**Supplementary Information**

*Study Species and Training*

Bats were kept in two groups of five individuals per cage and marked using non-toxic nail polish on their toes or via clipping of a small section of hair on the lower back. While in captivity individuals were fed a diet of mealworms provided in the cages or offered by hand after each flight session. Supplementary feeding was also provided using Harrison’s Bird Foods “Juvenile Formula” (Harrison’s Bird Foods, Brentwood, USA) mixed with water and offered by hand to the bats via a 1ml syringe.

*Metabolic Power Measurements*

Prior to all measurements bats were fasted for at least 6 h. To determine basal metabolic rate we measured oxygen consumption and carbon dioxide production of 10 bats using flow-through respirometry to determine basal metabolic rate. Bats were placed in 500 ml respirometry chambers through which outside air flowed at a rate of 350 ml min-1 STP. Bats were measured in their resting phase (from 10:00 to 16:00) and were fasted for at least 12h prior to measurements to ensure they were post absorptive. As the thermoneutral zone has yet to be established in this species we exposed each individual to controlled ambient temperatures between 28 and 35°C in 3°C increments. Ambient temperature was measured inside the respirometry using calibrated thermocouples and each bat remained at a given ambient temperature for at least 1.5h before the temperature was increased. We visually inspected the graph of VO2 against Ta to determine the inflection point for the lower critical temperature of the thermoneutral zone, which was below 31°C. Above this point VO2 was stable, and therefore we designated the thermoneutral zone *for P. nathusii* to lie between 31 and 35°C. We calculated basal metabolic rate as the average VO2 within this range. We used equation 10.6 from Lighton (1) to calculate the volume of oxygen consumed and converted this to W using a conversion factor of 20.1 J ml-1 O2 (2).

*Mechanical Power Measurements*

Images were captured using four cameras at a frame rate of fL=640 Hz and the system was calibrated using the LaVision Type 22 calibration plate, followed by the tomographic self-calibration routine in Davis 8.3.1 (LaVision Gmbh, Göttingen, Germany). We defined a right-handed coordinate system with *x* in the wind tunnel flow direction, *y* in the spanwise direction and *z* in the vertical upwards direction. TomoPIV raw images from our cameras were pre-processed using subtract sliding minimum over 5 pixels, followed by an intensity normalisation to a local average of 300 pixels, and finally a Gaussian 5×5 smoothing followed by multiplication with a factor 10. We used the processed images to calculate a 3D particle space using the FastMART routine. Velocity vectors were estimated using the 3D direct correlation routine with decreasing box size starting at 64×64×64 with 50% overlap (8×8×8 binning), followed by 48×48×48 with 50% overlap (4×4×4 binning), followed by 32×32×32 boxes with 50% overlap (2×2×2 binning), and for the final step 22×22×22 boxes with 50% overlap (three passes, no binning). Between rounds we used a two-times remove and insert filter (7×7×7 voxels) to remove erroneous vectors, followed by a two-times Gaussian smoothing (3×3×3 voxels). The last round was not smoothed. The resulting vector fields were post-processed using a remove and insert filter (5×5×5 voxels). Empty spaces were filled by interpolation and the final vector fields were smoothed with a one time 3×3×3 Gaussian filter. The final vector volume size was approximately 4.3×315×245 mm and approximately 4×217×170 vectors, resulting in a vector spacing of approximately 1.45 mm for all three axes (6.8 vectors/cm). For all further analyses we only used the second plane (in the x-dimension) in the volume.

The level of background noise in the flow varied notably between sequences and we therefore developed a method to reduce the influence of the background flow, which has a large impact on the mechanical power estimate. We estimated and subtracted the background flow for the individual sequences before estimating power. The procedure involved several steps, including an estimate of systematic variation (i.e. non-homogenous background flow over the measurement area) in the flow for all sequences, adjustment of the free stream flow for the individual sequences (i.e. the difference between expected and realized tunnel speed) and a masking procedure based on the total vorticity in the 3D-reconstruction of the wake. As the initial step we generated an averaged flow field for each of the three velocity components, u(y,z), v(y,z) and w(y,z), from all frames in each of the sequences. We then applied a separate threshold to each of the velocity components, adjusted to fit each sequence, to remove vectors deemed to belong to the wake of the bat. The areas occupied by the bat wake for each of the velocity components, were then combined and vectors deemed to belong to the wake were removed from each of each of the averaged velocity components, before we fitted a bipolynomial plane to each of the velocity components (using the Matlab fit functions poly33 for u and w and poly21 for v, with additional options “robust” and “bisquare”). For each of the velocity components we then averaged the fitted planes, after normalising with the free stream speed, for all the sequences in the analysis. In this way we estimated the systematic variation in the background flow in the measurement plane. The mismatch between the fitted plane and each of the velocity components in the averaged masked background flow was then calculated and added to the correction field i.e. making sure that the average velocity of the corrective flow field corresponded to the average velocity of each sequence. This background flow was subsequently subtracted from the flow of each sequence producing a flow field with the induced flow of the bat relative to a homogenous background flow.

Before analysing the data, we constructed a 3D mask using the total vorticity in the wake (3). This mask was adjusted manually for each sequence, depending on the background noise level, resulting in a narrow fit around the wake vorticity, excluding vorticity outside the wake. We then used the Helmholtz-Hodge decomposition to reconstruct the wake outside the wake. Visual inspection of the flow estimated by the Helmholtz-Hodge decomposition showed good agreement with the original wake, but with less noise. This reconstructed vector field, with the original measurements inside the mask, was then used to estimate the kinetic energy added to the wake during an integer number of wingbeats for each sequence.

where ⍴ is the density of the air.

The power was subsequently calculated by dividing the energy in the wake with the number of wingbeats in the sequence (Nwb) and multiplying with the wingbeat frequency (fwb).

**Supplementary Table S1. Conversion efficiency for *P. nathusii* flying in a wind tunnel at air speeds rounded to the nearest 1ms-1 between 5 and 9 ms-1.**Efficiency data were calculated from either a) average metabolic power and mechanical power across all bats at each air speed or b) following the methods of (4) where median metabolic power was divided by average mechanical power across all bats at each air speed.

|  |  |  |  |
| --- | --- | --- | --- |
| **Speed (ms-1)** | **Whole animal conversion efficiency** | **Conversion efficiency (W/L corrected)** | **Muscle conversion efficiency** |
| 5 | 7.0 ± 0.7 a | 7.3 ± 0.8 a | 8.4 ± 0.9 a |
| 6 | 8.1 ± 0.9 a | 8.3 ± 0.8 a | 9.7 ± 1.1 a |
| 7 | 8.8 ± 0.9 a | 8.2 ± 0.9 a | 10.5 ± 1.0 a |
| 8 | 10.4 ± 0.8 a | 10.6 ± 0.8 a | 12.5 ± 1.0 a |
| 9 | 10.2 ± 2.0 a | 9.9 ± 1.6 a | 12.2 ± 2.3 a |
| 5 | 6.5 ± 0.7 b | 7.1 ± 0.8 b | 7.7 ± 0.8 b |
| 6 | 9.5 ± 1.1 b | 8.1 ± 0.7 b | 11.5 ± 1.3 b |
| 7 | 9.1 ± 0.9 b | 8.0 ± 0.8 b | 10.9 ± 1.0 b |
| 8 | 11.3 ± 0.9 b | 10.7 ± 0.8 b | 13.7 ± 1.0 b |
| 9 | 10.4 ± 2.0 b | 10.1 ± 1.6 b | 12.4 ± 2.4 b |

**Supplementary Table S2. List of species and corresponding morphological parameters used to estimate mechanical power in the Animal Flight Power Tool (5).** \*wingbeat frequency and/or aspect ratio estimated from allometry

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Species** | **Body Mass (kg)** | **Wbf (Hz)** | **Cdb** | **Wingspan (m)** | **Wing Area (m)** | **Source** |
| *Anas crecca* | 0.237 | 8.0 | 0.2 | 0.582 | 0.046 | (6, 7) |
| *Anser indicus* | 2.6 | 3.9 | 0.2 | 1.46 | 0.250 | (8-10) |
| *Branta leucopsis* | 2.1 | 4.8 | 0.2 | 1.08 | 0.115 | (8) (11, 12) |
| *Calypte anna* | 0.0044 | 42.0 | 0.2 | 0.11 | 0.0016 | (10, 11) |
| *Carollia perspicillata* | 0.018 | 9.0 | 0.4 | 0.28 | 0.0136 | (4) |
| *Colibri coruscans* | 0.0085 | 24.0 | 0.2 | 0.185 | 0.005 | (13) |
| *Colibri thallasinus* | 0.0055 | 24.0 | 0.2 | 0.168 | 0.004 | (13, 14) |
| *Columba livia* | 0.326 | 5.5 | 0.2 | 0.67 | 0.0630 | (15, 16) |
| *Corvus cryptoleucus* | 0.480 | 4.2 | 0.2 | 1.01 | 0.1457\* | (17) |
| *Corvus ossifragus* | 0.275 | 5.2 | 0.2 | 0.56 | 0.0603 | (18) |
| *Eidolon helvum* | 0.315 | 4.4 | 0.4 | 0.78 | 0.0879 | (19) |
| *Hypsignathus monstrosus* | 0.258 | 5.1 | 0.4 | 0.88 | 0.1150 | (19) |
| *Larus atricilla* | 0.347 | 3.8 | 0.2 | 0.88 | 0.1015 | (20) |
| *Leptonycteris yerbabuenae* | 0.022 | 10.8 | 0.4 | 0.33 | 0.0155 | (21, 22) |
| *Melopsittacus undulatus* | 0.037 | 14.0 | 0.2 | 0.29 | 0.0116 | (23, 24) |
| *Nymphicus hollandicus* | 0.081 | 8.5 | 0.2 | 0.48 | 0.0333 | (23, 25) |
| *Pastor (Sturnus) roseus* | 0.072 | 9.8 | 0.2 | 0.359 | 0.021 | (26) |
| *Phyllostomus hastatus* | 0.093 | 9.6 | 0.4 | 0.56 | 0.0417 | (27-29) |
| *Pipistrellus nathusii* | 0.0088 | 9.9 | 0.4 | 0.23 | 0.0077 | This study |
| *Pteropus alecto (gouldii)* | 0.779 | 3.0 | 0.4 | 1.35 | 0.2675 | (28, 30) |
| *Pteropus poliocephalus* | 0.666 | 3.4 | 0.4 | 1.30 | 0.2475 | (19, 30) |
| *Sturnus vulgaris* | 0.085 | 10.8 | 0.2 | 0.37 | 0.0208 | (31, 32) |
| *Sylvia atricapilla* | 0.019 | 16.9 | 0.2 | 0.23 | 0.0100 | (33) |

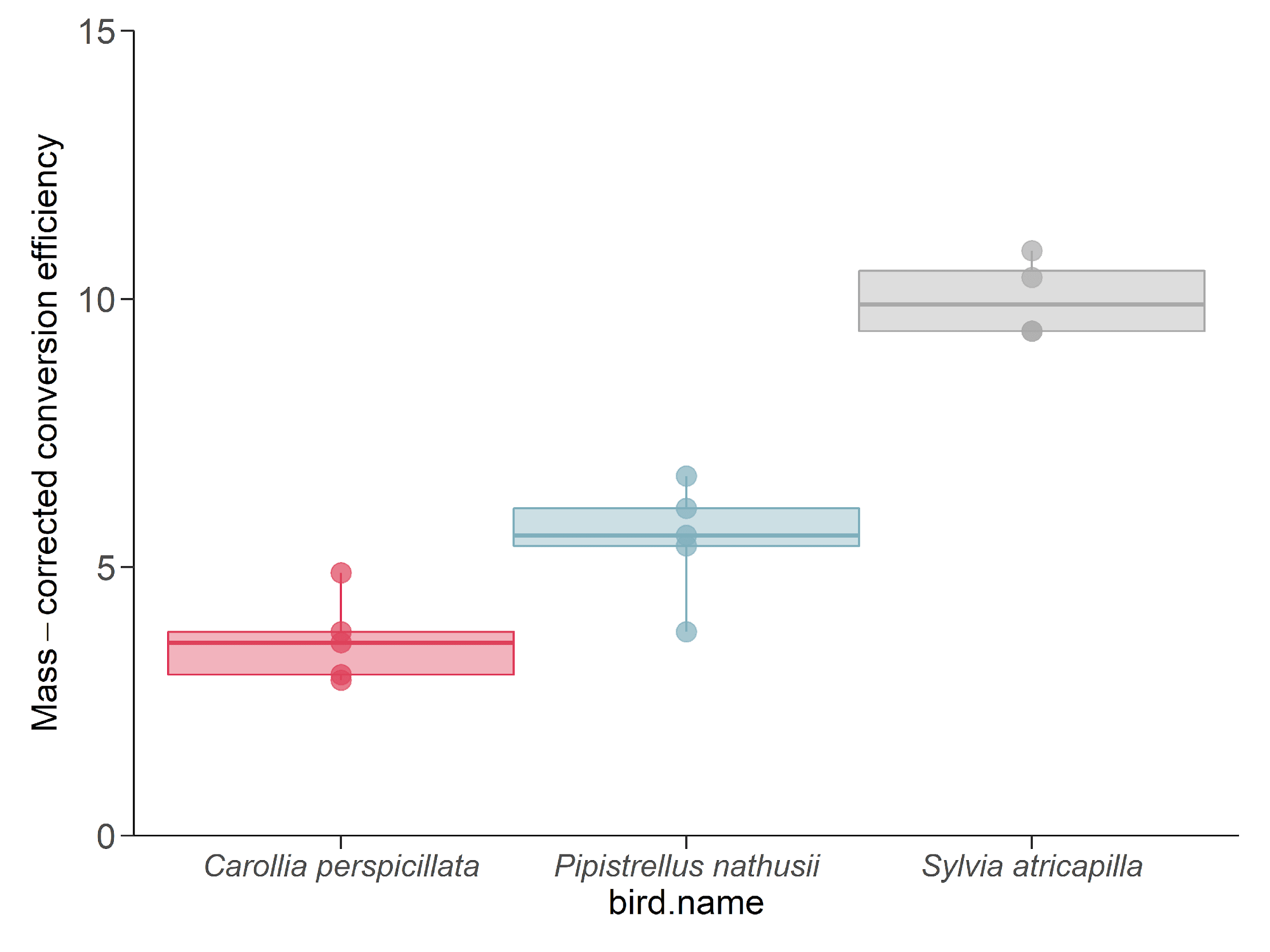
**Supplementary Table S3. Whole animal conversion efficiency estimated using Pmech from the *afpt,* and estimates made from our model incorporating body mass, compared to direct measurements for three species; *Carollia perspicillata* (4)*, Sylvia atricapilla* (33) and *Pipistrellus nathusii* (this study).** *N/A* marks data that were not calculated for our meta-analysis as they fell below the minimum power speed and/or were considered outside the range of accuracy given by the *afpt*.

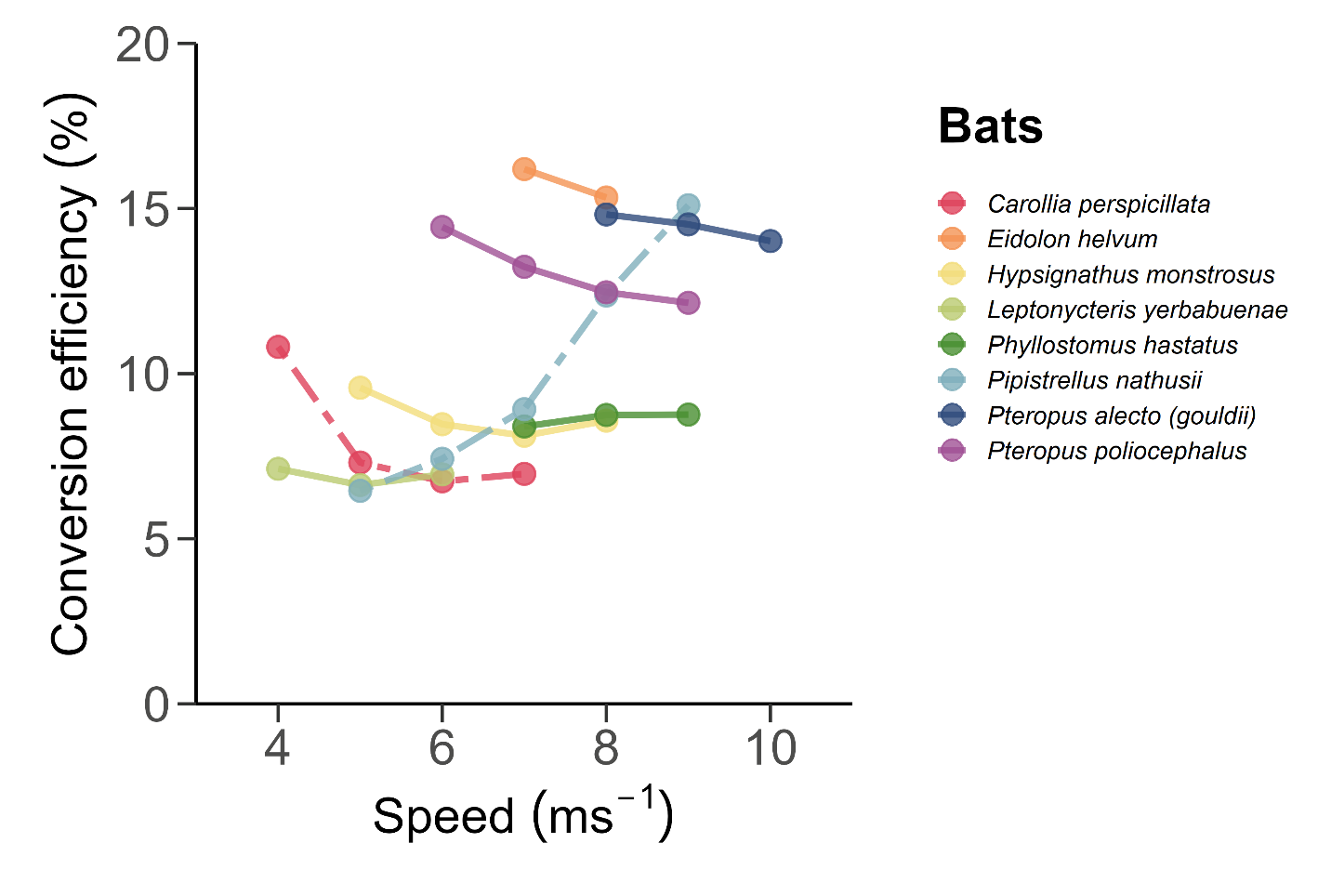
|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Species** | **Speed (ms-1)** | **Measured conversion efficiency (%)** | **Estimated conversion efficiency using *afpt* (%)** | **Estimated conversion efficiency from body mass (% ± s.e.)** |
| *Carollia perspicillata* | 3 | 7.6 | *N/A* | 6.7 ± 1.2 |
| *Carollia perspicillata* | 4 | 9.8 | 10.8 | 6.8 ± 1.2 |
| *Carollia perspicillata* | 5 | 7.2 | 7.3 | 7.0 ± 1.1 |
| *Carollia perspicillata* | 6 | 5.9 | 6.7 | 7.2 ± 1.1 |
| *Carollia perspicillata* | 7 | 6.1 | 7.0 | 7.4 ± 1.1 |
| *Pipistrellus nathusii* | 5 | 7.0 | 6.5 | 5.9 ± 1.2 |
| *Pipistrellus nathusii* | 6 | 8.1 | 7.4 | 6.1 ± 1.2 |
| *Pipistrellus nathusii* | 7 | 8.8 | 8.9 | 6.2 ± 1.2 |
| *Pipistrellus nathusii* | 8 | 10.4 | 12.4 | 6.4 ± 1.2 |
| *Pipistrellus nathusii* | 9 | 10.2 | 15.1 | 6.6 ± 1.2 |
| *Sylvia atricapilla* | 6 | 20.5 | *N/A* | 7.3 ± 1.1 |
| *Sylvia atricapilla* | 8 | 20.0 | 17.9 | 7.7 ± 1.1 |

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**Supplementary Figure S1. Vortex structures of a bat flying at 7.3 ms-1, visualized with isosurfaces of q-criteria (3000) coloured by vertical velocity (red upwards flow and blue downwards flow).** The downstroke generates thrust and weight support, while the upstroke wake show the bat-characteristic inverse vortex rings indicative of negative weight support and thrust production.

**Supplementary Figure S2.** Comparing empirical conversion efficiencies between species *P. nathusii* (in this study), *C. perspicillata* (4) and *S. atricapilla* (33). Whole animal conversion efficiency was mass corrected for comparison by dividing each value by body mass0.24.



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**Supplementary Figure S3.** Recreation of Figure 4A showing estimated conversion efficiency for 8 bat species on an extended axis.

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