Supplementary material Appendix 1

Goose parents lead migration V

Wing beat frequencies similar to ODBA

As an alternative and likely more comparable measure for flight mechanics, we calculated wing beat frequency from the acceleration burst data using the function “ACCwave()” of the R package “moveACC” (see https://gitlab.com/anneks/moveACC.git). Due to our acceleration data format, it took only 7 different values, but was strongly positively related to the overall dynamic body acceleration (ODBA; LMM with ID as random factor, \( \chi^2 = 8602, p<0.001, \text{slope} = 0.63, \text{Fig. S1} \)). Also results of leader vs. follower wing beat frequency and its relation with tail wind resemble the results obtained with ODBA – the father had the lowest wing beat frequency when leading and then experienced stronger tail wind than the mother (GLMM, \( \chi^2 = 711, p<0.001, \text{father} = -0.15, \text{mother} = -0.21, \text{leader} = 0.13, \text{father leader} = -0.27, \text{Fig. S2, see relationship to ODBA model in main text} \)). Because of its higher variability we have decided to present the results of ODBA in the main text. The linear relationship of wing beat frequency and ODBA indicates that the individuals of the family are similar enough in body weight and flight behaviour to compare ODBA values between them.

Figure A1. Positive relation between overall dynamic body acceleration (ODBA) and wing beat frequency.
Figure A2. Wing beat frequency and tail wind experienced by the parental leader and direct follower (< 3 m longitudinal displacement) of focal family. (a) Wing beat frequency of leader vs. follower indicating that the father flapped less when leading than the mother or following chicks. (b) Boxplots of wing beat frequency compared between family members and their leadership status. (c) Tail wind for father (orange) and mother (light blue) when leading. Big dots indicate medians, boxes quantiles and whiskers 5% and 95% quartiles of both measures for father (red) and mother (blue), revealing that there was stronger tail wind when the father was leading the family group. See in relation to Fig. 4 in the main text.
**Airspeed relations with wing beat, ODBA and tail wind**

In several studies, air speed is used as a representative of mechanical flight effort (Liechti 1995) and often found to be constant in different wind conditions (Safi et al. 2013). To support our findings of ODBA, we here additionally present how airspeed was determined by a combination of ODBA, wing beat frequency and tail wind (Fig. S3).

There seems to be a slight increase of air speed with ODBA (LMM with individual ID as random factor, $\chi^2=1019, p<0.001$) as well as wing beat frequency (LMM, $\chi^2=1400, p<0.001$), confirming the ideas that higher flapping frequency during flight leads to faster air speeds. Furthermore, air speed was highly variable and seems to have been related quadratically to tail wind (LMM, $\chi^2=159, p<0.001$) with a minimum air speed at weak tail winds. During head winds and extreme tail winds the birds possibly need to flap at higher frequencies to keep flying into the correct direction. In addition, the strongly positive relationship between tail wind and ground speed (LMM, $\chi^2=4350, p<0.001$) confirms that wind does not only affect air speed, but further adds to the ground speed of the bird. It is important to note that all those relationships were the same for leaders and followers and did not differ by individual. See Fig. S4 for general individual differences.

**Figure A3. Determinants and relations of air speed for the focal family.** (a) Slight positive relationship between overall dynamic body acceleration (ODBA) and air speed which is similar to (b) the relationship between wing beat frequency and air speed. (c) Quadratic relation of tail wind with air speed, which is not constant. (d) Strongly increasing relation between tail wind and ground speed, indicating the (to the air speed different) additional effect of head vs. tail winds on ground speed. Note that there are no differences in all the relations between leaders (purple) and followers (green).
Individual differences of wing beat, ODBA and airspeed

To obtain an impression of flight mechanics differences between individuals and especially individual juveniles, we present individual distributions of ODBA, wing beat frequency and air speed (Fig. S4). It can be observed that all juveniles fly with higher flapping frequency that the father, especially when he was leading. One outlier is juvenile B, which has a very low sample size (see Fig. 1 in main text) that is possibly driving its extremely high ODBA and wing beat frequency values. After exclusion of this individual, the distributions of air speed differ by individual (LM, F=8.0, p<0.001), but with low differences (model parameters between 0.02 m/s and 0.39 m/s) and high general variability (see Fig. S3 for relationships explaining this variability).

Figure A4. Boxplots of flight mechanics parameters compared between all individual family members and their leadership status. See relation to Figs. 4b and S2b; here the parameters are split up by single chicks, names as in Fig. 1. (a) overall dynamic body acceleration (ODBA), (b) wing beat frequency and (c) air speed. Note the large individual differences, especially between chicks, in ODBA and wing beat frequency, but not air speed.
Leadership and energy expenditure for a second tracked family

A second tracked goose family stayed together into spring migration. However, because the tag of the mother (F2 in Fig. S5c) performed very poorly, only few overlapping data were available, so we had to exclude it from the main study. However, we performed the same analyses of leadership and energetics on the data set of 5 GPS bursts (543 positions) to see if the results fit into the picture and thus allow some level of generalizability.

The second family headed off from the Netherlands with five juveniles (3 male, 2 female) on 30/03/2015 (Fig. S5), but four of the juveniles and the mother were shot or predated along their spring migration (F2 9/5/2015 Russia; J2a and J2c 20/04/2015 Russia; J2b 18/04/2015 Belarus; J2e 10/05/2015 Russia).

The positions of the juveniles in relation to the leading parent fit well with the formation angle determined from the first family (Fig. S5a). For 98.3% of the juvenile positions the leading parent was in front of it, this being the father 79.4% and the mother 18.9% of the time. Thus, the father of this family was a somewhat more dominant leader.

In terms of flight mechanics consequences of leading, in the second family both father and mother flapped more than the chicks (father +0.23, mother +0.17; GLMM, \( \chi^2=19.5, p<0.001 \)). However, when leading vs. following, flapping frequency only increased for the mother (+0.15), but decreased for the father (-0.50; Fig. S6). Both parents flapped less with stronger tail wind (GLMM, \( \chi^2=19.1, p<0.001 \)), but there was no difference in tail wind if the father or the mother were leading (GLMM, \( \chi^2<0.01, p=0.98 \)).
Figure A5. Migration tracks, V-formation and leadership of second family. (a) Flight formation as positions towards the leading parent (b) migration tracks and (c) timeline with used positions indicated. Dotted lines in (a) indicate the angle of flight formation of the first tracked family (see main text and Figure 2). The map (b) was created with R 3.4.3, package ‘ggmap’ using as background googlemaps (see https://developers.google.com/maps/documentation/maps-static/intro).

Figure S6. Flight mechanics and tail wind for second family. (a) Overall dynamic body acceleration (ODBA) of leaders vs. followers and (b) ODBA of the leading parent vs. tail wind, both for the second tracked family. See in relation to Figure 4 in the main text.
Supplementary References
