Geomagnetic map used in sea-turtle navigation

These migratory animals have their own equivalent of a global positioning system.

Migratory animals capable of navigating to a specific destination, and of compensating for an artificial displacement into unfamiliar territory, are thought to have a compass for maintaining their direction of travel and a map sense that enables them to know their location relative to their destination[1]. Compasses are based on environmental cues such as the stars, the Sun, skylight polarization and magnetism[2], but little is known about the sensory mechanism responsible for the map sense[3,4]. Here we show that the green sea-turtle (*Chelonia mydas*) has a map that is at least partly based on geomagnetic cues.

Ocean waves and the Earth's magnetic field both serve as orientation cues for newly hatched turtles as they migrate to sea for the first time[5]. These young turtles migrate towards geographic targets that are no more specific than a vast oceanic region, but the juvenile and adult turtles will return to particular coastal feeding sites with pinpoint accuracy after displacement and long migrations[6,7]. This implies that these older turtles are following a map that enables them to establish their position relative to some distant target[4,8].

The Earth's magnetic field varies across the planet's surface and is therefore a potential source of positional information[8,9]. To investigate whether juvenile turtles acquire a magnetic map to direct their navigation to a specific site, we captured green sea-turtles (Fig. 1) that were several years old from their coastal feeding grounds near Melbourne Beach, Florida, during July and August. At a nearby outdoor test site, the turtles were placed in cloth harnesses, tethered to a computerized tracking system[4] inside a circular arena filled with water (from a city supply) and surrounded by a coil system[10] (4.11 m on a side) that was used to control the ambient magnetic field. The orientation of each turtle was monitored as it swam in a magnetic field equivalent to the field at one of two distant locations. Turtles could view the sky but were restricted to the centre of the coil where the field was uniform.

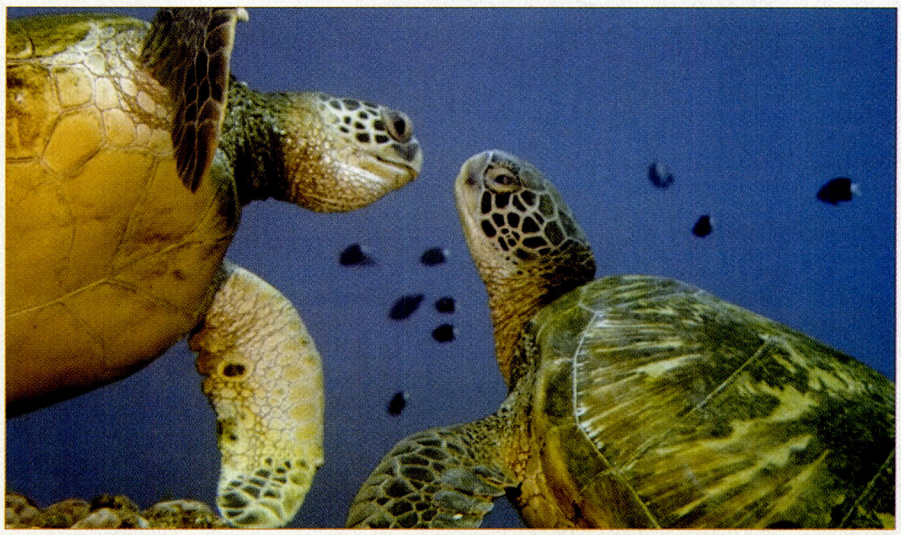

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Figure 1 Green sea-turtles, *Chelonia mydas*, are able to navigate accurately across vast distances.

Turtles exposed to a magnetic field equivalent to that existing 337 km north of the test site oriented themselves roughly southwards (Fig. 2). By contrast, those exposed to a field matching that of an area 337 km south of the test site swam approximately northwards (Fig. 2). The two distributions are significantly different ($U^2 = 0.486$, $P < 0.001$, Watson test), indicating that turtles can distinguish between the magnetic fields that characterize different geographic locations within their usual environment. Moreover, turtles responded to each field by orienting in a direction that would have led them towards the capture site had they actually been at the location where each field occurs naturally. These results indicate that juvenile turtles have a magnetic map sense that helps them navigate to specific targets.

The precise magnetic feature or features that turtles detect and exactly how the magnetic map is organized remain to be determined. Turtles may possess a map in which magnetic cues provide only one coordinate, with another environmental feature (which could be the coastline in this case) providing the second. The turtles may swim along the coastline until they encounter a magnetic parameter that marks a specific coastal location[8,10]. Alternatively, turtles might detect two magnetic elements (such as inclination and intensity) and rely on bicoordinate magnetic navigation[8,9]. Although the regional isolines of the various magnetic elements have similar patterns near Florida, no two sets of isolines are exactly parallel; bicoordinate magnetic navigation might therefore be possible if turtles are sufficiently sensitive to the two parameters.

Our findings show that, as sea-turtles mature, they acquire the ability to exploit magnetic information in a more complex way than hatchlings, using it as a component of a classic navigational map[1,3], which permits an assessment of position relative to specific geographic destinations.

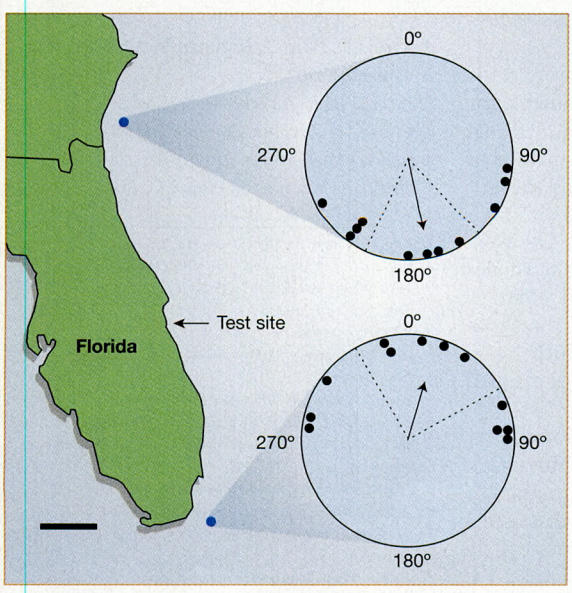

Figure 2 Orientation of juvenile green turtles (straight carapace lengths, 29–47 cm) tested in magnetic fields replicating those at the sites marked by blue dots. In the circles, each black dot represents the mean orientation angle of one turtle. The arrow in the centre of each circle indicates the mean angle of the group; arrow length is proportional to the magnitude of the mean vector **r**; circle radius corresponds to $\mathbf{r} = 1$. In a 'northern' field (inclination: 61.2°, total intensity: 49.3 μT; upper diagram), turtles were significantly oriented ($r = 0.70$, $P = 0.003$, Rayleigh test) with a mean angle of 171.7°. In a 'southern' field (inclination: 55.4°, total intensity: 45.4 μT; lower diagram), turtles were significantly oriented ($r = 0.54$, $P = 0.027$) with a mean angle of 15.8°. Dashed lines represent the 95% confidence interval for the mean angle. Data are plotted relative to magnetic north. Tests were done between 12:00 and 18:00 hours under diverse weather conditions. Map scale bar, 100 km.

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Environment

Whale-call response to masking boat noise

Background noise can interfere with the detection and discrimination of crucial signals among members of a species. Here we investigate the vocal behaviour in the presence and absence of whale-watcher boat traffic of three social groups (pods) of killer whales (*Orcinus orca*) living in the nearshore waters of Washington state. We find longer call durations in the presence of boats for all three pods, but only in recent recordings made following a period of increasing boat traffic. This result indicates that these whales adjust their behaviour to compensate for anthropogenic noise once it reaches a threshold level.

Killer whales are the largest of the dolphin species and are highly social, living in matrifocal pods whose membership is stable over decades[1]. The vocal repertoire of whales in our study region shows pod-specific dialects, and there is a single primary call for each pod that represents up to 52% of the sounds produced by that pod[2].

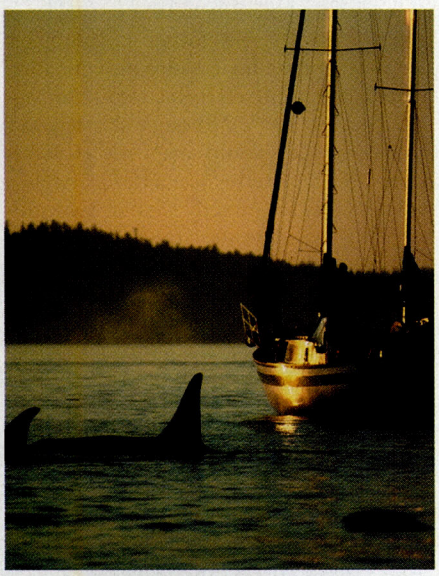

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Figure 1 Killer whales from the southern resident community in Washington state, pictured with onlookers.

We analysed the primary calls from each of the three pods that make up the collection of killer whales known as the southern resident community. Strategies that could be used by the whales to overcome interference from background noise include increasing the frequency, amplitude and duration of their signals. For example, humpback whales lengthen their song duration during playback of low-frequency active sonar[3]; and an improvement in perception threshold due to increased signal duration (in the context of the time required to integrate the signal) has been demonstrated in many species[4].

Today's southern resident population of killer whales is exposed to intense whale-watching activity (Fig. 1). This is associated with considerable boat engine noise — there is typically a fleet of 72 commercial vessels and an average of 22 boats following a pod during daylight hours. The number of boats has increased over the past decade and the population has been in decline since 1996 (Fig. 2). Southern resident killer whales may coordinate at least some aspects of cooperative foraging with their repertoire of discrete calls[2,5], and theoretical assessments[6,7] indicate that boat noise could impair communication between killer whales over a range of 1–14 km.

We compared recordings (for methods, see supplementary information) made in the presence or absence of boat noise during three time periods: 1977–81, 1989–92 and 2001–03 (some recordings provided by K. C. Balcomb). We found no significant difference in the duration of primary calls[2] in the presence or absence of boats for the first two periods, but a significant increase (about 15%) in call duration for all three pods in the presence of boats during the 2001–03 period (J pod: for *t*-test $t = 4.13$, for Mann–Whitney *U*-test $z = 4.09$, $P < 0.0001$, d.f. = 134; K pod: $t = 4.33$, $z = 3.36$, $P < 0.0008$, d.f. = 162; L pod: $t = 3.14$, $z = 2.97$, $P < 0.005$, d.f. = 192; see Fig. 2).

All comparisons of call rate were non-significant (and data were not available for an assessment of call amplitude). Functional differences between the repetition rate of calls and their duration may explain the lack of correlation for repetition rate, although we have no direct evidence for this. The average number of vessels attending the whales increased roughly fivefold from 1990 to 2000, suggesting that there is a threshold level of disturbance beyond which 'anti-masking' behaviour, such as increased signal duration, begins.

Structural changes have been found previously in the songs of birds and humpback whales in environments altered by humans[3,8], but our findings show a response that seems to be initiated to counteract anthropogenic noise only once it reaches a critical level.

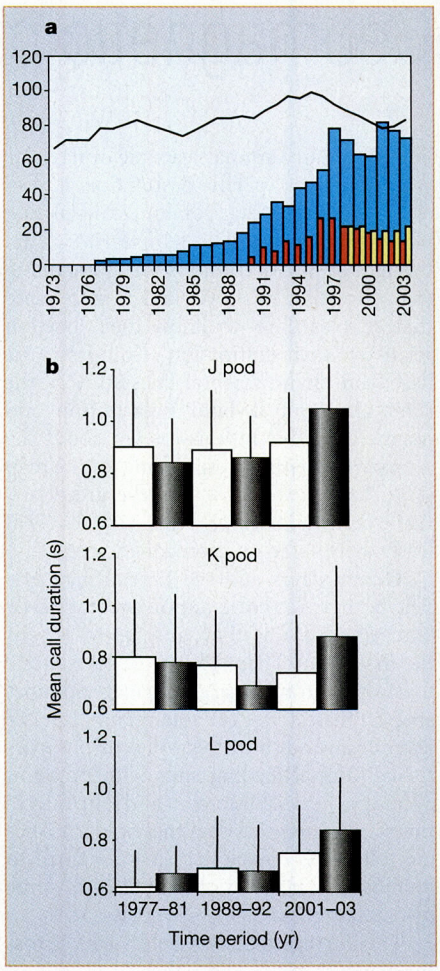

Figure 2 Effect of whale-watcher boat noise on calls made by killer whales. **a,** Boat and whale numbers are shown for the period between 1973 and 2003. Solid line, size of whale population; blue bars, number of active commercial boats per year; red bars, average number of boats following whales, measured from shore base (Lime Kiln Lighthouse, San Juan Island, Washington state; data for 1990–2003 only); yellow bars, average number of vessels following whales, measured using boat-based observations (1998–2003 only). **b,** Call duration in seconds for the three pods (termed J, K and L) recorded in the presence (black) and absence (white) of boats for each time period (error bars show 1 s.d.).

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