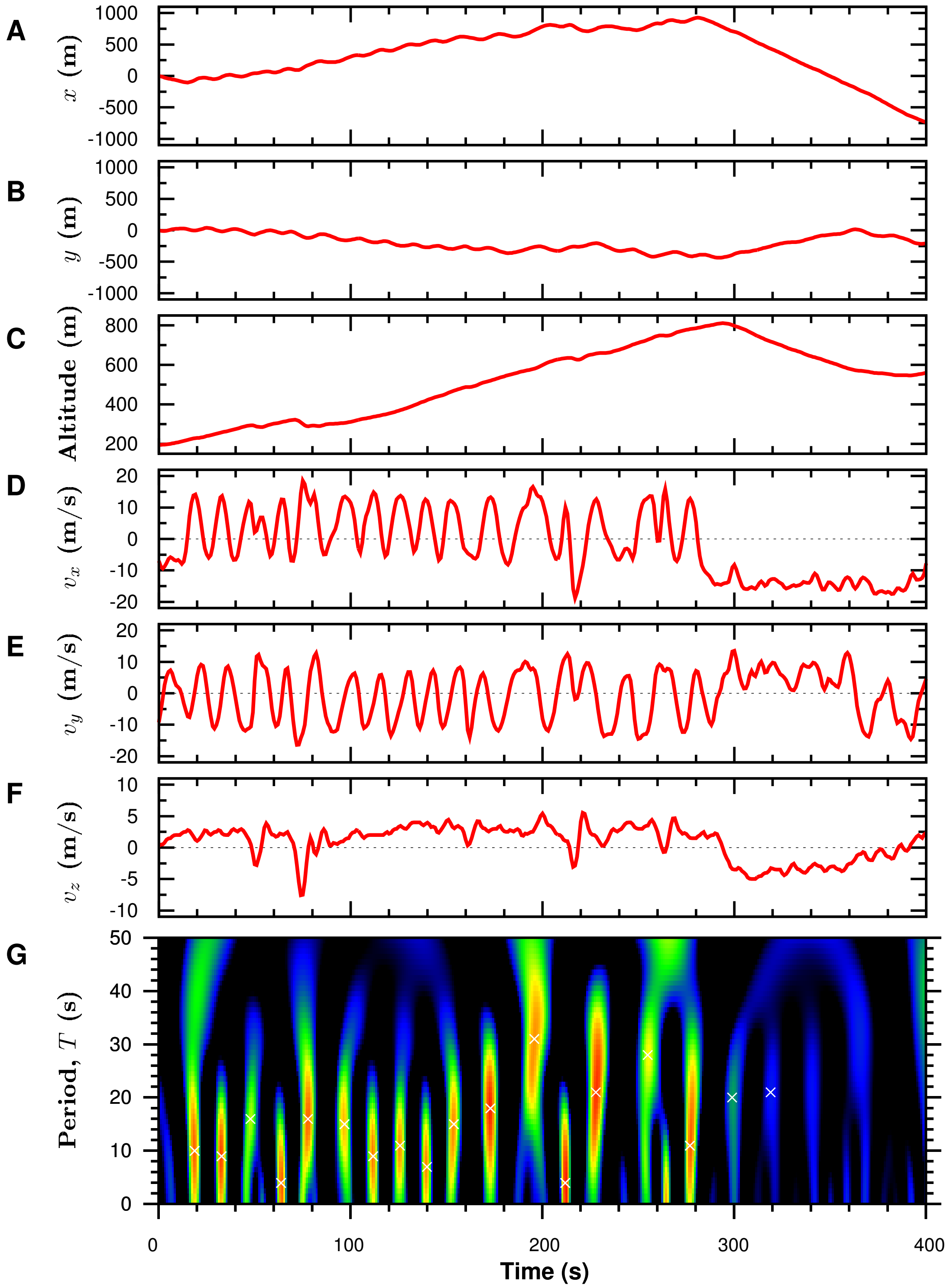

Figure 7: **Determination of the circling time by wavelet transformation.** The graphs show the positions (A, B, C) and the velocity components (D, E, F) of one time segment from the flight of the Peregrine falcon. The first 300 second containing the thermalling, the rest is gliding. The wavelet spectrum shows the periods in a time interval (G). White x marks denote the local maximum places.

$$C(t) = \frac{x'(t)y''(t) - y'(t)x''(t)}{\left((x'(t))^2 + (y'(t))^2\right)^{3/2}}$$

The thermalling and gliding parts were separated by using information about the curvature and the vertical velocity parameters. We required that a point of the trajectory belongs to the thermalling part only if the average local curvature (averaged over a 10 s time window around the given point) should be larger than 0.01 m^{-1} and the vertical velocity component $(z'(t))$ should be larger than 0. We also included parts of the trajectories that were shorter than 10 s but satisfied the above criterion for the curvature in average. After this automated procedure we identified the thermalling parts one by one, and made minor modifications by hand if it was necessary (the very beginning and the ending of the thermalling parts were occasionally shifted by a small amount (1-10 sec) to compensate for irregularities generated by the automated selection). The Probability Density Functions (PDF-s) we determined were intended to give information about the frequencies of the values of their variables. We used bins with a width small enough for the PDF displaying a well defined feature of the distribution but large enough to avoid large fluctuations of the PDF.

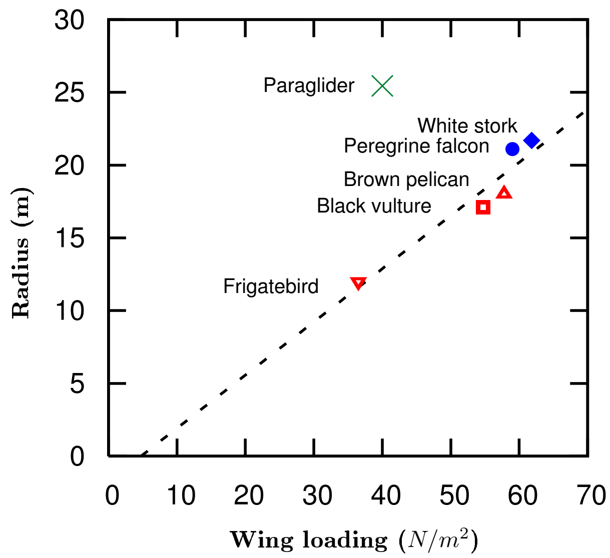

Figure 8: **Circling radius versus wing loading.** For three bird species (Frigate bird, Black vulture, Brown pelican; open red marks) Pennycuick found that the main circling radius is linearly proportional to wing loading. Our results for the Peregrine falcon and the White stork (solid blue marks) are in agreement with this tendency. The dashed line was fitted to the data on birds. The green X mark shows the measured data for the paraglider

Comparing circling radius and possible wing loading effects. Our finding concerning birds are in agreement with the observations and arguments by Pennycuick (i.e., the mean circling radius is linearly proportional to wing loading (see Fig. 8). Following the derivation by Pennycuick one arrives at the expression

$$r = \frac{W}{S}\frac{2}{\rho g}\frac{cos^2(\gamma)}{sin(\mu)C_l}$$

where the following notation was used: W - weight, S - wing area, L - lift force, μ - bank angle, γ - glide angle, C_l - lift coefficient, ρ - air density, r - turning radius, $g = 9.806\ m/s^2$.

From the linear dependence of r on W/S we conclude that in the case of birds the term

$$\frac{cos^2(\gamma)}{sin(\mu)C_l}$$

is about the same for the species investigated, while according to our data this quantity is different for paragliders.

Comparison of the actual and the predicted (by the MacCready theory) speeds. We have addressed this important point by i) visualizing the agreement/discrepancy between the actual "selected" horizontal speeds of the falcon and the paragliders as compared to the ones predicted by the MacCready theory for the climb speeds in the thermals of that day (see Fig. 9) and ii) by calculating the quality of the agreement using statistics.

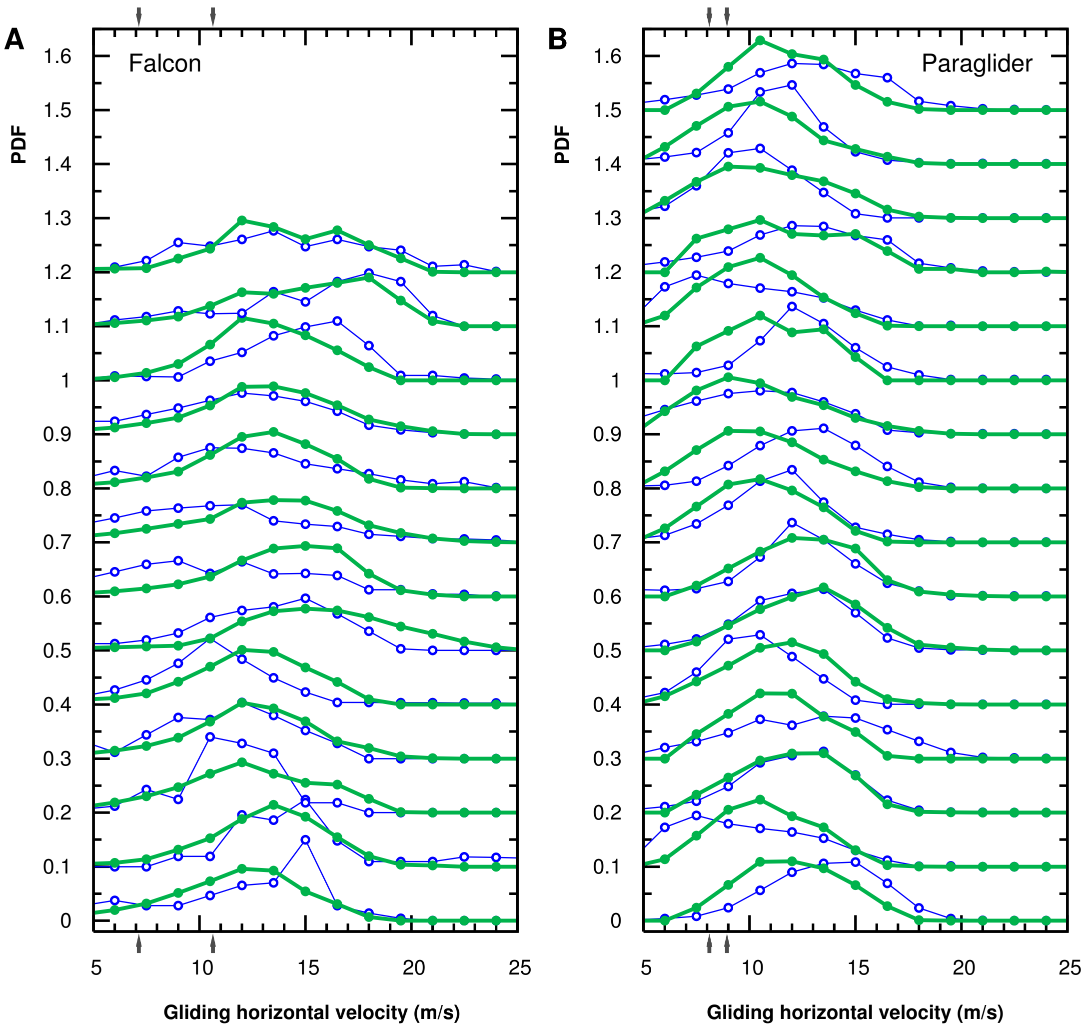

Figure 9: **Comparison of the actual and the predicted (by the MacCready theory) speeds for all analysed days.** This plot is an alternative version of Fig. 3 (in the main text), it shows two distributions for all analysed days. The data are shifted upward by a value 0.1 for different days in order to improve the visualization. The filled and empty symbols denote the PDF of the predicted and the actual values, respectively. The predicted values were obtained by feeding the climbing rate distribution into the MacCready formula and calculating the corresponding horizontal velocity distribution from it. A perfect agreement between the observed velocities and the predicted ones would correspond to birds and people applying the theory to a 100% degree. The left and the right arrows on the x-axis show the horizontal velocity value corresponding to the minimum sink and the best glide ratio, respectively.

We chose to quantify the agreement by calculating the mean square deviation of the actual and predicted curves. The values obtained in this way were averaged over days. Then, this average deviation was compared to an average deviation which would have been observed, if the birds and the paragliders had used an incorrect value (randomly selected from other flights) for the climb rate in the preceding thermal, when "calculating" the best theoretical value for the horizontal speed. The conclusion of this calculation is that for both the Peregrine falcon and the paragliders the actual deviations are significantly different from those obtained for the randomized case.

In particular, in order to test the level of significance of the results of the above analysis we carried out the Student's t-test. In the case of the Peregrine falcon the average (over 13 flights) of the average deviation of the distributions was 0.001532, with a standard deviation 0.000813. We compared the average value for the deviations to the same value obtained for the randomized case (over 1000 mixed series) being approximately 0.002065. The t-value for falcon was t_{falcon}=2.36. For a 2.5 % level of significance and 12 number of freedom the t-value was $t_{2.5}$=2.179. In the case of the paraglider the average (over 16 flights) of the average deviation of the distributions was 0.001069, with a standard deviation 0.000645. For the randomized case the same value was 0.001521. The t-value for paraglider was $t_{paraglider}$=2.80. For 2.5 % level of significance and 15 number of freedom the t-value is $t_{2.5}$=2.131. We also checked and found that the values of the average deviations followed a normal distribution.

The original MacCready theory (Ref. 7 in the main text) did not take into account several factors which can influence the optimal choice for the gliding speed. These factors include changing of the air density as a function of height or the fact that the various thermals even within a single flight are quite different as concerning their lifting potential (see [5] and Ref. 15 in the main text).

The latter factor involves non-linearity because taking into account the probability of finding a thermal with a good lift results in a non-trivial function of the altitude (considering that gliders should avoid a height loss leading to inevitable landing). To address this point we investigated how the vertical gliding velocity of the falcon depended on the altitude at which the gliding part of its flight started (Figure 10). Clearly, in average, the falcon chooses an average sinking rate that is smaller if the starting point is lower (inserts flapping periods more frequently).

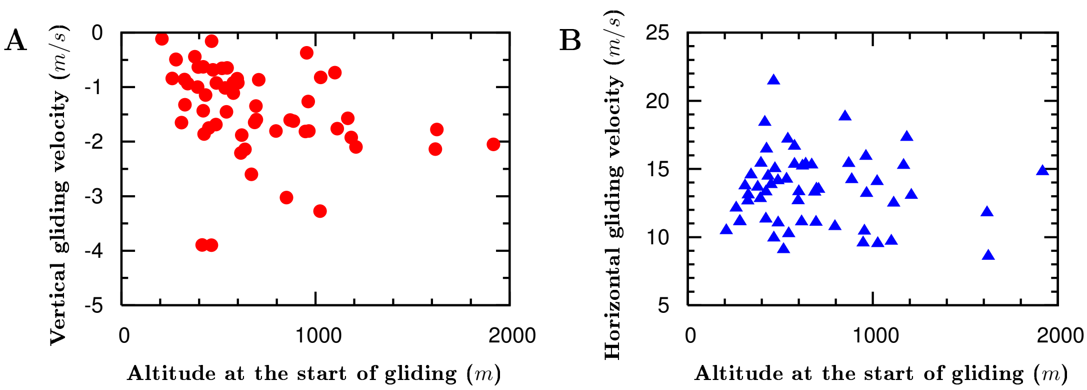

Figure 10: **Gliding velocity versus the altitude of the falcon immediately after leaving a thermal.** The data points show the average vertical (A) and horizontal (B) velocity components for each gliding parts between thermal lifts. While the vertical velocity shows correlation with the height, the horizontal speed is uncorrelated.

References

[1] http://www.fastrax.fi

[2] http://www.marshallradio.com/falconry/fproducts_transmitters.asp#specs

[3] http://home.earthlink.net/ x-plane/FAQ-Theory-FlatEarth.html

[4] http://graphics.idav.ucdavis.edu/education/CAGDNotes/Cubic-B-Spline-Curve-Refinement.pdf

[5] http://www.courant.nyu.edu/ almgren/papers/optsoar.pdf