Long-distance animal migrants often navigate in ways that imply an awareness of both latitude and longitude [1–3]. Although several species are known to use magnetic cues as a surrogate for latitude [4–8], it is not known how any animal perceives longitude [1, 9–11]. Magnetic parameters appear to be unpromising as longitudinal markers because they typically vary more in a north-south rather than an east–west direction [1, 2, 9, 10]. Here we report, however, that hatching loggerhead sea turtles (Caretta caretta) from Florida, USA, when exposed to magnetic fields that exist at two locations with the same latitude but on opposite sides of the Atlantic Ocean, responded by swimming in different directions that would, in each case, help them advance along their circular migratory route. The results demonstrate for the first time that longitude can be encoded into the magnetic positioning system of a migratory animal. Because turtles also assess north-south position magnetically [4, 8, 12], the findings imply that loggerheads have a navigational system that exploits the Earth’s magnetic field as a kind of bicoordinate magnetic map from which both longitudinal and latitudinal information can be extracted.

Results and Discussion

How animals that migrate long distances determine their geographic position has been debated for more than a century [1, 2, 13]. Several animals are now known to determine geographic position along a north–south axis using information in the Earth’s magnetic field [4–8]. Some migrants, however, can also determine their geographic position east to west [14–16]. Because the Earth’s magnetic field in most geographic areas varies primarily with latitude, extracting longitudinal information from the field appears to be difficult or impossible [1, 2, 9, 10]. The mechanism or mechanisms that underlie longitude perception, however, have remained enigmatic.

Hatching loggerhead turtles (Caretta caretta) from eastern Florida, USA, embark on a transoceanic migration immediately after entering the sea for the first time. Hatchlings initially swim eastward to the North Atlantic subtropical gyre (the circular current system that flows around the Sargasso Sea) and then remain within the gyre for several years, during which they gradually migrate around the Atlantic before returning to the North American coast [12, 17].

Sea turtles use magnetic cues to approximate their position along a north–south axis [4, 8]. To determine whether loggerheads can also use magnetic information to distinguish among positions along an east–west axis, we subjected hatchlings to fields replicating those found at two locations, both of which lie along the migratory route but on opposite sides of the Atlantic Ocean. Each location had the same latitude but a different longitude (Figure 1A). Turtles were tested in a circular, water-filled orientation arena surrounded by a computerized coil system, which was used to control the magnetic field in which each turtle swam. Each hatchling was tethered to an electronic tracking unit that relayed the turtle’s swimming direction to a computer.

Turtles exposed to a field like one that exists on the west side of the Atlantic near Puerto Rico swam approximately northeast (Figure 1B). Those exposed to a field like one that exists on the east side of the Atlantic near the Cape Verde Islands swam approximately southwest (Figure 1B). Both groups were significantly oriented at p < 0.03 or less (Figure 1), and the two distributions were significantly different (Watson test, p < 0.002). Thus, the results show that loggerhead turtles can distinguish between magnetic fields that exist at different longitudes along the same latitudinal parallel.

Functional Significance of Orientation Responses

The orientation behavior elicited by the two fields is consistent with the interpretation that these responses have functional significance in the migration. Near the Cape Verde Islands, southwesterly orientation coincides with both the migratory pathway and the direction of the wide, slow-moving Canary Current (Figure 1; [18]). Swimming southwest in this area presumably helps turtles move back toward North America. It might also help them avoid the Guinea Current, the southeast-flowing branch of the Canary Current that can potentially displace turtles from the gyre and carry them along the coast of Africa.

Near Puerto Rico, the gyre currents are slowed and diverted as they meander through the numerous islands and reefs of the Antilles and Bahama Archipelagos, but in deeper water to the northeast, the Antilles Current flows unobstructed toward Florida [18, 19]. Northeasterly orientation near Puerto Rico is thus likely to help turtles stay within the gyre and embed in currents that facilitate movement back toward the North American coast, where most Florida loggerheads spend their late juvenile years [17].

These results add to the growing evidence that specific regional magnetic fields elicit orientation responses that help young loggerheads remain in the gyre and advance along the migratory route [4, 12, 20]. The hatchlings that we tested had never been in the ocean, demonstrating that turtles do not need migratory experience in order to recognize and respond to fields that exist along their oceanic pathway. Because the Earth’s field gradually changes, this orientation behavior is consistent with the hypothesis that strong selective pressure acts to maintain an approximate match between the responses of turtles and the fields that mark critical positions along the migratory pathway at any point in time [12, 17].

Organization of the Turtles’ Magnetic Map

Our results indicate that, for sea turtles, the problems of perceiving longitude and perceiving latitude share a common...
solution. In each case, magnetic information can be used to distinguish among different geographic regions.

The ability of turtles to derive both latitudinal and longitudinal information from the Earth’s field necessarily implies that turtles exploit at least two different geomagnetic features that vary in different directions across the Atlantic. Thus, the results demonstrate that turtles use a kind of bicoordinate magnetic map in position finding, an ability that has long been hypothesized to exist in animals [13, 20–23] but has never before been demonstrated.

The precise way in which the turtles’ magnetic map is organized is not yet known. Along the migratory route, the four magnetic parameters that might hypothetically provide a turtle with positional information all have isolines that trend east-west and intersect meridians on both sides of the Atlantic (Figure 2). Thus, although any one of these parameters might be used as a surrogate for latitude, none of them, by themselves, appear to be suitable for assessing longitude over the entire migratory route.

It is not necessary, however, to assume that turtles exploit one magnetic parameter as a surrogate for latitude and another as a proxy for longitude. Nearly all geographic regions along the migratory route, including the two used in our experiment, have fields defined by unique combinations of inclination and intensity, two magnetic parameters loggerheads detect (Figure 3) [4, 20]. A reasonable hypothesis is thus that turtles can distinguish among different longitudes using these unique “magnetic signatures.” Such a strategy appears feasible in that the fields that exist in locations with the same latitude but on opposite sides of the Atlantic always differ in both inclination and intensity (Figure 3), with the differences exceeding what turtles are known to perceive [4, 8, 20]. Likewise, use of “magnetic signatures” might also explain how turtles distinguish among geographic regions that differ in latitude [4, 12]. Viewed in this way, turtles might have a bicoordinate magnetic map based on inclination and intensity, one that does not encode latitude and longitude per se but that nonetheless provides turtles with both east-west and north-south positional information along the migratory pathway.

In stating that turtles have a bicoordinate magnetic map, we use the term “map” in accordance with recent usages [2, 23–27] that make no assumptions about the nature of the internal spatial representation (if any) that an animal has. It is possible, and perhaps even likely, that hatchling turtles lack any real conception of their geographic location and that they advance blindly along their migratory route by swimming in particular directions in response to specific magnetic fields. It is also possible that other cues besides magnetic fields play a role in guiding the transoceanic migration and that the navigational system of young turtles provides a foundation to which additional strategies or mechanisms needed for the navigational tasks of older turtles [8, 28] can be added during maturation. Indeed, the experience of migrating across the Atlantic and back may provide turtles with an extended opportunity to acquire information (magnetic and otherwise) that can be incorporated into later navigational processes.

Whether animals other than sea turtles extract both latitudinal and longitudinal information from the Earth’s field is not known. In principle, some animals might have bicoordinate maps in which each of the two axes depends on a different kind of sensory information; moreover, different ways of assessing longitude might have evolved in different animal groups. It is interesting to note that human navigators first solved the longitude problem in a very different way than turtles: by developing a precise and reliable clock that allowed time of day at a given location to be compared with that at a distant site [1]. For an animal to determine longitude in a similar way, it would presumably need a biological clock that did not reset to local time (or at least not immediately). A recent experiment designed to investigate whether migratory birds might assess longitude using two clocks, one of which synchronizes to local time more rapidly than the other, failed to find evidence in support of this mechanism [29]. These results are consistent with the interpretation that birds, like turtles, have evolved a way to assess longitude that is independent of time-keeping. Other possible mechanisms that animals might hypothetically use involve olfactory cues [30, 31], infrasound [32, 33], or the use of declination in geographic areas where this parameter varies longitudinally [9].
Regardless of these considerations, our results provide the first demonstration that longitude can be encoded into the magnetic positioning system of an animal. In addition, the findings demonstrate the existence of bicoordinate magnetic maps, which are capable of simultaneously providing animals with both latitudinal and longitudinal information. Similar mechanisms may help to explain some of the most impressive feats of navigation in the animal kingdom, including those of diverse long-distance migrants such as insects, fish, birds, and marine mammals [3, 34–37].

Experimental Procedures

Methods have been described in detail previously [4, 12]. Briefly, each turtle was tethered to an electronic tracking unit in the center of a water-filled orientation arena. The arena was surrounded by a computerized coil system (description below), which was used to control the magnetic field in which the turtles swam. Each turtle began its trial in a magnetic field matching that found at the natal beach (inclination = 57.7°, intensity = 46.5 μT) and was allowed to establish a course toward a dim light (an LED with peak wavelength = 550 nm) in magnetic east. After 10 min, the light was turned off and the magnetic field was simultaneously changed to either (1) a field replicating one near Puerto Rico or (2) a field replicating one near the Cape Verde Islands. Turtles were allowed to acclimate to the new field for 3 min. A computer then monitored the direction that each turtle swam toward during the next 5 min and calculated a mean heading.

Each turtle was tested a single time under one of the two field conditions. No more than two turtles from the same nest were tested in the same field. The field used to approximate magnetic conditions near Puerto Rico had an inclination of 46.4° and a total intensity of 39.0 μT (as assessed by four independent measurements with an Applied Physics Systems tri-axial fluxgate magnetometer, model 520A). The field used to approximate conditions near the Cape Verde Islands had an inclination of 26.1° and an intensity of 35.0 μT. The experimental fields were selected on the basis of estimates provided by the International Geomagnetic Reference Field Model (IGRF-10) [38] for July 2007 (the time when the experiment began) using latitude 20.0°N, longitude 65.5°W for Puerto Rico and latitude 20.0° N, longitude 30.5° W for the Cape Verde Islands. The IGRF-10 declination estimates for the target locations were −13.1° for Puerto Rico and −12.9° for the Cape Verde Islands. Experiments were conducted in Melbourne Beach, Florida, USA (declination estimate = −6.0°).

The coil system consisted of two different coils arranged orthogonally. The coil controlling the horizontal component of the magnetic field measured 2.41 m on a side, and the coil controlling the vertical component measured 2.54 m. Both were constructed in accordance with the four-coil design by Merritt et al. [39]. Turtles were restricted to the center of the coil in an area defined by a horizontal circle of radius 42 cm and a vertical area of about 5 cm; in this region, calculated [39] and measured deviations from perfect field uniformity were less than 1%.

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