SI Appendix

Appendix 1

Table S1. Summary of observed effects

Group	Category	Variable	Motion		Navigation	
			H	*D*	*H*	*D*
r	Geography	Terrain ruggedness	–0.0006 (0.00036)	NS	0.070 (0.024)	0
		Latitude	NS†	NS	–2.7 (0.596)**	NS
	Meteorology	Turbulence kinetic energy	0.085 (0.034)	0.640 (0.11)	–6.48 (2.49) ***	NS
		Vertical wind velocity	NS **	NS***	NS***	NS
		Horizontal wind speed	NS	–0.12 (0.047)	1.43 (0.81)	NS
		Horizontal wind direction	NS	NS**	NS†	NS
		Cloud top height	NS	0.0001 (0.00005)	NS	NS
u_t	Motion-navigation effects	Distance (Motion)		**	–0.657 (0.179)	0.13 (0.055)
		Bearing deviation (Navigation)	–0.0018 (0.00044)	0.234 (0.089)	***	**
	Past behavior	Altitude at start	0.00036 (0.00009)***	NS**	NS	NS
		Speed at start	0.0068 (0.001)***	NS	NS	NS
	Auto-regressivity	Past position---AR(1) correlation coefficient	***	0.48	0.33	0.32
$r \times u_t$	Interactions	Terrain Ruggedness:TKE	–0.00068 (0.00022)	NS	NS	NS

Variables are divided into three categorical groups: external factors (r), temporal factors (u_t), and their interaction ($r \times u_t$). Motion is measured using distance as a dependent variable, and navigation is measured using angular deviation from a local mean. The influence of past positions was assessed through auto-regressive integrated moving average modeling for the correlation structure. All other variables were independent main effects. Angle models used degrees, and negative coefficients indicate less deviation and thus a straighter path. All two way interactions within and between the external effects and temporal variables were tested. The only significant interaction was between terrain ruggedness and TKE. Information is organized as follows: parameter estimate (standard error) significance. NS, not significant; [dagger], *P* [lt] 0.1; *, *P* [lt] 0.05; **, *P* [lt] 0.01; ***, *P* [lt] 0.001.

Appendix 2

Movement ecology interactions	Hourly scale	Daily scale	Annual scale
Effects of external factors (*r*) on motion capacity (Ώ)	Winds and turbulence (1), sociality (drafting for thermal discovery (2, 3)	Weather fronts, ridges, and troughs determine winds and turbulence available (1, 4). Food availability affects refueling decision.	Climate change alters the availability and timing of weather patterns (5).
Effects of external factors (*r*) on navigation capacity (Φ)	Sensory information like light and olfaction (6, 7) affect spatial knowledge and route choice.	Weather patterns will allow both adaptive wind drift and wind drift correction to influence routes (8, 9)	Long term trends in habitat and weather will determine timing; natal dispersal as well as later dispersal events will affect migratory route choice (10).
Effects of internal state (*w*) on motion capacity (Ώ)	Fat stores, circulating metabolites, and muscular fatigue determine costs of flight (1). Costs of movement determine distances (11).	Organ condition (12, 13) and hormonal states will regulate the impulse to continue flight (1).	Age and experience lead to optimized decisions on distance and timing (8, 14).
Effects of internal state (*w*) on navigation capacity (Φ)	Energy state will determine a shift from migratory behavior to local food searching and roost locating. Behaviors such as aerial foraging mediate this process (2).	Decisions on length of stopovers, the lengths of paths between stopovers, and the degree of foraging within the migratory journey are all mediated by internal state.	Birds optimize route choice through experience (15). Previous dispersal events affect routes (10).

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Appendix 3

Summary tables for linear mixed effects models describing movement and navigation decision functions

Hourly Movement Model

Log(Distance) ~ altitude + speed + bearing deviation + terrain ruggedness + TKE + terrain ruggedness * TKE

Random effect = ~1|Bird/Migratory Event; (Intercept-only random effect structured with bird as highest level, and migratory event beneath this)
Standard Deviation: 7.2e-05 (intercept), 0.59 (residual)
No random effects were significant in model comparison across all analyses.

Correlation structure = ARIMA(1,0,0); Phi (correlation coefficient) = 0.446;
Degrees of Freedom = 708;

Variable	Value	SE	*t*	*P*
(Intercept)	2.199	0.067	32.9	0.0000
Altitude	0.000363	0.000091	3.97	0.0001
Speed	0.006782	0.001003	6.59	0.0000
Bearing deviation	–0.00177	0.000435	–4.06	0.0001
Terrain ruggedness	–0.00061	0.000358	–1.71	0.0872
TKE	0.085413	0.033559	2.55	0.0111
Terrain ruggedness*TKE	–0.00067	0.000224	–3.02	0.0026

Derived Equations of Movement:
Log(Distance) = .446* $\text{Log(Distance)}_{t-1}$ + .00036*Altitude + .0068*Speed + –0.0017 * Bearing deviation + –0.00061*Terrain Ruggedness + .085*TKE + –0.00067*Terrain Ruggedness*TKE

Daily Movement Model

Log(Distance) ~ bearing deviation + TKE + cloud top + horizontal wind strength + food

Random effect = ~1|Bird/Migratory Event;
Standard Deviation: 7.1e-05 (intercept), 1.34 (residual)

Correlation structure = ARIMA(1,0,0); Phi = 0.336;
Degrees of Freedom = 137;

Variable	Value	SE	*t*	*P*
(Intercept)	0.791	0.799	0.99	0.3237
Bearing deviation	0.234	0.0896	3.97	0.0001
TKE	0.640	0.110	6.59	0.0000
Cloud top	0.000129	0.0000512	–4.06	0.0001
Wind strength	–0.120	0.0467	–1.71	0.0872

Derived Equation of Movement:
$Log(Distance) = .336* Log(Distance)_{t-1} + .234*Bearing\ deviation + .64*TKE + .00013*cloud\ top\ height + -0.12*Wind\ Strength$

Hourly Navigation Model

Bearing Deviation ~ latitude + log(distance) + terrain ruggedness + TKE + horizontal wind strength

Random effect = ~1|Bird/Migratory Event;
Standard Deviation: 0.0037 (intercept), 50.1 (residual)

Correlation structure = ARIMA(1,0,0); Phi=0.48;
Degrees of Freedom = 709;

Variable	Value	Std. Error	t-value	p-value
(Intercept)	161.	22.1	7.29	0.0000
Latitude	–2.70	0.596	–4.54	0.0000
Distance	–0.657	0.180	–3.66	0.0003
Terrain ruggedness	0.0696	0.0245	2.84	0.0046
TKE	–6.48	2.49	–2.60	0.0095
Wind Strength	1.43	0.812	1.76	0.0794

Bearing Deviation = .48* Bearing Deviation$_{t-1}$ + -2.7*Latitude + –0.657*Distance + .07*Terrain Ruggedness + -6.48*TKE + 1.43*Wind Strength

Daily Navigation Model

Bearing Deviation ~ log(distance) + food

Random effect = ~1|Bird/Migratory Event;
Standard Deviation: 7.41e-05 (intercept), 1.08 (residual)

Correlation structure = ARIMA(1,0,0); Phi=0.262;
Degrees of Freedom = 140

Variable	Value	Std. Error	t-value	p-value
(Intercept)	1.40	0.200	7.00	0.0000
Distance	0.131	0.0552	2.37	0.0189

Derived Equation of Motion:
Bearing Deviation = .262*Bearing Deviation$_{t-1}$ + 1.4*Distance

Appendix 4

In the U.S., Turkey Vultures were captured on the carcasses of roadkilled deer (*Odocoileus virginianus*) and groundhogs (*Marmota monax*). Padded leghold traps that had been modified by the removal of one spring and the addition of foam-tube padding, were set around carcasss. Traps were monitored from a blind, and birds were removed from traps immediately upon capture. In Canada, birds were caught by hand on the nest in abandoned farmhouses in Saskatchewan. Vultures were fitted with a solar GPS transmitter (Microwave Telemetry, 70 g) using a sewn harness of teflon ribbon. Transmitters were attached with unwaxed dental floss, which will naturally rot away after several seasons (E. Henkel, personal communication). To measure heart rate in a subset of birds, heart-rate loggers (A.J. Woakes; Biometistics) were implanted peritoneally and held in place using silk threads sewn into subcutaneous fat. All captured and tagged birds were offered dead mice, and were released within 24 hours. There was no visible effect of capture on behavior after 2-3 days.

GPS locations have a published accuracy of 15 meters for horizontal and vertical locations.