

Migratory birds can extract positional information from magnetic inclination and magnetic declination alone

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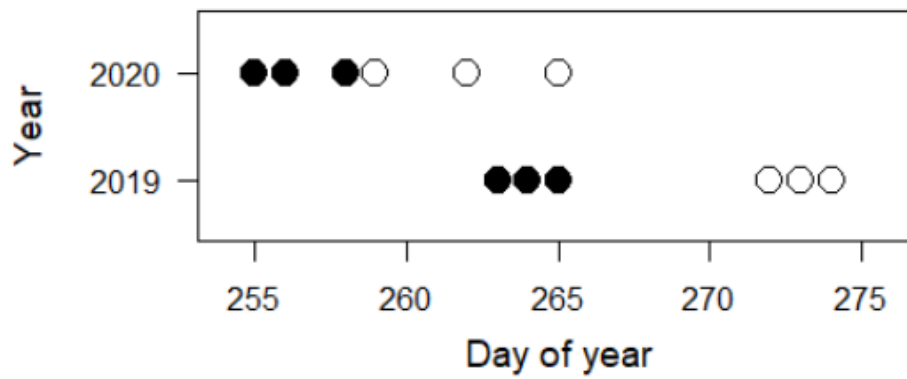


Figure S1: Periods used for orientation tests during our virtual magnetic displacement experiment in 2019 and 2020. The day of the year for orientation tests under NMF conditions (black dots) and CMF conditions (white dots) are given. The overall test period ranged from day of the year 255-274 (Sept 12th-Oct 1st). Note that the NMF and CMF periods overlap, which suggests that the shift in orientation between NMF and CMF conditions is unlikely to be a seasonal effect (see also [1]).

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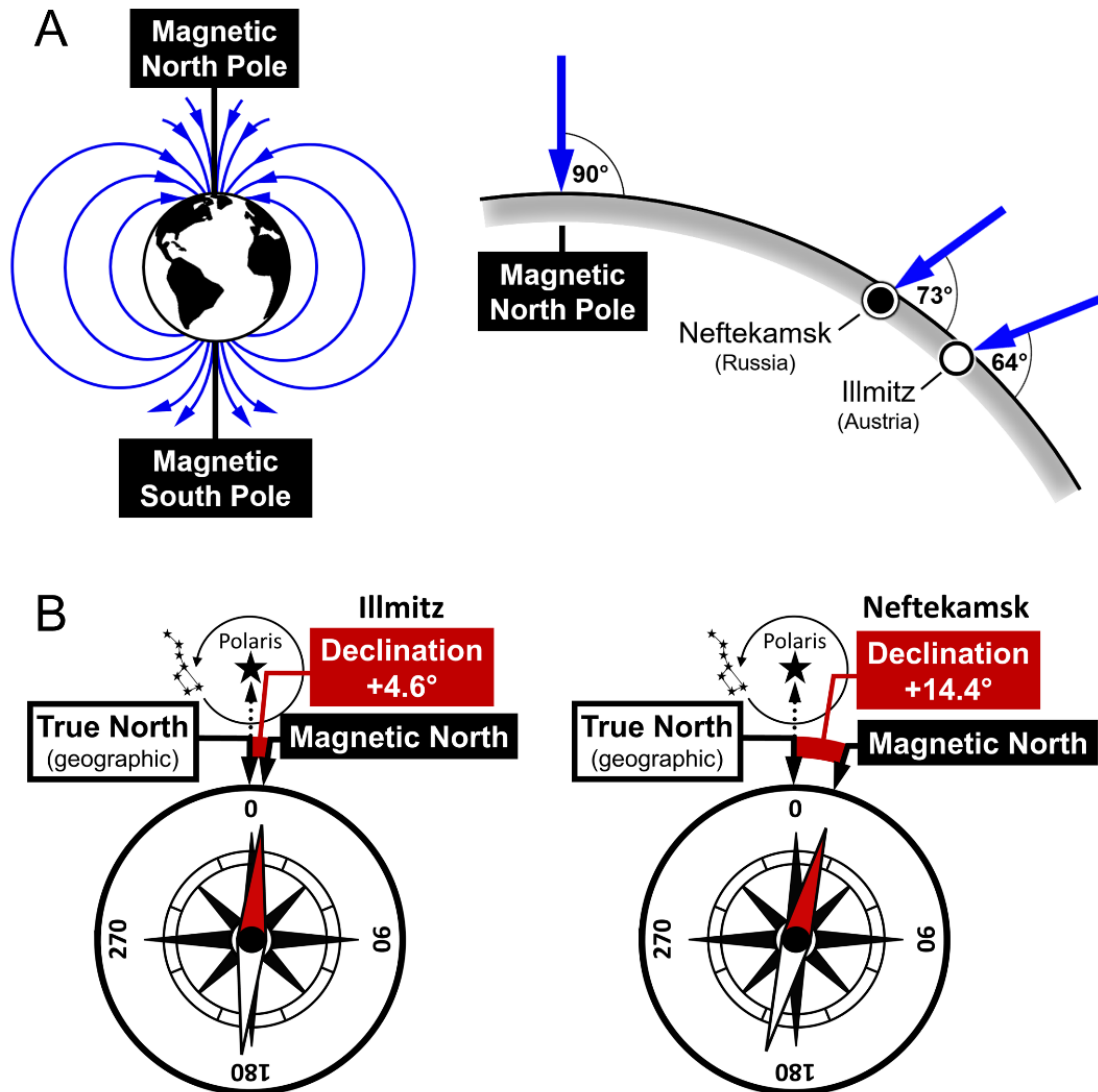


Figure S2: Magnetic inclination and magnetic declination at our study site (Illmitz, Austria) and at our virtual displacement site (Neftekamsk, Russia). (A) Schematic depiction of the Earth's magnetic field with its magnetic field vectors (blue arrows). The inclination (i.e., the dip-angle of the Earth's magnetic field vectors) at the magnetic North Pole (90°), near Illmitz (~64°) and near Neftekamsk (~73°) are given. (B) Schematic depiction of the declination (i.e., the angle between directions towards geographic and magnetic North) near Illmitz (4.6°) and near Neftekamsk (14.4°).

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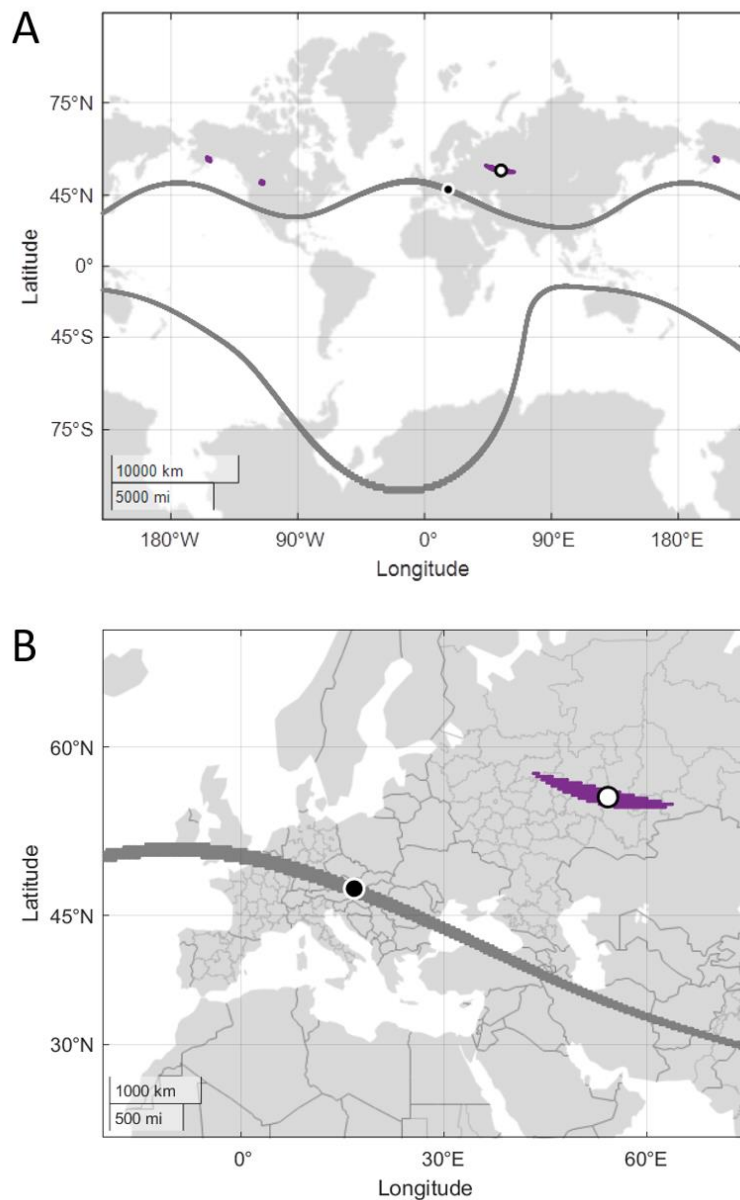


Figure S3: Global map (A) and map of Europe and North Africa depicting all possible locations for the CMF conditions of the current virtual magnetic displacement with the inclination and declination of the virtual displacement site (Neftekamsk, Russia; white dot), but the total magnetic intensity of the study site (Illmitz, Austria; black dot). Purple areas show all locations with the same inclination and declination ($\pm 0.5^\circ$), dark gray areas show locations with the same total magnetic intensity (± 200 nT) as presented under the CMF conditions of the current virtual magnetic displacement. Note that the combination of all three magnetic cues as presented under these CMF conditions does not exist anywhere on Earth under natural conditions. The combination of magnetic inclination and magnetic declination alone, however, exists in three areas globally: around our virtual displacement site and in two areas in North America, which are thousands of kilometers outside the natural distribution range of our study species, the Eurasian reed warbler, and therefore cannot have been realistically extrapolated based on the magnetic information experienced by the birds we used in our tests. Maps were produced using the visualization tool “VirtDAL” for MATLAB [2].

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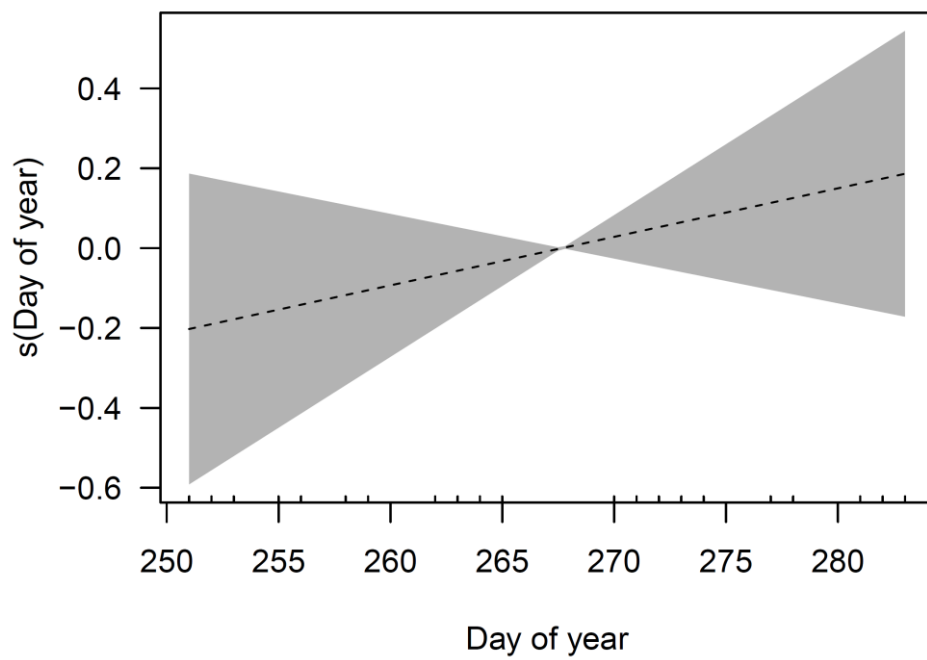


Figure S4. Non-significant effect of the smoothing term day of year on the sine of birds' individual directions from the combined data sets of [1] and the current study extracted from the Generalized Additive Mixed Model (GAMM) which is summarised in Table S2.

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Table S1: Summary of the ΔAICc and the AICc model weights (w) from the 10 orientation models described in [3] from the data obtained from experienced Eurasian reed warblers under NMF and CMF conditions. Values from the respective best models with a $\Delta\text{AIC} < 2$ are shown in bold and highlighted by asterisks.

Model	NMF		CMF	
	ΔAICc	w	ΔAICc	w
M1 (uniform)	6.30	0.03	3.58	0.07
M2A (unimodal)	0.00*	0.69*	1.16*	0.23*
M2B (symmetric modified unimodal)	3.10	0.15	0.00*	0.40*
M2C (modified unimodal)	5.36	0.05	3.20	0.08
M3A (homogenous symmetric bimodal)	11.32	0.00	4.36	0.05
M3B (symmetric bimodal)	7.22	0.02	3.75	0.06
M4A (homogenous axial bimodal)	10.34	0.00	2.92	0.09
M4B (axial bimodal)	15.26	0.00	7.68	0.01
M5A (homogenous bimodal)	5.25	0.05	6.87	0.01
M5B (bimodal)	9.80	0.00	14.59	0.00

w = AICc model weights

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Table S2: Summary of the Generalized Additive Model assessing the effect of magnetic conditions and the day of year on the sine of birds individual directions from the combined data sets of [1] and the current study.

Individual directions:

Parametric coefficients	Est. (SE)	z-value	p-value	Deviance explained	n
Intercept	-0.71 (0.15)	-4.83	<0.001	22.1 %	178
Magnetic conditions (NMF)	1.20 (0.22)	5.52	<0.001		
Smoothing term	EDF	χ^2	p-value		
Day of year	1.00	1.08	0.30		
Random effect	EDF	χ^2	p-value		
Year	2	0.00	0.63		
Bird ID	52	0.00	0.62		

Table S3: Mean directions for each individual bird, both under NMF and CMF conditions.

Bird ID	NMF condition		CMF condition	
	Mean direction [°]	No. of indiv. directions	Mean direction [°]	No of indiv. directions
V044753	216	2	99	3
V044885	213	2	249	2
V044984	197	2	244	2
V045327	166	2	254	3
V045510	110	3	270	3
V045524	92	3	291	2
V045534	90	2	314	3
V045774	174	3	229	3
V067303	264	2	348	3
V067305	185	3	245	2
V067384	129	2	143	2
V067429	184	2	308	3
V045367	-	0	272	3
V067302	158	2	-	0
V067354	-	0	-	1
V044454	-	1	288	3
V045425	-	1	-	1
V048436	-	1	-	1
V067432	-	1	245	3
V048348	-	1	175	2
V045464	38	3	-	0

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Table S4: Birds' individual directions from the combined data sets of [1] and the current study used for the analysis of time within season (Model summary: Table S2).

BirdID	Date	Direction [°]	Condition	Year
V041304	08.09.2018	135	NMF	2018
V041311	08.09.2018	220	NMF	2018
V041558	08.09.2018	130	NMF	2018
V042035	08.09.2018	130	NMF	2018
V026965	08.09.2018	200	NMF	2018
V041675	08.09.2018	190	NMF	2018
V041669	09.09.2018	285	NMF	2018
V029372	09.09.2018	315	NMF	2018
V041654	09.09.2018	75	NMF	2018
V026232	09.09.2018	120	NMF	2018
V041936	09.09.2018	150	NMF	2018
V041860	09.09.2018	230	NMF	2018
V034619	09.09.2018	130	NMF	2018
V041875	09.09.2018	180	NMF	2018
V042217	09.09.2018	330	NMF	2018
V041758	09.09.2018	200	NMF	2018
V041882	09.09.2018	235	NMF	2018
V026965	10.09.2018	70	NMF	2018
V034221	10.09.2018	60	NMF	2018
V041311	10.09.2018	50	NMF	2018
V041558	10.09.2018	75	NMF	2018
V041598	10.09.2018	80	NMF	2018
V041302	10.09.2018	140	NMF	2018
V026965	27.09.2018	130	NMF	2018
V041675	27.09.2018	160	NMF	2018
V034643	27.09.2018	165	NMF	2018
V042045	27.09.2018	315	NMF	2018
V034732	27.09.2018	165	NMF	2018
V041598	27.09.2018	160	NMF	2018
V041349	27.09.2018	140	NMF	2018
V042170	27.09.2018	150	NMF	2018
V041331	27.09.2018	135	NMF	2018
V042223	27.09.2018	145	NMF	2018
V041820	27.09.2018	115	NMF	2018
V042035	28.09.2018	210	NMF	2018
V041311	28.09.2018	50	NMF	2018
V034221	28.09.2018	125	NMF	2018
V041331	28.09.2018	125	NMF	2018
V041900	28.09.2018	80	NMF	2018
V042216	28.09.2018	180	NMF	2018
V029372	29.09.2018	245	NMF	2018
V041671	29.09.2018	175	NMF	2018
V041654	29.09.2018	25	NMF	2018
V041706	29.09.2018	235	NMF	2018

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V041860	29.09.2018	100	NMF	2018
V042217	29.09.2018	60	NMF	2018
V041882	29.09.2018	285	NMF	2018
V041349	30.09.2018	210	NMF	2018
V034643	30.09.2018	105	NMF	2018
V034732	30.09.2018	85	NMF	2018
V041875	30.09.2018	95	NMF	2018
V041304	30.09.2018	240	NMF	2018
V041900	30.09.2018	80	NMF	2018
V042170	30.09.2018	165	NMF	2018
V034619	30.09.2018	135	NMF	2018
V034221	30.09.2018	170	CMF	2018
V041331	30.09.2018	180	CMF	2018
V042035	30.09.2018	260	CMF	2018
V041311	30.09.2018	280	CMF	2018
V034619	04.10.2018	300	CMF	2018
V034221	04.10.2018	185	CMF	2018
V041331	04.10.2018	260	CMF	2018
V041900	04.10.2018	40	CMF	2018
V041598	04.10.2018	165	CMF	2018
V041349	04.10.2018	170	CMF	2018
V042035	04.10.2018	270	CMF	2018
V042216	05.10.2018	180	NMF	2018
V041820	05.10.2018	75	NMF	2018
V041671	05.10.2018	85	NMF	2018
V041875	05.10.2018	105	CMF	2018
V041311	05.10.2018	310	CMF	2018
V034619	05.10.2018	25	CMF	2018
V041598	05.10.2018	225	CMF	2018
V034732	05.10.2018	210	CMF	2018
V041349	05.10.2018	295	CMF	2018
V026965	05.10.2018	35	CMF	2018
V041900	05.10.2018	155	CMF	2018
V041654	08.10.2018	35	CMF	2018
V041671	08.10.2018	10	CMF	2018
V041882	08.10.2018	140	CMF	2018
V041671	09.10.2018	45	CMF	2018
V041860	09.10.2018	195	CMF	2018
V041882	09.10.2018	265	CMF	2018
V034643	09.10.2018	260	CMF	2018
V041654	09.10.2018	235	CMF	2018
V041304	09.10.2018	225	CMF	2018
V042216	09.10.2018	275	CMF	2018
V042217	09.10.2018	220	CMF	2018
V041304	10.10.2018	225	CMF	2018
V041654	10.10.2018	210	CMF	2018
V041860	10.10.2018	175	CMF	2018
V041882	10.10.2018	195	CMF	2018

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V042216	10.10.2018	240	CMF	2018
V042217	10.10.2018	235	CMF	2018
V041671	10.10.2018	25	CMF	2018
V045524	20.09.2019	85	NMF	2019
V045464	20.09.2019	222	NMF	2019
V045510	20.09.2019	125	NMF	2019
V044885	20.09.2019	235	NMF	2019
V044753	20.09.2019	257	NMF	2019
V045774	20.09.2019	205	NMF	2019
V045327	20.09.2019	232	NMF	2019
V045464	21.09.2019	25	NMF	2019
V044753	21.09.2019	175	NMF	2019
V045510	21.09.2019	72	NMF	2019
V045524	21.09.2019	247	NMF	2019
V045327	21.09.2019	100	NMF	2019
V045534	21.09.2019	110	NMF	2019
V045774	21.09.2019	165	NMF	2019
V045425	21.09.2019	47	NMF	2019
V044984	21.09.2019	112	NMF	2019
V045510	22.09.2019	130	NMF	2019
V044885	22.09.2019	190	NMF	2019
V045524	22.09.2019	75	NMF	2019
V045464	22.09.2019	55	NMF	2019
V045774	22.09.2019	152	NMF	2019
V045534	22.09.2019	70	NMF	2019
V044984	22.09.2019	282	NMF	2019
V045425	29.09.2019	180	CMF	2019
V045367	29.09.2019	272	CMF	2019
V045534	29.09.2019	352	CMF	2019
V044885	29.09.2019	310	CMF	2019
V045774	29.09.2019	192	CMF	2019
V045327	29.09.2019	230	CMF	2019
V045510	29.09.2019	262	CMF	2019
V044753	29.09.2019	25	CMF	2019
V045327	30.09.2019	257	CMF	2019
V045534	30.09.2019	312	CMF	2019
V045510	30.09.2019	265	CMF	2019
V045367	30.09.2019	190	CMF	2019
V045524	30.09.2019	205	CMF	2019
V045774	30.09.2019	205	CMF	2019
V044984	30.09.2019	242	CMF	2019
V044753	30.09.2019	97	CMF	2019
V045327	01.10.2019	275	CMF	2019
V045534	01.10.2019	277	CMF	2019
V045774	01.10.2019	322	CMF	2019
V045367	01.10.2019	5	CMF	2019
V044984	01.10.2019	245	CMF	2019
V045524	01.10.2019	17	CMF	2019

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V045510	01.10.2019	285	CMF	2019
V044753	01.10.2019	182	CMF	2019
V044885	01.10.2019	187	CMF	2019
V067384	11.09.2020	187	NMF	2020
V067305	11.09.2020	130	NMF	2020
V044454	11.09.2020	85	NMF	2020
V067432	11.09.2020	43	NMF	2020
V067302	12.09.2020	190	NMF	2020
V067303	12.09.2020	300	NMF	2020
V048348	12.09.2020	273	NMF	2020
V067429	12.09.2020	158	NMF	2020
V067384	12.09.2020	70	NMF	2020
V067305	12.09.2020	235	NMF	2020
V067305	14.09.2020	188	NMF	2020
V048436	14.09.2020	10	NMF	2020
V067429	14.09.2020	210	NMF	2020
V067302	14.09.2020	125	NMF	2020
V067303	14.09.2020	228	NMF	2020
V044454	15.09.2020	313	CMF	2020
V048348	15.09.2020	105	CMF	2020
V067429	15.09.2020	300	CMF	2020
V067432	15.09.2020	200	CMF	2020
V067303	15.09.2020	0	CMF	2020
V067429	18.09.2020	335	CMF	2020
V067432	18.09.2020	245	CMF	2020
V044454	18.09.2020	310	CMF	2020
V067303	18.09.2020	40	CMF	2020
V067305	18.09.2020	215	CMF	2020
V067384	18.09.2020	70	CMF	2020
V048348	21.09.2020	245	CMF	2020
V044454	21.09.2020	235	CMF	2020
V048436	21.09.2020	30	CMF	2020
V067303	21.09.2020	270	CMF	2020
V067305	21.09.2020	275	CMF	2020
V067429	21.09.2020	290	CMF	2020
V067432	21.09.2020	290	CMF	2020
V067354	21.09.2020	140	CMF	2020
V067384	21.09.2020	215	CMF	2020

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References

1. Kishkinev D, Packmor F, Zechmeister T, Winkler H, Chernetsov N, Mouritsen H, Holland RA. 2021 Navigation by extrapolation of magnetic cues in a migratory songbird. *Curr. Biol.* **31**, 1–7. (doi:10.1016/j.cub.2021.01.051)
2. Schneider WT, Packmor F, Lindecke O, Holland RA. 2023 Sense of doubt: inaccurate and alternate locations of virtual magnetic displacements may give a distorted view of animal magnetoreception ability. *Commun. Biol.* 2023 **61** **6**, 1–8. (doi:10.1038/s42003-023-04530-w)
3. Schnute JT, Groot K. 1992 Statistical analysis of animal orientation data. *Anim. Behav.* **43**, 15–33. (doi:10.1016/S0003-3472(05)80068-5)