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Navigation by extrapolation of geomagnetic cues in a migratory songbird

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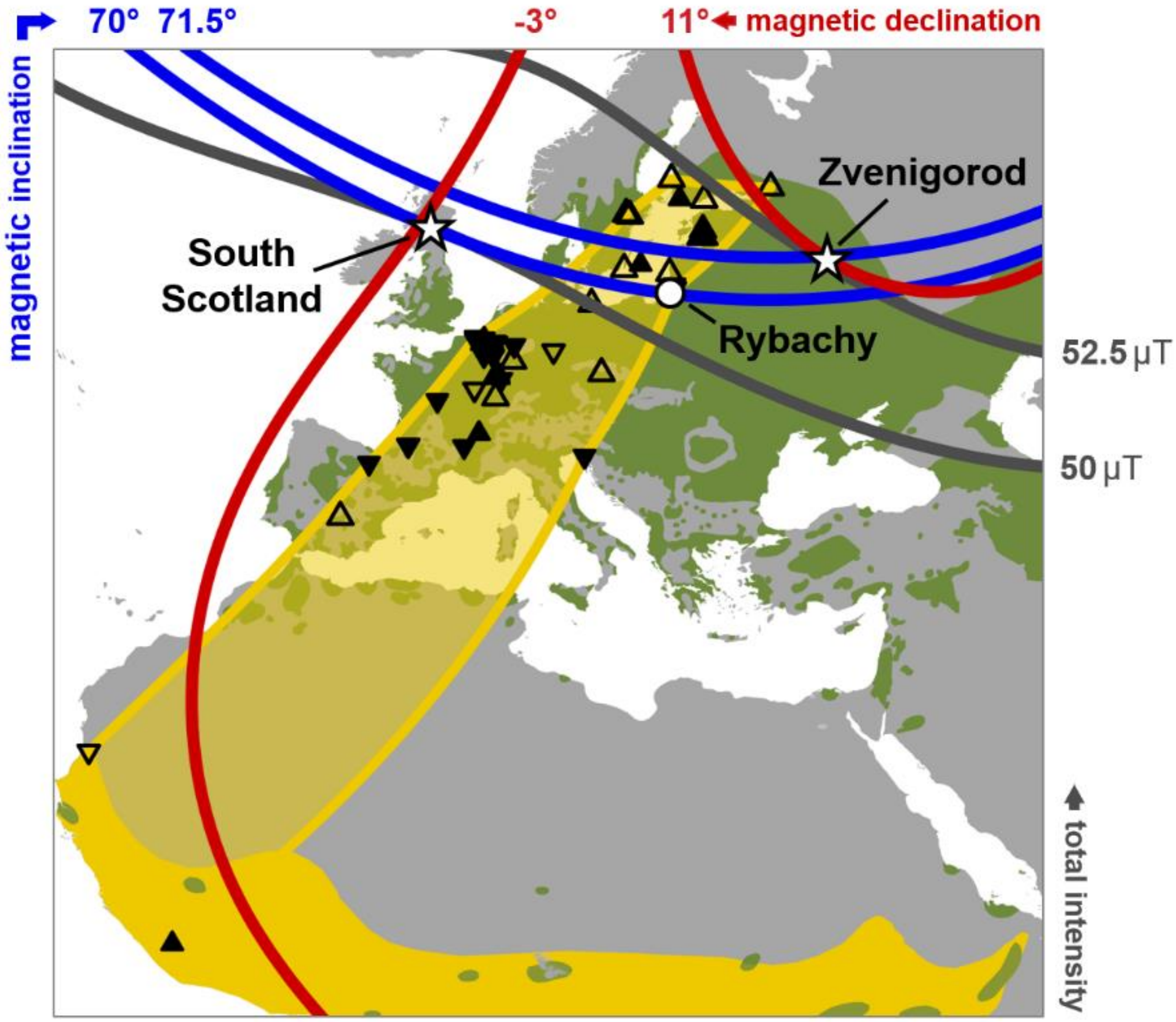

Figure S1. Illustration of the design of the previous magnetic displacement studies when birds could be exposed to familiar magnitudes of geomagnetic cues. Related to Figures 2, 3. In these studies, the reed warblers used could be familiar with the magnitudes of the geomagnetic cues presented [S1, S2, S3, S4–S6]. Solid yellow – wintering grounds; green – breeding grounds (all species range data are from [S7]). Rybachy – the capture side for the above studies. Triangles (pointing upwards – recaptured during spring migration, April-mid June, pointing downwards – recaptured during fall migration, mid-August to November, filled – same year, open – not same year, see [S6] for the data references) are the bird band recoveries from Rybachy (banded on migration, recovered elsewhere). The yellow semi-transparent polygon – the most likely familiar area of the Baltic population based on the band recoveries. Zvenigorod (field research site, Moscow region) was used for the experiments with real displacements [S1, S4, S6] as well as virtual magnetic displacements during spring migration [S2, S5]. South Scotland was used for a declination-only virtual displacement study during fall migration [S3]. Color isolines passing through the two virtual displacement sites show where all three geomagnetic cues of the same magnitudes occur within the species range [S8]. In the cases of the Zvenigorod and South Scotland displacements [S1, S2, S4–S6], the isolines cross the year-round distribution range of the Baltic population and could be familiar to at least some experimental birds, but the birds of the present study were exposed to the geomagnetic cues of completely unfamiliar magnitudes to test for the ability to use a true navigation based on geomagnetic cues (Figures 3A, B). The map represents an orthographic projection with Rybachy as the projection center.

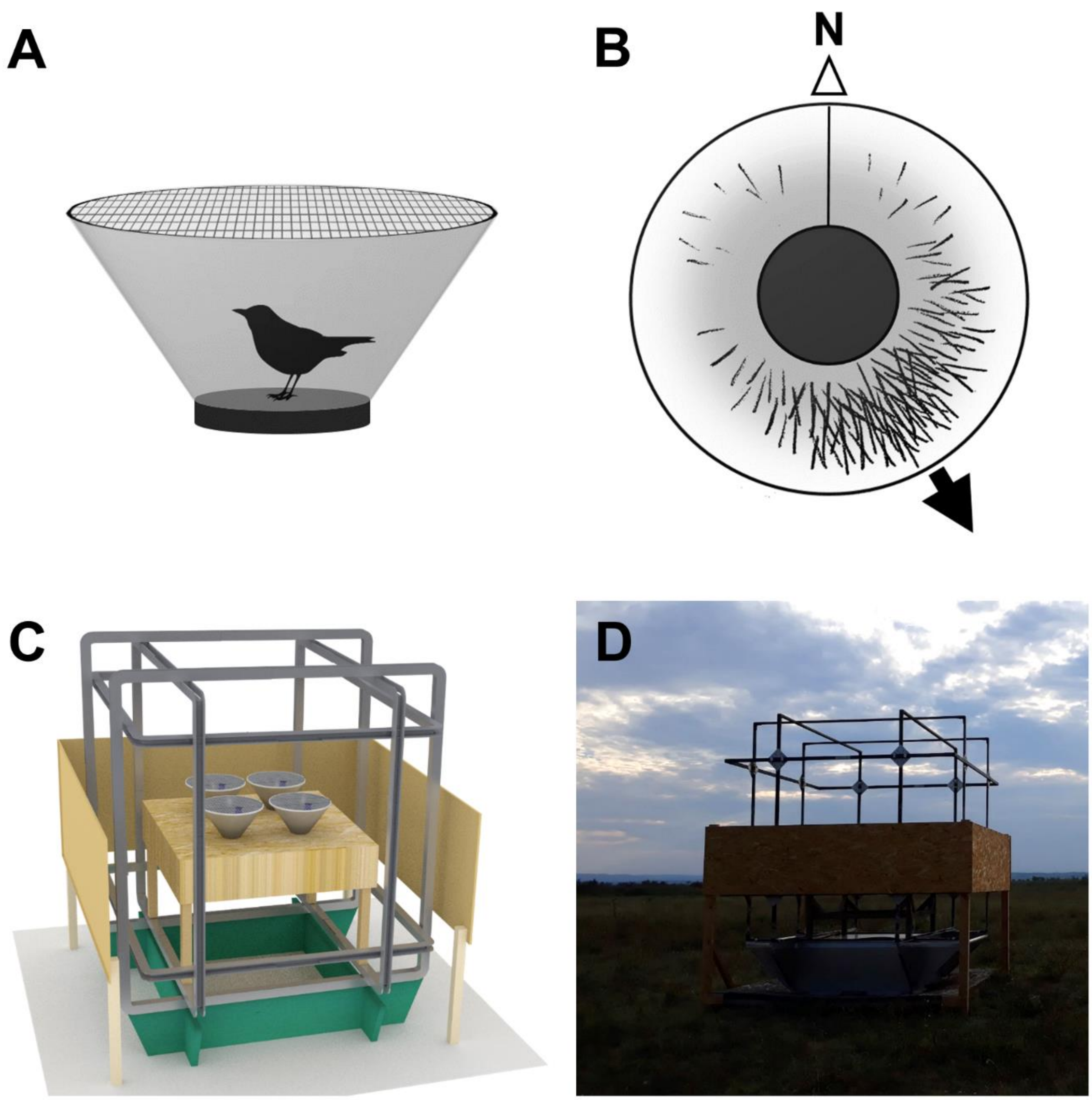

Figure S2. Illustration of a typical Emlen funnel orientation test (A, B) and magnetic coil system used in this study (C, D). Related to STAR Methods sections "Orientation tests" and "Magnetic set-up and magnetic field measurements". (A) A bird is placed on a platform in the center of a funnel-shaped cage with sloped walls (transparent here for illustration) covered with a scratch sensitive film. The top is covered with a net allowing a bird to see the sky during an orientation test. (B) Schematic illustration of a typical scratch mark pattern generated during an orientation test by a bird jumping on walls. N – the north direction. Black arrow – a mean individual direction taken into analysis if its orientedness is confirmed by the Rayleigh test of uniformity [S9]. (C) A 3D model of the system showing the arrangement of 4 Emlen funnels during magnetic displacement orientation tests (at night-time). The funnels were grouped in the center where the magnetic field was most homogeneous. The side shields (the frontal one is removed for better visualization) screened off artificial light sources at the horizon. During the daytime, a cubic housing cage was placed at the same place (not shown here). (D) A photo of the magnetic coil system in the field during the late afternoon.

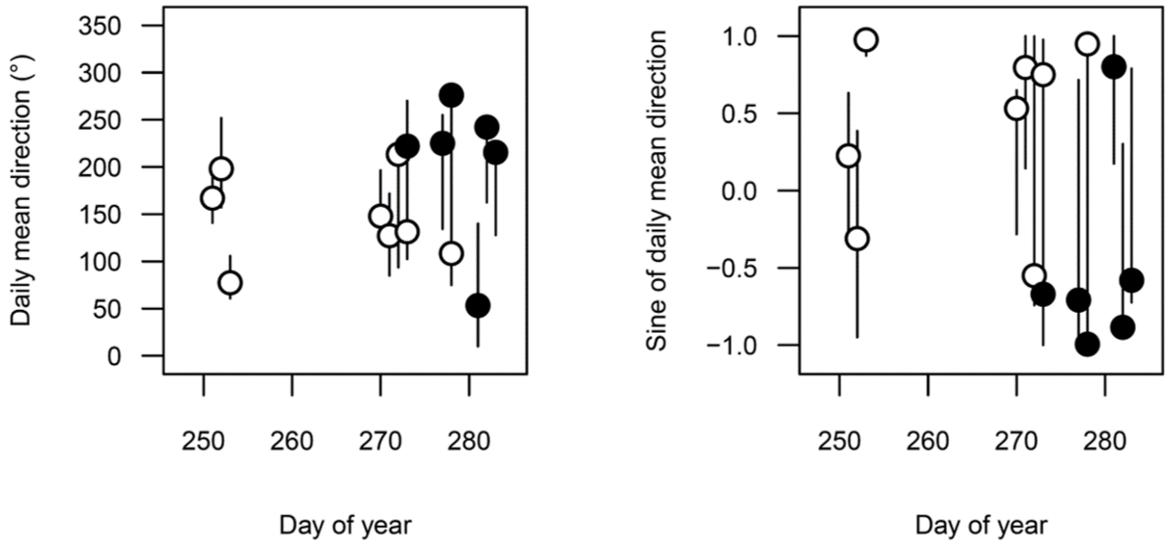

Figure S3. Daily mean directions (left) and sine of daily mean directions (right) obtained under NMF (white dots) and aCMF (black dots) conditions during Experiment 2 plotted against the day of year. Related to STAR Methods section "Testing the effect of time on birds' orientation". 95% confidence intervals (CIs) for each data point are given as vertical black lines. Note that the apparent skewness of the CIs for the data points close to the upper and lower boundaries is largely due to the sine being bound between -1 and +1.

Daily mean directions:

Parametric coefficients	Est. (SE)	z-value	*p*-value	Deviance explained	n
Intercept	-0.99 (0.51)	-1.96	0.05	46.6 %	14
Magnetic conditions (NMF)	1.85 (0.74)	2.49	0.013		

Smoothing term	EDF	χ^2	*p*-value
Day of year	1.0	0.33	0.57

Individual directions (global model):

Parametric coefficients	Est. (SE)	z-value	*p*-value	Deviance explained	n
Intercept	-0.72 (0.25)	-2.83	0.005	45.8 %	95
Magnetic conditions (NMF)	1.34 (0.33)	3.99	<0.001		

Smoothing term	EDF	χ^2	*p*-value
Day of year	1.0	0.79	0.37

Random effect	EDF	χ^2	*p*-value
Bird ID	9.0	14.58	0.023

Individual directions (most parsimonious model):

Parametric coefficients	Est. (SE)	z-value	*p*-value	Deviance explained	n
Intercept	-0.57 (0.19)	-2.94	0.003	23 %	95
Magnetic conditions (NMF)	1.12 (0.25)	4.55	<0.001		

Table S1: Summaries of the Generalized Additive Models assessing the effect of magnetic conditions and the day of year on the sine of daily mean directions and the sine individual directions. Related to STAR Methods section “Testing the effect of time on birds’ orientation”.

Model	Magnetic conditions	Day of year	bird ID (random effect)	df	AIC_c	Δ_i AIC_c	ω_i
1	+			3	-34.2	0.00	0.63
2	+	+		4	-33.1	1.14	0.36
3	+		+	16	-25.6	8.65	0.01
4	+	+	+	16	-23.3	10.94	0.00
5		+		4	-22.5	11.67	0.00
6				2	-18.3	15.87	0.00
7		+	+	15	-12.4	21.79	0.00
8			+	9	-9.9	24.25	0.00

Table S2: Comparison of candidate Generalized Additive Models to assess the effect of magnetic conditions and the day of year on sine of individual directions. Related to STAR Methods section "Testing the effect of time on birds' orientation". AICc – Akaike information criterion corrected; Δ_i AIC_c – difference between an AICc of a given model and the best model; ω_i – AIC_c model weight.

Supplemental References

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