SUPPORTING ONLINE MATERIAL

Migrating Songbirds Recalibrate their Magnetic Compass Daily from Twilight Cues

by

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Materials and Methods

Experimental birds and magnetic field manipulations

The 30 to 42 g *Catharus* Thrushes we observed were netted during stopover in wooded areas near Champaign-Urbana, Illinois, USA (c. 40.1 ^{0}N , 88.2 ^{0}W). Transmitters (0.7-1.0 g, Sparrow Systems, Fisher, Illinois, USA) were attached to their backs using the method of Raim (*S1*). Release at the net site provided data for naturally initiated migratory flights (N = 44; *S2, S3*). Experimental birds (N=18) were placed in cages on platforms centered within Helmholtz coils located in open fields providing an almost completely unobstructed view of the horizon and sky.

Two coil-platform arrangements were used. Prior to 2003, 25 cm diameter x 25 cm (H) cages were mounted 2 m above ground inside 1 m diameter coil pairs. In 2003, a four-compartment 60 cm (L) x 60 cm (W) x 30 cm (H) cage was placed 80 cm above ground inside 2 m diameter coil pairs. Both arrangements used the same principles for altering the horizontal magnetic field using a single Helmholtz coil pair (*S4*).

The plane of the coils was plumbed vertical so that there would be no change in the vertical component of the geomagnetic field. The parallel coil planes were angled with respect to magnetic north by half the desired experimental direction. With this configuration, when the current is adjusted to give the experimental direction (measured by a Suunto Professional Compass, Suunto, Helsinki, Finland; accurate to <0.5°), the natural horizontal field is cancelled and a resultant horizontal field of equal intensity is produced in the experimental direction (e.g. coils planes at 045° M with the proper current will produce an 090° M (East) horizontal field). Precision current regulated power supplies and regular checks and fine adjustments further assured that the desired field was maintained. Since the space covered by the cages, and thereby the possible positions of the birds, in both setups, remained within the central 60% of the radius of the coils, the heterogeneities of all our artificial fields were <1% of the applied field strength, that is <200 nT (*S5*). Thus, the variations in our artificial magnetic fields were no greater than the natural daily variations of the Earth's magnetic field, which are in the order of 200-500 nT.

If, for unknown reasons, the birds would take note of any small irregularities in the experimental magnetic fields, such variations (being inherently symmetric around the center of the coil system) would be in opposite directions in different parts and/or compartments of the cages. Thus, any possible influences on a hypothetical magnetic map would have been in opposite directions for different individual birds and could therefore not have led to the systematic orientation behavior of the birds (all going approximately westward). In addition, there exists no convincing evidence from birds showing that young or even adult experienced migrants can determine their east-west position from any global cue (*S6, S7*).

Release Procedure

The eight releases prior to 2003 were made from a blind, using a string and pulley arrangement to lift the cage slowly off the platform, thereby freeing the bird. Although gently raised, cage movement appeared to initiate escape behavior in the May 16, 18, and 20, 1978 and the May 30, 1984 birds (Tables *S1, S2*). The other four pre-2003 birds remained calm and flew some minutes after the cage was raised. The ten birds released in 2003 were physically tossed vertically into the air from inside the coil system (*S4*). Thus, in both cases, we can be sure that all birds (Tables *S1, S2*) embarked on their experimental migratory flights directly from within the coil system and thus from within the changed magnetic field. All releases took place after most stars were visible and after all traces of polarized overhead skylight were absent. We tested the latter by viewing the overhead sky through a polaroid filter. When the sun was 8° or more below the horizon, no intensity changes could be detected while rotating the filter. To be certain that all solar cues were absent, all experimental birds were released after the sun was 11° or more below the horizon. At this time, the natural horizon skylight is uniform in all directions, providing no directional cue. However, horizon skyglow from man-made light overwhelmed natural skylight in some directions. Treatment and releases prior to 2003 were conducted 3 km south of Champaign-Urbana, where scattered light from the city filled the sky from WNW to NE, quite intense to at least 30° above the horizon. Similarly, almost all natural flights (Fig. 1D, 1E column 1) began from near the city, about half from near the experimental release site and the other half from 4 km NE of the city, with city glow centered toward SE. All releases during 2003 were from open farmland 10 km SSE of the cities and 3 km WSW of the airport, where man-made skyglow was less intense but still substantial from NNE to ENE. Due to the consistency of control flights independent of release site, and because both experimental and controls were released from the same locations, we can safely assume that man-made light had no measureable effect on naturally migrating *Catharus* thrush orientation during and after departure (*S2*), and also no noticeable effect on the natural or experimental flights we report here.

<u>Radio-tracking procedures and how to measure a bird's heading in mid-air</u>

When the birds took off, we radio tracked them during their nocturnal migrations using cars with turnable roof-mounted direction-finding antennas. A detailed description of special tactics and equipment for obtaining the track vector and altitude of migrating birds, and three methods of determining their true headings in mid-air is given in Cochran & Kjos (*S2*), from which we very briefly summarize methods used to measure headings:

The vector method requires measuring the track vector and the wind vector at the bird's altitude, which must also be measured. The heading is the track vector minus the wind vector. The vector method can be accurate to 2 or 3 degrees if wind variation with height is small and if the winds are light, but with the typical wind speeds similar to bird air speeds and high sheer, errors can be 10° or even 20°. The head-null and cross-polarization methods are more reliable and become possible because the affixed radio transmitter's antenna is parallel with the bird's body and therefore also with the bird's heading, and because the transmitter's antenna has a null (transmits no energy) along its axis. For example, an observer driving rapidly across the projected path ahead of a bird can monitor the decrease and increase of signal as he thus passes through the null. The bearings taken during the null passage will average as the reciprocal of the bird's heading to a typical accuracy of about 5°. The cross-polarization method requires the observer to maneuver approximately underneath the bird, as determined by polar direction finding. Then, with the receiver antenna pointed up at the bird, it is rotated for a null, which occurs when the plane of its elements is at right angles to the horizontal direction of the bird's transmitter antenna. At the null, the heading is plus or minus 90° from the horizontal plane of the receiving antenna elements. The null is quite sharp and accuracy is typically 2° or 3°.

All three methods were variously used in measuring the headings reported in this paper. Often two or even all three methods were used on a single flight. For all the flights reported in Table S1 and S2, the vast majority of heading measurements were based on the more reliable cross-polarization and head/tail null methods, whereas none were based exclusively on the vector method. We made as many heading measurements during a flight as the situation permitted. Three to five determinations of heading were typical and the error of their mean for one night's flight was usually less than 10°.

<u>Headings versus ground tracks</u>

The distinction between a bird's heading and ground track is important in these experiments because individual *Catharus* thrushes maintain a consistent preferred heading during spring migratory flight over Central North America (*S1*), whereas their ground track directions often vary markedly from flight to flight due to lateral wind drift (*S2*). These flight-to-flight variations of ground track directions make them unsuitable for orientation experiments on free-flying *Catharus* thrushes. However, lateral wind drift over long migratory journeys tends to cancel out (*S2*), eg., the 312° preferred heading of a

Swainson's thrush (*S2*) was only 8° less than the 320° azimuth from the start to end of its monitored journey. Because *Catharus* thrushes do not compensate for wind drift but keep consistent headings (*S2*), headings are the relevant measure for *Catharus* thrush orientation. To easily visualize orientation behavior, we therefore used measured headings, airspeeds and durations of flight to calculate and map a flight's ground track as if there were no wind. For example, the long serpentine flight track in Figure *S2* is presented in Figure 2B as it would have been without wind.

References

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S3. W. W. Cochran, M. Wikelski, In: *Birds of Two Worlds*, P. Marra, R. Greenberg, Eds. (Johns Hopkins Press, Baltimore, 2004), in press.

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Tables

Table S1. Gray-cheeked thrushes

a) Individuals that were treated in an experimentally changed magnetic field and released, but which did not migrate on the first night. Instead, these birds migrated during a subsequent night (thus after exposure to natural twillight cues without experimental treatment).

Treatment date	Shift in magnetic field	Sun's angle below the horizon at time of departure	Minutes of exposure to sun *	Departure date	Heading	Predicted shift in heading
5-14-1972	70°	-22°	0	5-15-1972	000°	0°
5-20-1978	70°	-8°	61	5-22-1978	010°	0°
5-13-2003	80°	-31°	87	5-16-2003	356°	0°
5-13-2003	80°	-25°	87	5-19-2003	011°	0°
5-25-2003	90°	-25°	100	5-26-2003	337°	0°

b) Individuals that were released after being treated in an experimentally changed magnetic field and which migrated on the night of release. A negative 'minute of exposure to sun' means that the bird was put into the experimental magnetic field after sunset. A negative value in the columns "predicted shift in heading" and "measured shift in heading relative to magnetic North" indicates a counter clockwise shift.

Treatment Date	Shift in magnetic field	Sun's angle below horizon at release	Minutes of exposure to sun *	heading	Predicted shift in heading	Measured shift in heading[&]
5-16-1978	70°	-12°	-8	297°	-70°	-60°
5-18-1978	70°	-12°	65	355°	-70°	-2°
5-15-1979	70°	-11°	-13	300°	-70°	-57°
5-28-1979	70°	-13°	57	291°	-70°	-66°
5-12-2003	80°	-25°	98	235°	-80°	-122°
5-12-2003	80°	-17°	98	300°	-80°	-57°
5-19-2003	90°	-16°	125	285°	-90°	-72°
5-20-2003	90°	-15°	186	290°	-90°	-67°

* minutes in experimental magnetic field prior to sunset

[&] relative to the mean true heading of the controls (357^o, column 1 in Fig. 1D).

Table S2. Swainson's thrushes

Individuals were treated in an experimentally changed magnetic field, released and subsequently followed throughout a complete, natural nocturnal migratory flight. The same individuals then made a natural stopover and were followed during their subsequent natural migratory flight. We group the flights by individual, i.e. the first row of a continuous record is always the experimental flight, whereas subsequent row(s) represent natural flight(s) of the same individual. A dashed line (---) indicates that these data are not relevant. A negative value in the columns "predicted shift in heading" and "measured shift in heading" indicates a counter clockwise shift.

Date	Shift in magnetic field	Sun's angle below the horizon	Minutes of exposure to sun *	heading	Predicted shift in heading ^	Measured shift in heading
5-21-1978	70°	-14°[§]	68	311°	---	---
5-25-1978	natural	-9° [#]	---	029°	-73°	-78.5°
5-30-1984	88°	-14°[§]	-5	206°	---	---
06-1-1984	natural	-8° [#]	---	304°	-88°	-98°
06-3-1984	natural	-8° [#]	---	305°	+3°	+5°
06-4-1984	natural	-7° [#]	---	310°	+3°	+2°
06-5-1984	natural	-6° [#]	---	313°	+1°	+3°
5-20-2003	90°	-15°[§]	186	280°	---	---
5-21-2003	natural	-5°[#]	---	335°	-91.5°	-55°
5-20-2003	90°	-18°[§]	186	325°	---	---
5-25-2003	natural	–12°[#]	---	035°	-93°	-70°
5-21-2003	90°	-14°[§]	150	270°	---	---
5-22-2003	natural	–8°[#]	---	013°	-91.5°	-103°

[§] at time of release
[#] at time of natural departure
* minutes in experimental magnetic field prior to sunset
^ shift in magnetic field plus clockwise change in sun azimuth between date and latitude of the release site and date and latitude of the second night's flight.

Fig. S1. Plot of deviations of track directions and estimated headings, for individual thrushes, from the respective mean value of tracking direction and estimated heading. Large dots are from one Swainson's thrush followed for six consecutive nights. Reprinted from *S2*, with permission.

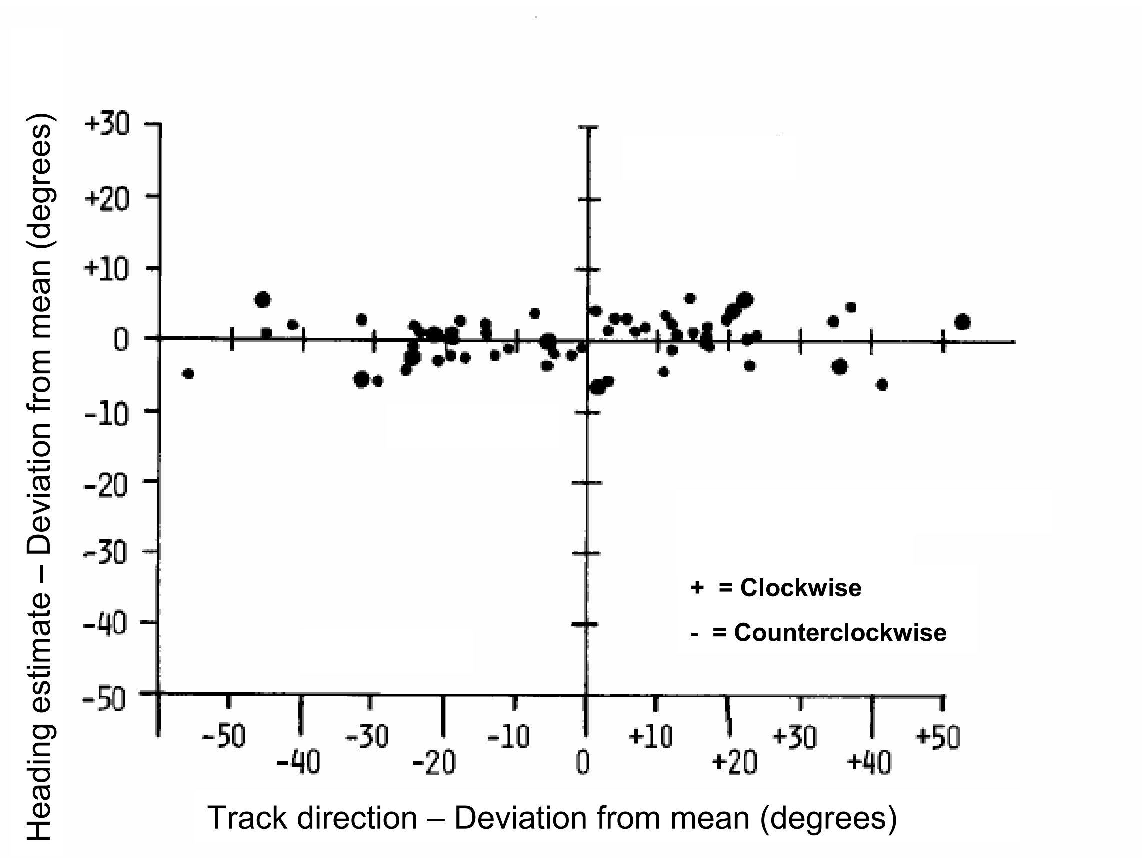

Fig. S2.

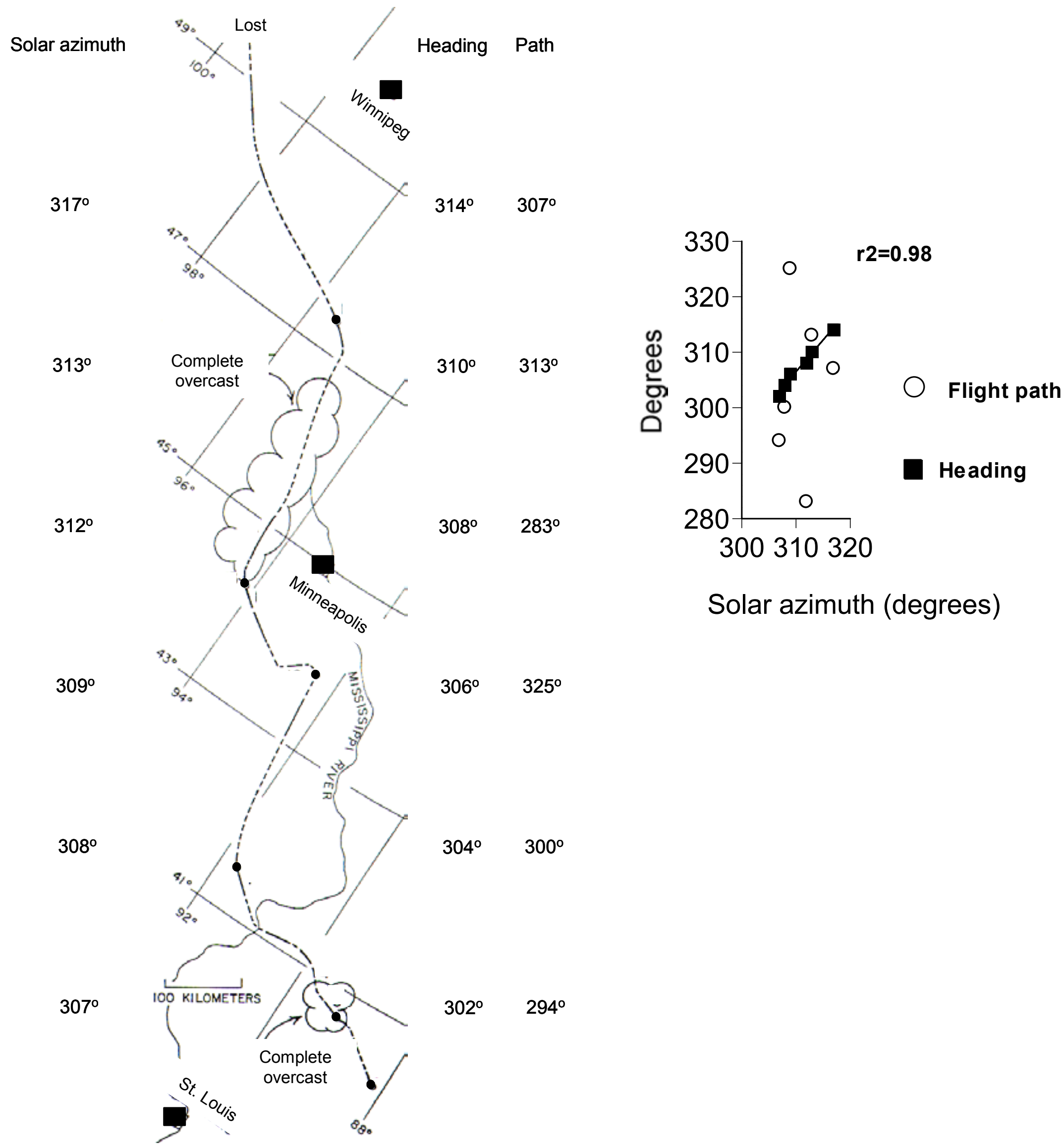

Fig. S2. Migration behavior of a single Swainson's Thrush between 13 and 20 May 1973, as followed for 1512 km. Left panel: The flight path is indicated by lines (solid line: heading information available; dotted line: no heading information). The six stopover sites are depicted by circles along the path. The bird kept a constant heading throughout its flight even when flying under completely overcast skies (nights 2 and 5) and landed when it hit cold fronts, such as during 13/14 May (first night) and 15/16 May (third night). The heading of the bird (second right column) always showed a constant relationship toward the solar azimuth (left column), whereas the realized flight path (right column) showed no relationship to the solar azimuth. Right column: We depict the relationship between solar azimuth, heading, and flight path, showing an almost complete congruence of the bird's heading and the solar azimuth (heading was always 3-4^0 less than the solar azimuth). Note that solar azimuth changes with latitude, as did the bird's heading. Modified after *S3 and S8*.