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Author for correspondence:
Hester Brønnvik
e-mail: hbronnvik@ab.mpg.de

†These authors contributed equally to this study.

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Decoupling of emigration timing and skill acquisition in a saturated population of golden eagles

Hester Brønnvik[1,2], Martina Scacco[1,4], Michael Chimento[1,5], Enrico Bassi[6,7], Wolfgang Fiedler[1,2], Julia S. Hatzl[8], Petra Sumasgutner[9,10], Matthias Tschumi[8], Martin Wikelski[1,2], Svea-Sophie Zimmermann[8,11], Kamran Safi[1,2,†] and Elham Nourani[1,2,3,†]

[1]Max Planck Institute of Animal Behavior, 78315 Radolfzell, Baden-Wuerttemberg, Germany
[2]Department of Biology and [3]Centre for the Advanced Study of Collective Behaviour, University of Konstanz, 78464 Konstanz, Baden-Wuerttemberg, Germany
[4]Dynamic Macroecology, Swiss Federal Institute for Forest, Snow and Landscape Research, ETH Zurich, 8903 Birmensdorf, Switzerland
[5]Department of Evolutionary Biology and Environmental Studies, University of Zürich, Zürich, Switzerland
[6]CISO ODV – Centro Italiano Studi Ornitologici. Sede legale e operativa: Via Maqueda, 110 – 90134 Palermo, Sicily, Italy
[7]Vulture Conservation Foundation (VCF), Wuhrstrasse 12, CH-8003 Zurich, Switzerland
[8]Swiss Ornithological Institute, CH-6204 Sempach, Switzerland
[9]Konrad Lorenz Research Center (KLF), Core Facility for Behavior and Cognition, Department of Behavioral and Cognitive Biology, University of Vienna, 4645 Grünau/Almtal, Austria
[10]Department of Behavioral and Cognitive Biology, University of Vienna, 1030 Vienna, Austria
[11]Department of Wildlife Ecology and Management, University of Freiburg, Freiburg, Germany

HB, 0000-0002-3061-0630; MS, 0000-0003-4821-4051; MC, 0000-0001-5697-1701; EB, 0000-0002-0698-4800; WF, 0000-0003-1082-4161; JSH, 0000-0002-7915-9588; PS, 0000-0001-7042-3461; MT, 0000-0002-7991-7780; KS, 0000-0002-8418-6759; EN, 0000-0003-4420-3902

Many animals must gain independence from parental care by acquiring skills necessary for survival. Thus, the rate of skill acquisition can predict when parental care ends and animals emigrate. However, young animals sometimes acquire adult-like skills long before they emigrate. We asked why the timing of emigration decouples from the rate of skill acquisition and proposed that skill acquisition may instead link to the timing of excursions from natal territories before emigration. We used global positioning system tracking of 14–64 juvenile golden eagles (*Aquila chrysaetos*),

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which learn to fly and hunt under parental care. We expected flight performance to predict the timing of excursions better than the timing of emigration. Using time-to-event models, we predicted excursion and emigration rates based on flight performance and patterns of daily movement. Contrary to our prediction, flight performance failed to predict either event, whereas daily movement predicted both. Daily movement may capture motivation and weather together with flight skills, and those factors probably drive emigration. Juveniles may delay emigration not because they lack skill, but because the costs of independence outweigh its benefits. This decoupling of ability and choice may also obscure the link between skill acquisition and the end of parental care in other systems.

1. Introduction

Independence from parental care is an important life-history milestone for many animals. Independence, defined as the ability to operate without parental provisioning and care, can correspond to achieving adult-like body size in some species; however, for species that occupy complex niches, several key abilities are prerequisite to independence [1,2]. Particularly, to be independent, individuals must have sufficient foraging skill to locate, access and perhaps process enough nutritious food [3–7]. Additionally, individuals must be capable of avoiding predation and competition without parental protection, which requires them to find safety and compete for opportunities independently [8–10].

Such abilities are often acquired over time rather than appearing abruptly at maturity. Thus, determining the rate at which skills are acquired can allow us to predict the timing of the transition to independence. First, individuals must develop physiologically—for example, by increasing their lung capacity to dive for prey [11], growing feathers that support flight or building the musculoskeletal structures to accelerate and escape predators [12]. Second, animals must reach behavioural maturity through acquiring foraging skills [13], competitive abilities [14–16] and refined movement skills. For many animals, these movement skills may be highly specialized—for example, cryptic prey approaching [17], manipulation of tools [18] or specialized flight modes [19]. Finally, individuals require environments that support their bids for independence, including parental tolerance while their skills develop [20–24], available food [25,26], suitable weather [27,28] and potentially either social partners or sufficiently low competition [29–31]. Once these physical, behavioural and habitat-specific criteria have developed, individuals can depart parental care.

Emigrating (i.e. initiating dispersal from the natal area) early could improve an individual's chances to secure a vacant or high-quality breeding territory [32,33]. Good individual condition has been linked to early emigration timing, with healthier, more competitive or more capable individuals being those more likely to emigrate [16,34–39]. For example, juvenile Eurasian eagle owls (*Bubo bubo*) in good body condition emigrate from their natal territories earlier than less healthy conspecifics of similar age and spend less time in the dispersal phase before settling in their own territories [40]. Individual state in the context of behavioural maturity has received less attention, but presumably acquiring the skills for survival is a necessary component of individual condition. Thus, we can expect a link between acquiring adequate skills and emigrating early to secure opportunities. This skill hypothesis suggests that skill acquisition acts as a constraint on emigration timing [41] and explicitly predicts that individuals emigrate when they acquire adult-like skills, and thus that individuals acquiring those skills more quickly emigrate earlier [42].

Yet, some systems do not support this predicted relationship between rate of skill acquisition and emigration timing. Instead, adult-like skills may be acquired long before emigration and individuals continue to exploit parental care even when they no longer require it [42–50]. For example, although New Caledonian crows (*Corvus moneduloides*) need 10–12 months to achieve adult-level proficiency in tool use, they do not emigrate until around 20 months of age [51]. This raises the question of why the timing of emigration decouples from the rate of skill acquisition, resulting in extended parental care.

One possible answer is that emigration timing may be strongly influenced by factors other than skill, perhaps including food availability [52,53] and competitive ability [54]. Importantly, the decision of when to emigrate is not at the sole discretion of the juvenile, but indicates parental motivation and ability to continue providing care.

In many systems with extended parental care, emigration is preceded by excursions from the natal area (also termed forays or simply extraterritorial movements). While on excursions, individuals are not under parental care or protection and must operate independently. These excursions serve as

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prospecting opportunities [55], providing information about the environment in which dispersal will take place. Young animals on excursions can acquire information about competitors, habitat quality and mate availability, allowing increased post-dispersal breeding success [56]. This can be accompanied by stress [57], but potentially delays the dangers associated with emigration while allowing information gathering—a strategy dubbed stay-and-foray [58]. Thus, periods of extended parental care can be punctuated by independent excursions if individuals have the ability to operate independently.

Here, we ask whether the ability to be independent is distinct from the decision to be independent. We explore the role of skill acquisition in determining the timing of independence in the context of movement-related skills. We suggest that excursions before dispersal can be a better indicator of when individuals have acquired the ability to be independent than the decision to emigrate is. We test this by investigating the link between how quickly individuals acquire movement skills and how quickly they begin excursions or emigrate from their parents' territory. We expect that animals which quickly acquire movement capacity will go on their first excursions early, but that this may not predict early emigration because skilled individuals can still acquire other benefits from parental care.

Golden eagles (*Aquila chrysaetos*) serve as a model to quantify the link between movement-related skills and the timing of independence. Soaring flight is a vital movement skill for golden eagles, allowing them to move the long distances required to hunt, scavenge and disperse, while incurring very low energetic costs and soaring can be measured using high-resolution global positioning system (GPS)-tracking data. In addition, golden eagles have large individual- and population-specific variation in the duration of parental care. After juveniles leave the nest, parental care lasts from roughly 32 to 260 days in the western USA [59, p. 666], 39 to 250 days in Scotland [60], 44 to 395 days in France [61], 63 to 176 days in Norway [62], 84 to 269 days in Greece [63], and 143 to 283 days in Spain [59, pp. 200, 237]. This constitutes a range of 363 days overall, during which many individuals undertake excursions. This provides the opportunity to test whether the rate at which individuals acquire soaring skill can predict their transition to independence.

Golden eagles are clumsy after leaving the nest and only fly poorly [64], but improve their soaring flight over time [65, p. 227; 24,61]. Young eagles also have to learn hunting skills, but can make use of scavenging early in their lives [66, p. 373]. Thus, soaring skill should act as a constraint on when individuals can perform long-distance movements, whereas hunting skill may not be a constraint. We predicted that acquisition of soaring skill would predict time-to-excursion.

Yet, when young eagles are able to leave the natal territory, they may not find a supportive environment. Our data track golden eagles from the Alps. These eagles are in a saturated population where there are high densities of competitors and there are no available territories. This probably makes a challenging social environment for inexperienced juveniles. Young eagles have to compete for food and have to be able to find safe roost sites in spite of territorial adults. Thus, social context (i.e. parental tolerance, competition with other floaters, and aggressive territorial adults), food availability and the availability of uplifts for soaring should act as constraints on emigration timing in this system. We expected daily movement patterns to reflect these influences. For example, an eagle searching for a carcass may cross large distances, whereas an eagle exploiting a carcass may stay near that carcass [67]. We predicted that how individuals move at the scale of a day would predict emigration timing better than soaring skill would.

This saturated golden eagle population allows us to address the question of why the timing of emigration decouples from the rate of skill acquisition. If the ability to be independent is distinct from the decision to be independent, we expected to find that movement defined by skill (i.e. soaring performance) would predict time-to-excursion and that movement defined by the social environment and energy availability (i.e. daily movement) would predict time-to-emigrate.

2. Methods

2.1. Data collection

We used biologging data from a long-term study of juvenile golden eagles in the Alps. Juvenile eagles were tagged in the nest at approximately 50 days post-hatching (determined using plumage) using solar-powered GPS transmitters from e-obs GmbH (Munich, Germany) and a leg-loop harness [69]. The mass of the tag and harness together was 60 g, constituting 1.8% of the average mass at tagging for these eagles (mean = 3.42 kg, minimum = 2.06 kg). Adult golden eagles tend to weigh 4–5 kg [69], indicating

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that the relative tag mass will probably decrease as tagged eagles age. We used data collected for a total of 92 juveniles (supplementary material, tables S1–S3) over 2019–2024 (downloaded from the Movebank repository on 25 January 2025). GPS data were recorded every 20 min. Additionally, the GPS loggers collected 'super bursts' when the batteries were charged above a threshold, which mostly occurred during midday. These bursts included 15 min collection of 1 Hz GPS. We used the super bursts for our analysis of soaring flight before emigration. We performed all of the data processing and statistical analyses in R version 4.5.2 [70].

2.2. Identification of emigration and excursions

Emigration is defined as leaving the natal territory and not returning at all or returning only briefly, marking the start of natal dispersal. Determining emigration dates can be challenging, especially for excursive species [60]. However, for golden eagles, the area used by juveniles is a good indicator of the territory that their parents defend [71]. In addition, Alpine golden eagles build nests close to the tree line (so that they can hunt in open areas at high altitude) [72] and defend the valley containing the nest site; thus, ridge lines and valley floors tend to form the borders between territories [66, p. 368]. Minimum convex polygons and kernel densities using only movement data both consistently overestimate territory borders for birds that went on excursions, but underestimate territory borders for birds that did not go on excursions. Thus, we manually drew polygons around the highest density of early locations for each individual (e.g. supplementary material, figure S1) following the terrain of the valley where a nest was found and defined this as the natal territory. For territories inside of Switzerland, we compared our polygons to those published by Jenny *et al.* [66, p. 368] and found that they were in agreement, but we had no such comparisons for other countries. We defined emigration date as the day that an eagle in its first year of life left its natal territory and either did not return at all or returned for less than 24 hours. Young eagles that stopped transmitting within 10 days of leaving the territory ($n = 4$) were considered inconclusive, and we did not count these as emigrations. We defined excursions as any movement outside of the natal territory before emigration, and focused our analysis on long-distance (≥10 km) excursions (see code in the supplementary material).

2.3. Classification of flight modes

We identified soaring and gliding flight using the 1 Hz GPS data before emigration. We isolated bursts of continuous 1 Hz GPS data and calculated turning angle and vertical speed between consecutive locations (using the *move* R package [73]). For the classification of the flight behaviour, we applied a moving window of 25 s to calculate the absolute cumulative sum of the turning angles (hereafter cumulative turning angle) and a moving window of 5 s to calculate the average vertical speed. We then applied a *k*-means clustering algorithm with $k = 2$ on the average vertical speed to distinguish between soaring and gliding behaviour. We subcategorized soaring observations into circular soaring or linear soaring based on the cumulative turning angle, where a value of 200° or greater indicated circular soaring. Observations with a ground speed ≤ 3.5 m s^{-1} were considered as non-classified ('other behaviour').

2.4. Soaring performance metrics

We categorized each bout of circular soaring lasting at least 30 s and separated by not more than 60 s as a thermal. Although tags may alter flight performance relative to untagged individuals [78], here we only compared tagged individuals. For each thermal, we calculated three metrics to describe how young eagles soared. The vertical speed inside a thermal has been used to describe climbing skill [65, p. 227] because vertical speed depends on position within a thermal and individuals that centre more effectively climb more quickly. We calculated vertical speed as height gained per time spent, i.e. a bird soaring for 10 min and gaining 600 m of height has a vertical speed of 1 m s^{-1}. Wind can make thermals more difficult to soar in; thus, we expected skilled individuals to be more able to maintain thermals in windy conditions [74]. We extracted wind-corrected circling radius (using the *moveWindSpeed R* package [75,76]) and took the mean of the 1 Hz wind speeds [76]. We expected greater vertical speeds to reflect better exploitation of thermals, smaller circling radii to indicate soaring closer to the thermal core (where thermals are strongest) and higher wind speeds to indicate more skilful use of thermals.

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Table 1. The four TTE models using movement metrics to predict latency to first excursion or to emigration. (We predicted each event (first long-distance excursion or emigration) at two scales: (i) within soaring performance metrics summarized to per-day medians; and (ii) the daily movements.)

model	formula
soaring performance	
A	time-to-excurse ~ circling radius + vertical speed + wind speed
B	time-to-emigrate ~ circling radius + vertical speed + wind speed
daily movement	
C	time-to-excurse ~ scaled daily distance + scaled daily maximum height
D	time-to-emigrate ~ scaled daily distance + scaled daily maximum height

2.5. Daily movement metrics

Based on prior work assessing the movement behaviour of golden eagles [24,61], we extracted four metrics describing how young golden eagles moved on a daily basis. To consider overall mobility, we estimated ground speeds by down-sampling the data to consistent (20 min) intervals and extracting the daily maximum speed. We also down-sampled the data to one location in the hour of noon or 13.00 and calculated distances between consecutive midday locations [24] (with the Vincenty method using the *geosphere R* package [77]). On the assumption that climbing in thermals requires skill, we extracted the maximum height above ellipsoid per day to reflect how high individuals flew [61]. Finally, because individuals that have learned to fly will spend more time in flight, we estimated the proportion of time spent in flight as observations per day with ground speeds ≥ 3.5 m s^{-1} given all observations on that day [61].

2.6. Time-to-event analysis

Time-to-event (TTE) analysis, also known as survival modelling, estimates how much time is required for an event to occur and what factors influence that timing [78]. This approach has been applied outside of survival and health contexts, for example, in assessing birds' time-to-solve puzzles [79,80]. Of the ways to model TTE, Cox proportional hazard models relate event timing to multiple explanatory variables [81]. We chose to use this approach because it allowed us to treat excursions and emigrations as events predicted by either soaring performance or daily movement. This examines the rate of events occurring over time, and we can expect that rate to increase with increasing levels of soaring skill or coarser daily movements.

We built four separate TTE models (table 1). The models predicting first long-distance excursions used only data up to and including the first day of that excursion, and the models predicting emigration used only data up to and including the date of emigration (i.e. the post-fledging dependence period). To align birds in terms of age, we used each individual's days since tagging. The models used intervals of 1 day, but our soaring performance metrics were measured at the per-thermal level. Thus, we summarized our soaring performance data to per-day medians of circling radius, vertical speed and wind speed. We coded each day with a binary outcome (event = 1, no event = 0), with the day right-censored (event = 0) if the event (either first long-distance excursion or emigration) was not observed. The fine-scale data had gaps on days when the biologging devices did not transmit data classified as thermal soaring. If there were no data on the day of excursion/emigration, but there were data within 10 days after this (excursions $n = 3$, emigration $n = 6$), we used the first of those thermals for the final skill level (i.e. last follow-up time). For the daily-scale metrics, the final skill level was measured on the day of first excursion or emigration. Owing to relatively small repeated measures per-individual, we did not include frailty terms in our models.

Daily distance travelled between midday locations was correlated with maximum daily ground speed ($r = 0.50$) and time spent in flight ($r = 0.55$); thus, we only included daily distance and maximum flight height (which had a correlation of $r = 0.17$) in models C and D (table 1). Because golden eagles can fly at

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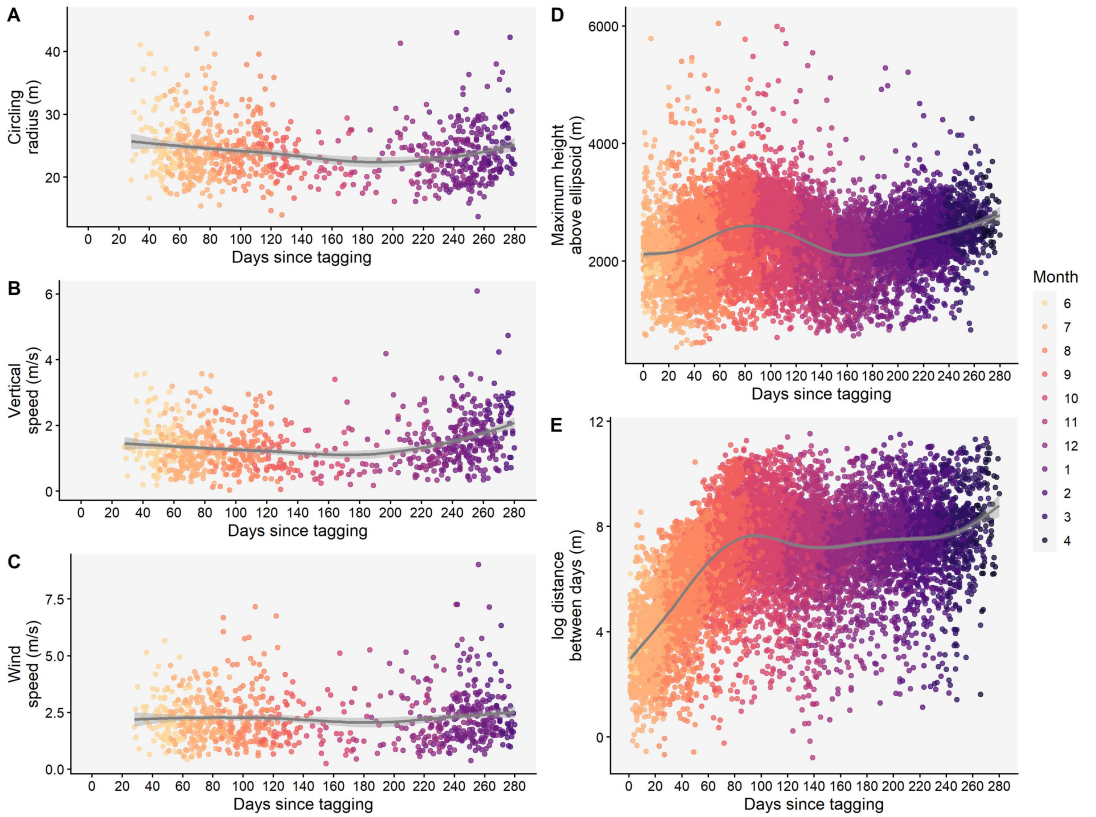


Figure 1. The data used in the models from table 1. (A) Circling radius within thermal uplifts varies and decreases slightly after 120 days. (B) Vertical speeds of thermals (metres gained in a thermal per seconds spent in that thermal) vary. (C) Wind speeds experienced within thermals vary. (D) Maximum height reached per day initially increases until around 80 days after tagging, but then decreases until 160 days before increasing again. (E) Distances between consecutive midday locations increases until around 80 days after tagging and then levels off. The median days-to-excursion was 79. The interval of 90–160 days corresponds roughly to October through to December. Curves drawn using ggplot locally estimated scatterplot smoothing for visualizing trends.

up to 30 m s^{-1} [82], we *z*-scaled the daily movement metrics to use units of standard deviations rather than individual meters. We built separate models for the daily movement and soaring performance predicting TTE using Cox proportional hazards in the *survival* [83] package in *R*. For all four models, we checked the proportional hazard assumption and the distribution of the Schoenfeld residuals [84].

3. Results

Of the 92 juveniles, 66 emigrated before the spring of 2025, 59 of which also performed long-distance excursions. An additional 7 individuals performed long-distance excursions but did not emigrate. Only 14 individuals transmitted 1 Hz data containing classified thermal soaring flight before going on a long-distance (≥10 km) excursion and 18 before emigration. These subsets of 14 and 18 individuals contributed data to our analysis of soaring performance metrics (figure 1A–C). For the daily movement metrics (figure 1D,E), 60 individuals contributed to the emigration models and 64 to the excursion models.

Eagles made their first long-distance excursions between 55 and 246 days after tagging (median = 79; supplementary material, figure S2A). The maximum distances reached on these excursions varied between 10 and 77 km (median = 16.7; supplementary material, figure S2B) and lasted between 1 h and 13 days (median = 4.82 h; supplementary material, figure S2C). Emigration occurred between 61 and 283 days after tagging (median = 229; supplementary material, figure S2D).

The hazard functions for excursions showed an initially steep increase followed by a plateau in both soaring performance and daily movement consistent with a type III survivorship curve (figure 2A,C). The hazard functions for emigration showed a more gradual and sustained increase in soaring performance and daily movement consistent with a type I survivorship curve (figure 2B,D).

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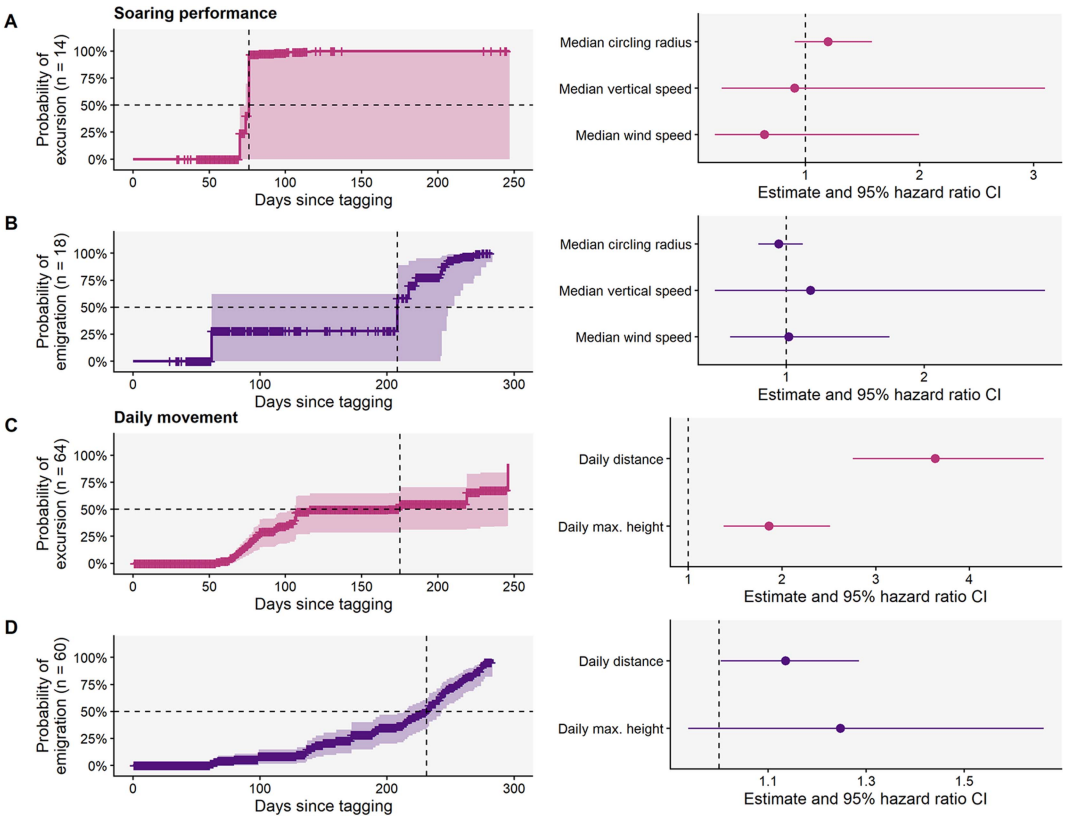


Figure 2. The association of soaring performance and daily movement metrics with time-to-excursion and time-to-emigrate. (A) No soaring performance metric had a detectable effect on excursion timing. (B) No soaring performance metric had a detectable effect on emigration timing. (C) Both daily distance and daily maximum flight height had positive effects on time-to-excursion. (D) Daily distance had a positive effect and maximum flight height had no significant effect on time-to-emigrate.

None of the soaring performance metrics was significantly associated with excursion or emigration rates (figure 2A,B; supplementary material, figure S3A,B). However, the daily movement metrics had effects on both time-to-excursion and time-to-emigration (figure 2C,D; supplementary material, figure S3C,D). For each standard deviation increase in daily distance (one s.d. = 6736 m) and in maximum daily height (one s.d. = 558 m), we found corresponding increases in the rate of excursions of 264% (hazard ratio = 3.64) and 86% (hazard ratio = 1.86), respectively; thus, individuals travelling farther and flying higher were more likely to go on their first excursions (table 2). Each standard deviation increase in daily distance was associated with a 14% (hazard ratio = 1.14) increase in rate of emigration (table 2). We found no significant effect of maximum daily height on the rate of emigration. We did find a seasonal pattern of lower daily heights and daily distances in winter (figure 1).

4. Discussion

We found that daily movement was more strongly associated than soaring performance with both excursion and emigration timing. Specifically, travelling longer distances between days and achieving higher flight heights were associated with shorter time-to-excursion, but none of our measures of soaring performance was. Similarly, longer daily distances were associated with shorter time-to-emigrate, and soaring performance failed to predict time-to-emigrate. This is probably because daily movement patterns capture more than movement capacity, which may be acquired within just a few months.

Daily movement patterns are shaped by interactions between internal state (e.g. energetic needs) and external conditions (e.g. perceived risk, weather) [85–87]. Essentially, even while skills remain the same, motivations may change across changing contexts. For Alpine golden eagles, winter is likely to pose many difficulties. Prey availability decreases, carcasses are buried under snow, thermal uplift availability decreases and territories are defended year-round by aggressive adults [66].

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Table 2. Hazard ratios and associated confidence from Cox proportional hazards tests. (Models A and C predicted time-to-excursion; models B and D predicted time-to-emigration (table 1).)

soaring performance					
model	**predictor**	**hazard ratio**	**2.5% CI**	**95% CI**	***p*-value**
A	circling radius	1.197	0.906	1.581	0.207
A	vertical speed	0.906	0.265	3.098	0.875
A	wind speed	0.640	0.205	1.994	0.441
B	circling radius	0.944	0.797	1.119	0.507
B	vertical speed	1.177	0.482	2.876	0.721
B	wind speed	1.018	0.593	1.749	0.947
daily movement					
model	**predictor**	**hazard ratio**	**2.5% CI**	**95% CI**	***p*-value**
C	daily distance	3.635	2.758	4.790	<0.0001
C	daily maximum height	1.862	1.379	2.514	<0.0001
D	daily distance	1.135	1.003	1.286	0.045
D	daily maximum height	1.248	0.936	1.663	0.131

Daily movements of golden eagles should account for all of these factors as young eagles must soar, obtain food and escape competition. The contradictory signals we found in flight height indicate a change in prevailing weather conditions—eagles are more likely to make their first excursions before winter when they are flying higher, but to emigrate after winter and the corresponding reduction in flight height (figure 1; supplementary material, figure S2). Increasing daily distances were associated with both shorter time-to-excursion and shorter time-to-emigrate (figure 2). Young eagles were moving across their natal territories more and perhaps making some short-distance forays before they went on their first long-distance excursions. They also made excursions and thus had higher daily distances before emigration. We expect that these higher daily distances are associated with the availability of supportive weather conditions and potentially with hunting/scavenging behaviour. The end of winter also brings increased prey densities as prey species respond to increasingly available forage; this particularly applies to marmots and young ungulates [66,88–90]. Spring also coincides with a shift in the motivations of adult golden eagles, which may begin a new breeding effort and grow less tolerant of continued investment in the previous year's offspring. The combination of better weather and more prey along with parental motivation probably makes spring an attractive time to emigrate. Our results support the role of these external factors in driving eagle movements better than the role of flight skills. Essentially, movement capacity is a necessary, but not sufficient, component of the decision to depart parental care.

The contrasting shapes of the survival curves (figure 2)—type III survivorship curves for excursions and type I survivorship curves for emigration—show high excursion rates early in life decreasing over time and the opposite for emigration rates (low emigration rates early in life that increase sharply with time). This could be maximizing the time between the first long-distance excursions and emigration, providing opportunities to practise independence and sample the environment before choosing to emigrate.

In fact, before emigration from the natal territory, most juvenile eagles were clearly capable of remaining outside of parental care for several days at a time and traversing large distances quickly, as demonstrated by their excursions. Four young eagles departed their natal territories in 80 days or fewer. This is close to the age at which most Alpine eagles started their long-distance excursions (supplementary material, figure S2) and to the ages at which Alaskan (63 days [91]) and Norwegian (100 days [62])

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golden eagles migrate. Golden eagle parents may stop actively provisioning juveniles at around 120 days [65, p. 228], which could also indicate that juveniles are capable of scavenging for themselves within four months of leaving the nest. Taken together, this suggests that golden eagles achieve the ability to be independent with regard to maturity of movement capacity in three to four months. Thus, in contrast to the hypothesis that acquisition of complex skills delays emigration, it seems that soaring performance is unlikely to act as a constraint on eagle emigration after a very early age. Instead, aligning with our prediction, the ability to be independent seems better captured by excursion timing than by emigration timing.

Yet, we did not find an association between movement capacity—in this case, soaring flight performance—and time-to-excursion. This could be for two non-mutually exclusive reasons: (i) golden eagles quickly reach their maximum soaring proficiency; and/or (ii) there was a pattern that our data did not capture. It is possible that the way eagles soar in thermals does not change with age as much as thermal structure itself changes with hour and season. Thus, if eagles quickly learn to soar, the adjustments they later make to soar well could be masked by riding weaker thermals. Observations of juvenile eagles flying with their parents suggest that adult-like vertical speeds can be obtained within 60 days of leaving the nest [65, p. 227]. It may be that after approximately two months, juveniles are exploiting at peak proficiency the subset of thermals that they choose to use. However, we might also not have found a signature of learning because the early learning period of up to 60 days post-fledging accounts for only around 5% of our 1 Hz data. The poor coverage of the very early periods of post-fledging is because nestlings and fledglings tend to sit in the shade; thus, the GPS devices rarely had full battery before eagles were spending time soaring with their backs exposed to sunlight. In addition, fledglings simply fly less [92], meaning that we were less likely to capture their flight in our burst data structure. Finally, we only accounted for circular, thermal soaring, but young eagles may rely on orographic soaring [93], and how they perform in orographic uplifts may prove as important for them as thermals. Future work collecting high-resolution tracking data from juvenile animals may find a signature of improvement as these data gaps are filled, but we did not find a learning curve in soaring performance.

Our findings suggest that the transition to independence in juvenile golden eagles is not a simple process following the smooth trajectory of a learning curve, but shaped by a combination of development, environment and decisions. The variability in golden eagle emigration highlights that independence is often a choice. For golden eagles, soaring is a vital skill that allows them to hunt and scavenge, but they seem to acquire this skill—at least under optimal soaring conditions—long before they emigrate. Instead, they may engage in long-distance excursions after they acquire adult-like movement abilities, using excursions as an opportunity to practise moving and scavenging in unfamiliar environments and to prospect for available habitats from the safety of their natal territories [24,62,94,95]. The golden eagle population in the Alps is at its carrying capacity, with no territories unoccupied [66, p. 370]. Thus, juveniles that are, otherwise, ready to disperse may simply have nowhere to go. Competitive ability, parental tolerance, conspecific densities, prey densities, hunting skills and human disturbance are among many factors both internal and external to a young animal that are likely to interact in affecting the decision of whether or not to forgo parental care. Whereas movement capacity is certainly a necessary part of the ability to survive independently, it is just one factor contributing to the complex decision of whether and when to become independent.

The transition to independence is often associated with energetic costs and mortality [96–99]. Yet, being independent of parental care is necessary for adult animals. This produces a trade-off between the costs and benefits of independence [100]. Unless the expected profit of undertaking this risky transition is great enough, young animals that can exploit parental tolerance should continue to do so, even if they could potentially survive on their own. Both the costs and the benefits of leaving parental care are probably best assessed during excursions from the natal territory, which may link excursion timing to when individuals have reached the developmental stage to attempt independence. Although movement capacity may be acquired relatively early in development, emigration often occurs later, which indicates that the timing of independence can be decoupled from skill acquisition. Delaying independence allows juveniles to make a choice about the timing of emigration, aligning it with favourable external conditions rather than with internal developmental milestones. Thus, juveniles may remain in the natal area not because they are unskilled, but because the costs of leaving parental care outweigh the benefits. Our results indicate that independence in a saturated population of golden eagles is shaped less by gradual skill acquisition than by external conditions and behavioural decisions. Emigration timing should be viewed through the lens of ecological opportunity and individual choice rather than simple developmental milestones.

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Ethics. The handling and ringing of golden eagle nestlings in Switzerland was carried out under the authorization of the Office for Food Safety and Animal Health (ALT) of the canton Grisons (licence no. GR 2017_06, GR 2018_05E, GR 2019_03E). In Italy, the permissions for handling, tagging and marking were obtained from the autonomous region of South Tyrol (Dekret 12257/2018 and Dekret 8788/2020), as well as from the region of Lombardia for ringing and tagging through in Lombardia and South Tyrol by Istituto Superiore per la Protezione e la Ricerca Ambientale with the Richiesta di autorizzazione alla cattura di fauna selvatica per scopi scientifici(l.r. 26/93). In Austria, all procedures for handling, tagging and marking were approved by the Ethics committee of the University of Vienna (no. 2020-008) and permitted by the Federal Ministry for Education, Science and Research (no. 2020-0.547.571), Styria (BHLI-165942/2021-2) and Upper Austria (LFW-2021-263262/7-Sr). Finally, in Germany, birds handled, tagged and ringed were done so under the permission issued by the government of Oberbayern (2532.Vet_02-16-88 and 2532.Vet_02-20-86). All procedures followed the ASAB/ABS guidelines for the ethical treatment of animals in behavioural research and teaching, and all applicable international, national and/or institutional guidelines for the care and use of animals were followed. The handling of birds was performed with maximum care and minimal disturbance to nests and the landscape. Ethical approval for involving animals in this study was received through the application procedure for ringing permits and the scientific commission of the Swiss Ornithological Institute and the national authorities as well as the guidelines imposed through the European Commission on the basis of the guidelines of the Federation or the European Laboratory Animals Association.

Data accessibility. Data for this work are stored on Movebank with the identifiers 282734839 and 453975008. Relevant code for this work is stored on GitHub: https://github.com/kamransafi/GoldenEagles/tree/4acf2cb1f7fc8e281b3c6d50db8744acca9c780a/WP3_Soaring_Ontogeny/MS1_soaring_skills. Data and code have been archived within the Edmond repository [101].

Supplementary material is available online [102].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. H.B.: conceptualization, formal analysis, investigation, methodology, validation, visualization, writing—original draft, writing—review and editing; M.S.: methodology, validation, writing—review and editing; M.C.: methodology, validation, writing—review and editing; E.B.: resources, writing—review and editing; W.F.: data curation, project administration, resources; J.S.H.: data curation, validation, writing—review and editing; P.S.: resources; M.T.: data curation, writing—review and editing; M.W.: funding acquisition, resources; S.-S.Z.: data curation; K.S.: conceptualization, funding acquisition, methodology, project administration, resources, writing—review and editing; E.N.: conceptualization, investigation, resources, supervision, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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