How Sea Turtles Navigate

As soon as they hatch, sea turtles swim across hundreds of miles of featureless ocean; as adults, they navigate home to nest. Research has begun to identify the biological compasses and maps that guide them

by Kenneth J. Lohmann

After sunset on summer nights, when the heat of Florida's Atlantic coast beaches finally dissipates, newly hatched loggerhead sea turtles lying dormant in underground nests begin to stir. In sporadic bursts of activity, the hatchlings squirm and thrash, dislodging sand from the roof of the nest chamber and trampling it onto the floor. The floor slowly rises, and the chamber ascends like a miniature elevator until at last the baby turtles break through the surface of the sand.

The hatchlings, each no bigger than a child's hand, immediately confront a dangerous world. Pursued by ghost crabs, foxes and raccoons, the turtles scramble across the dark beach to the ocean and plunge into the surf. They quickly establish a course away from land and toward the open sea. Buffeted by waves and currents, attacked by predatory fish and seabirds, the turtles maintain their seaward bearings day and night as they swim toward the relative safety of the Gulf Stream. There, some 30 to 50 miles offshore, they may find shelter in floating sargassum seaweed, as well as food in the form of small invertebrates. Years later those that survive to adulthood (perhaps one out of every 1,000) navigate back, often returning to the same, specific beach each nesting season.

How do the turtles navigate through a vast ocean that contains no obvious landmarks? Only recently have investigators, through observation in the laboratory and at sea, begun to identify the environmental cues the turtles use to maintain their bearings.

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A turtle's ability to orient itself seems quite sophisticated and reliable. For some sea turtle populations, the initial offshore migration appears to be just the first step of a transoceanic journey lasting several years. After leaving Florida as hatchlings, for example, loggerhead turtles (*Caretta caretta*) are not seen again in U.S. waters until their shells have grown to more than half a meter in length. No one has yet tracked the tiny turtles through the miles of open sea into which they vanish. Circumstantial evidence, however, suggests that the Florida loggerheads eventually cross the Atlantic and navigate back. There is an orderly progression of juvenile turtle sizes along the North Atlantic gyre, the clockwise oceanic current system that encircles the Sargasso Sea (the relatively still portion of the central north Atlantic). Thus, after entering the Gulf Stream, young turtles may swim eastward across the Atlantic, then south around the Sargasso Sea and westward back to the Florida coast.

Adult turtles navigate even more skillfully than young turtles do. For instance, green turtles (*Chelonia mydas*) that frequent feeding grounds off the coast of Brazil regularly migrate eastward across more than 1,400 miles of open ocean to reach their nesting grounds at Ascension Island. This remote speck of land is so isolated and difficult to find that during World War II air force pilots required to stop there for refueling summed up the situation with a rhyme: "If you miss Ascension, your wife gets a pension."

Tagging studies at Ascension Island have shown that females remain remarkably faithful to their nesting site; no turtle seen at Ascension has ever been found nesting elsewhere. Instead the turtles swim to the Brazilian feeding grounds from Ascension after nesting, then repeat the long migration to the island and back once every two to four years. Recent studies by John C. Avise and his colleagues at the University of Georgia have shown that the mitochondrial DNA of Ascension Isla[nd] green turtles is distinct from that [of] other green turtle populations. This g[e]netic study is additional evidence th[at] these turtles consistently navigate ba[ck] to their natal beaches to nest and d[o] not mix with other populations.

Green turtles that nest at Tortuguer[o,] Costa Rica, demonstrate a similar [fi]delity to their home beaches. Turtl[es] tagged there have been recaptured [at] feeding grounds dispersed througho[ut] the Caribbean and as far north as Flo[ri]da, but no turtle in the more than [...] years of tagging at Tortuguero has ev[er] been found nesting elsewhere.

A logical first step toward uncov[er]ing the mechanisms used in navigati[on] by sea turtles is to determine the orie[n]tation cues hatchlings use. Their o[ff]shore migration resembles the lon[g-] distance migrations of adult turtles [in] that both require oriented moveme[nt] through seemingly featureless ocea[n.] Hatchlings and adults probably ha[ve] similar sensory abilities. But hatchlin[gs] are small and easily studied in the lab[o]ratory, whereas adults may exceed [a] meter in length and 180 kilogra[ms] (about 400 pounds) in weight. Worki[ng] with my colleagues Michael Salm[on] and Jeanette Wyneken of Florida [At]lantic University, I began to study h[ow] hatchling sea turtles on the east coa[st] of Florida maintain their seaward o[ri]entation while swimming offshore.

We knew right from the very b[e]ginning that many orientati[on] cues might be available to t[he] hatchlings. Other migratory anim[als,] for example, rely on multiple cues su[ch] as the position of the sun or stars, [po]larized light, odors, wind direction, [in]frasound (low-frequency sound, su[...]

GREEN TURTLE swims in the waters [of] Hawaii. Such turtles may use the ear[th's] magnetic field and the direction of oce[an] waves to navigate between their fee[ding] grounds and nesting sites.

as that from waves breaking on a beach) and the earth's magnetic field.

Indeed, the geomagnetic field is one of the most pervasive and consistent sources of directional information available to animals. Unlike most other potential cues, it is essentially constant throughout the day and night and remains largely unaffected by weather changes. Although physicists and biologists alike once ridiculed the idea that certain animals can sense the geomagnetic field, research during the past 15 years has shown that a surprising number of diverse animals are able to do so. Among these are various migratory birds and fish (such as salmon, tuna and shark), as well as certain amphibians, insects and mollusks. We reasoned that a search for this ability in hatchlings would be a good beginning.

We began by testing the orientation of Florida loggerhead hatchlings in a water-filled arena made from a fiberglass satellite dish about one meter in diameter. In each experiment, a hatchling turtle was placed in a nylon-Lycra harness and tethered to a lever arm. Because the lever arm was free to rotate in the horizontal plane and could easily be pulled by a swimming turtle, the arm reliably tracked the turtle's position. Hatchlings could swim freely within a radius defined by the tether. In an adjacent room, a chart recorder or a computer wired to the lever arm provided a continuous record of the turtle's direction.

At the start of each experiment, we provided a dim light in the magnetic east so that hatchlings would begin swimming in the appropriate seaward direction. (In their natural habitat, turtles emerging from their nests at night encounter a similar light cue in the direction of the ocean, which reflects more starlight and moonlight than land does.) After an hour or more, we turned the light off, plunging the hatchlings into complete darkness.

Immediately after the light went out, the hatchlings circled the satellite dish as if confused. After several minutes, the turtles usually established a consis-

tent course toward a specific direction, which they held for several minutes before circling again. The hatchlings continued this curious behavior for hours in complete darkness, alternating between brief periods of oriented swimming and periods of circling.

When we calculated the average direction that different hatchlings swam toward in darkness, it became clear that the turtles were not swimming randomly. Instead most hatchlings swam toward points between magnetic north and east, adopting bearings that would lead them away from the east coast of Florida and toward the Gulf Stream.

We hypothesized that this directional preference in complete darkness was based on magnetic orientation. To verify the hypothesis, we needed to show that changing the direction of the magnetic field around the turtles changed the course in which they swam. We therefore constructed a system of five square coils of copper wire (known as a Rubens cube coil) and placed it around the orientation arena. When activated, the coil generated a weak, relatively uniform magnetic field throughout the area it enclosed. The coil was adjusted to generate a field twice as strong as the horizontal component of the earth's field but opposite in direction. Thus, we could reverse at will the magnetic field experienced by the turtles.

Now we could test the orientation of hatchlings under two different magnetic field conditions. Each hatchling began the new experiment swimming in the earth's magnetic field while a light shone in the magnetic east. We then turned the light off and let each hatchling swim in complete darkness under one of two magnetic fields. Half of the turtles swam in the unaltered magnetic field of the earth (with the coil turned off). For the other half, we turned the coil on, so that the direction of the magnetic field was reversed.

As in the preliminary experiments, hatchlings tested in darkness in the geomagnetic field usually adopted bearings between magnetic north and east. Turtles tested in the reversed magnetic field, however, swam in approximately the opposite direction. These data demonstrated that hatchling loggerhead turtles can sense the magnetic field of the earth and orient themselves to it.

Armed with this new information, we thought we had solved the puzzle of how hatchlings maintain their bearings during the offshore migration. We reasoned that soon after entering the ocean, hatchlings must begin to rely on a magnetic compass. The compass would continue to function after hatchlings passed beyond sight of shore, enabling them to maintain their steady seaward path to the Gulf Stream.

But this hypothesis, formulated the laboratory, needed to be tested more natural settings. To study the o entation of hatchlings in the ocean, devised a floating orientation cage [*bottom illustration on page 104*]. tethering a hatchling to a floating bu in the cage, we could observe the dire tion in which the turtles swam.

During our next few field expe ments, the turtles paddled vigorou toward the open ocean, even when te ed nearly 15 miles from shore whe land could not possibly be seen. Th swam seaward, we initially presume by detecting the geomagnetic field.

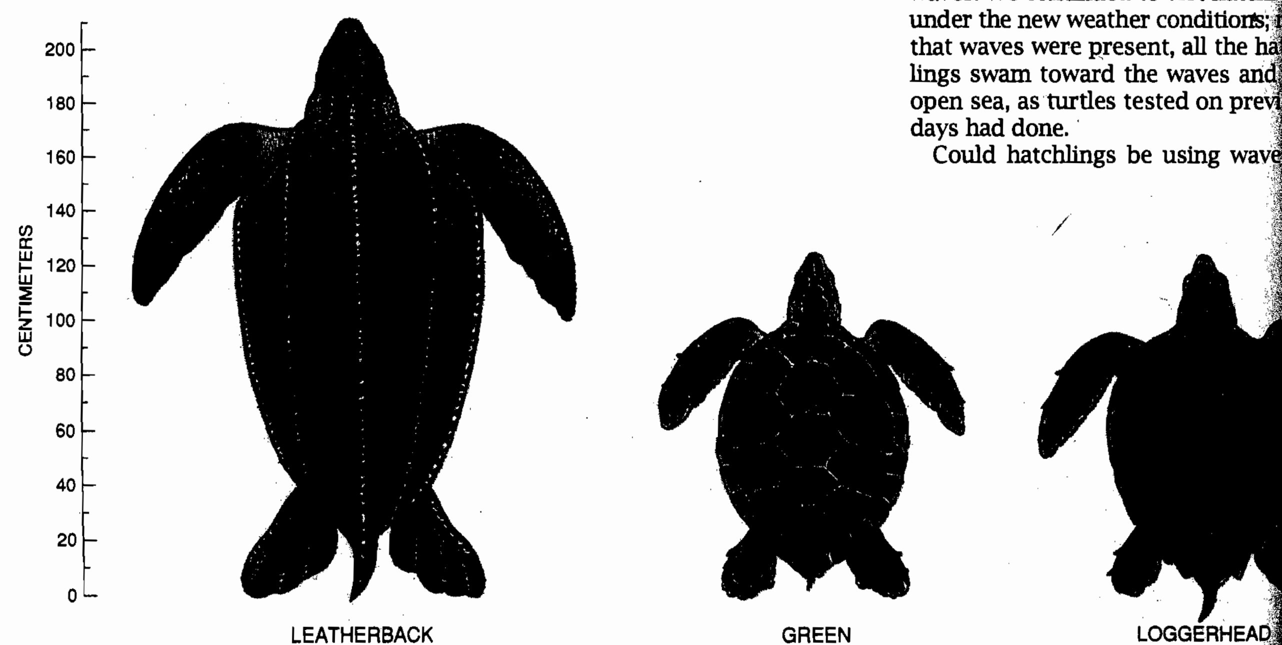
But a few days later, on a hot, usually calm morning with most no breeze, the behavior the hatchlings took a surprising tw We had run our research boat just a f miles offshore and tethered hatchlin to the floating buoy as before. For first time, the turtles behaved as if co fused: some swam aimlessly in circl others established courses in seemin random directions, including back ward shore. We were confused as wel the hatchlings were using the magne field of the earth to guide them tow the open ocean, why didn't they beh like the turtles we had tested before

As we sat in the boat pondering t unexpected change in behavior, a bre slowly picked up, generating sm waves on the glassy ocean surface. most as soon as we noticed these waves moving westward toward sh the hatchling turtle under observat turned abruptly and began to swim toward the open ocean, adopting course straight into the approach waves. We continued to test hatchli under the new weather conditions; that waves were present, all the hat lings swam toward the waves and open sea, as turtles tested on previ days had done.

Could hatchlings be using wave

Sea Turtles of the World

Most species are found throughout the world's tropical and subtropical waters; leatherbacks are occasionally sighted as far north as Scandinavia. Some species, however, do not range far. Kemp's ridley turtles remain in Atlantic waters, and flatbacks inhabit the South Pacific, near Australia. Some taxonomists consider the green turtle in the eastern Pacific Ocean to be a distinct species.



MIGRATORY PATHS of sea turtles (*red*) provide evidence of extraordinary navigational abilities. After leaving their Florida nesting beach, loggerhead hatchlings may swim around the Sargasso Sea a number of times before returning to their home area to nest several years later. They are about half-grown at that time. Arrows indicate the flow of ocean current.

rection as an orientation cue? To find out, we took hatchlings of three species of sea turtles—loggerheads, green turtles and leatherbacks (*Dermochelys coriacea*)—to the laboratory and tethered them inside a wave tank. The tank was partly constructed of steel beams, which distorted the local magnetic field. Under these conditions, hatchlings did not show directional preferences when waves were absent. When waves were generated, however, the turtles swam into them, demonstrating that they could maintain a consistent course by using waves as an orientation cue.

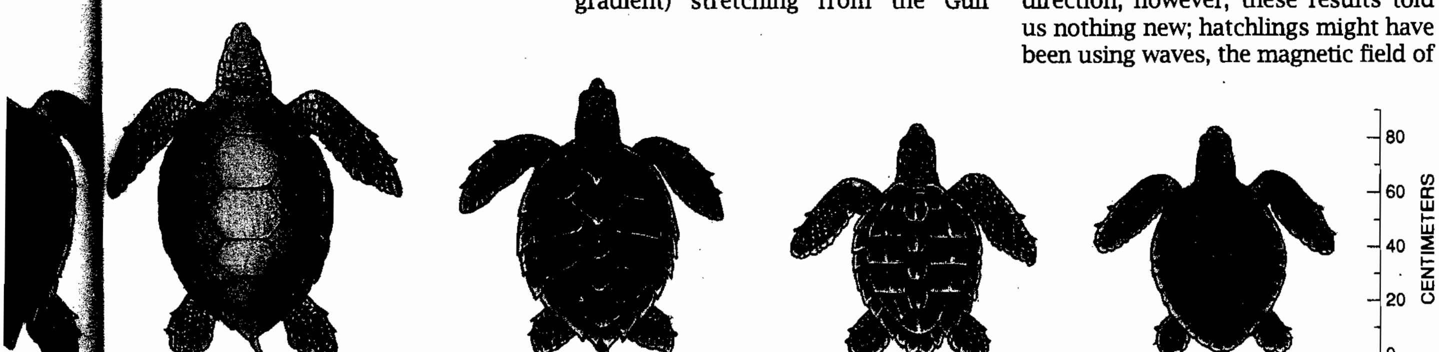
So we knew, at least in the laboratory, that hatchling turtles could orient themselves by detecting waves as well as by detecting the earth's magnetic field. But under natural conditions, do sea turtles use waves, the geomagnetic field or some completely different cue to guide their offshore migration? When would they prefer one cue over another or use a combination of cues? If the geomagnetic field is used, then why did turtles tested on the calm day in the ocean fail to swim seaward using their magnetic compass sense?

The questions were not easy to answer. On the few occasions when waves moved in directions other than toward shore, hatchlings in the floating cage usually swam toward the waves regardless of the direction from which the waves came. Suggestive as the results were, a problem persisted: the restraint imposed on the turtles by the tethering system might conceivably have prevented hatchlings from using other, as yet unidentified cues.

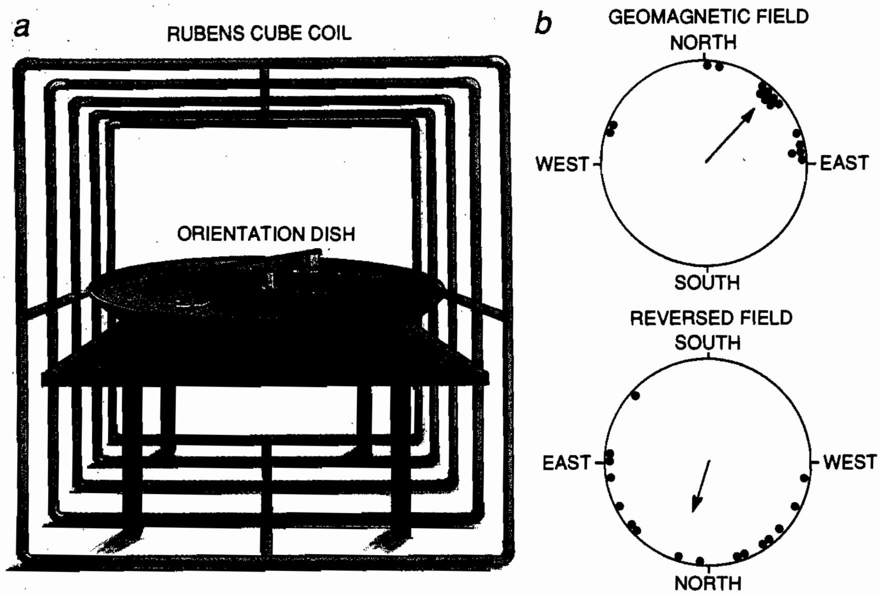
For example, nearly two decades ago laboratory studies by Marion Manton and his colleagues at Columbia University showed that juvenile green turtles can detect chemicals dissolved in water. If hatchlings normally migrated offshore by detecting a chemical gradient (or even a temperature or salinity gradient) stretching from the Gulf Stream to the Florida coast, then tethering turtles in one location would prevent them from comparing the water in different locations, thus precluding detection of a gradient at all. Tethered hatchlings might therefore swim toward waves because other cues they might prefer to use were not available.

To examine these possibilities, we studied the orientation of unrestrained hatchlings released offshore. In contrast to the floating-cage experiments, we made no attempt to monitor the orientation of turtles for prolonged periods. We simply dropped each hatchling into the ocean and recorded the direction it swam as it paddled away. The hatchlings presumably had access to all cues available to them during the normal offshore migration.

In initial tests conducted under typical weather conditions, unrestrained hatchlings oriented themselves into waves as they swam away. Because waves approached from the seaward direction, however, these results told us nothing new; hatchlings might have been using waves, the magnetic field of



FLATBACK (*Chelonia depressa*) HAWKSBILL (*Eretmochelys imbricata*) KEMP'S RIDLEY (*Lepidochelys kempi*) OLIVE RIDLEY (*Lepidochelys olivacea*)



MAGNETIC-ORIENTATION APPARATUS demonstrates that Florida loggerhead hatchlings can detect the earth's magnetic field (*a*). Each turtle is tethered to the lever arm, which electronically tracks the turtle's swimming direction. The Rubens cube coil is used to reverse the direction of the magnetic field. Findings (*b*) show that most individuals (*dots*) swim in directions between magnetic north and east under both conditions. The arrow represents the average direction of the group.

the earth, a chemical gradient or some other cue to establish their offshore bearings. To determine whether waves were of primary importance, we needed a day in which waves moved in an unusual direction—that is, in some direction other than straight toward shore. Then the hatchlings would have to decide whether to swim toward the waves or to move seaward using another cue.

Our chance to resolve the issue finally arrived in the autumn of 1989, when Hurricane Hugo swept north along the coast of Florida. On its way to landfall, the storm spawned peculiar weather throughout much of the Southeast. One morning soon after the hurricane passed, we awoke to find a strong wind blowing out of the west, away from land and toward the open sea. Recognizing a unique research opportunity, we loaded hatchlings into a Styrofoam cooler and hastily ran our research boat out to sea.

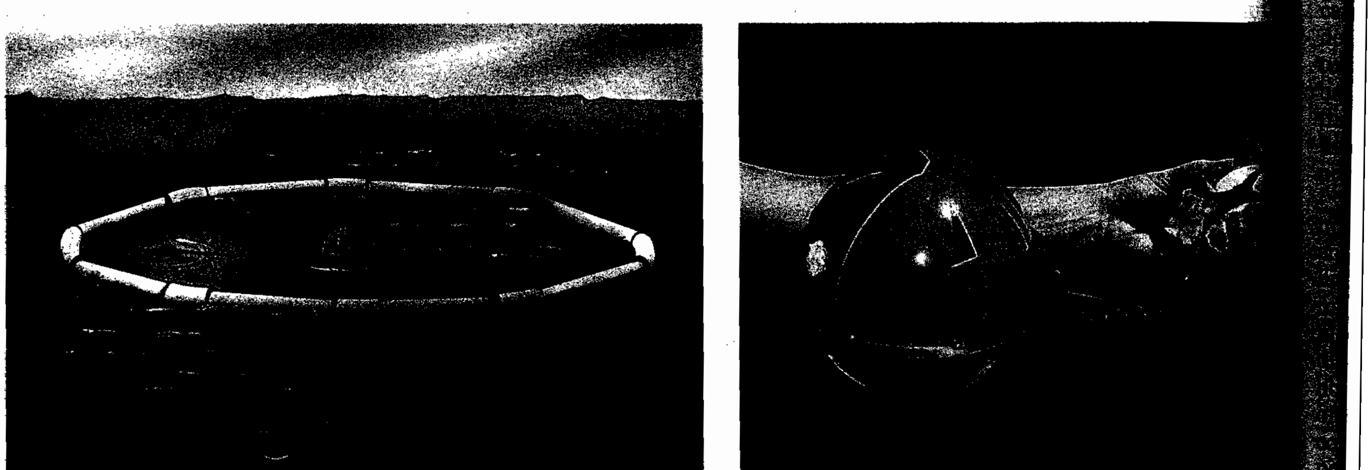
Five miles offshore we found what we were looking for: an area in which waves were clearly moving eastward toward the open ocean and away from land. Under these rare and short-lived conditions, we released hatchlings one by one and observed the direction in which they swam. The results were rem ably clear: most of the turtles swa ward the waves, even though this entation led them back toward sho

We were fortunate enough to be to repeat this experiment several t during the next few weeks, as more usual weather temporarily gener waves in other atypical direction each case, the hatchlings swam to approaching waves, regardless o magnetic direction from which waves came. These results indic that the hatchlings were indeed u the direction of wave propagatio guide their migration.

Why might hatchlings use o waves as an orientation cue? Wave tering the shallow waters near the b refract until they move toward shoreline. Thus, wave movement is mally a reliable indicator of offshor rection, and swimming into waves ally results in movement toward open sea.

Although wave direction is appar ly the primary cue used by hatchl during the early phases of the offs migration, other cues may simult ously or subsequently be used. The netic sense, for example, might e tually supplant wave orientation w hatchlings enter deeper water, w waves are a less reliable indicator o shore direction. Partial reliance on o mechanisms, including chemosens visual or other as yet unidentified c also cannot be ruled out.

As remarkable as the orienta abilities of hatchlings seem, adult turtles are capable of even more c plex and sophisticated navigati feats. Unfortunately, it is difficul track these creatures over the imm stretches of water through which migrate, and their size and we

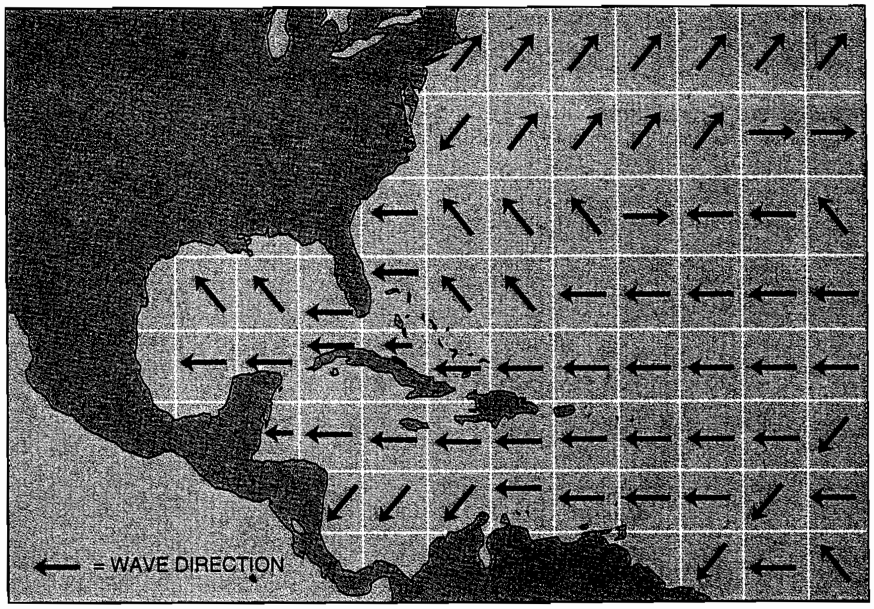


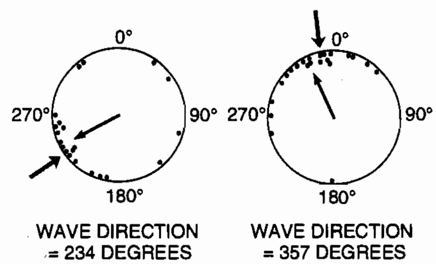
FLOATING ORIENTATION ARENA studies the cues hatchlings use in the ocean. A harnessed turtle (*photograph*) is tethered to a partially submerged buoy. The net around the buoy protects the hatchlings from predatory fish. Beca the buoy rotates easily, a turtle can swim toward any di tion. Most hatchlings head directly into approaching wa

make them mostly unsuitable for laboratory experiments. But based on the limited research done on adults (mostly tagging studies) and our own experience with hatchlings, we can infer the navigation problems adult turtles face and speculate about how they might overcome them.

One important difference between hatchlings and adults is that adult turtles seem to be able to fix their position with respect to their destination. Because the Gulf Stream flows parallel to the coast, Florida hatchlings need only maintain a consistent offshore course to intersect the current. Such orientation can be accomplished with a simple compass sense or perhaps just by swimming into the waves. But a compass sense alone is not sufficient to guide an adult female turtle back to a specific nesting beach; she also needs to know where she is. Researchers refer to such an ability in animals as a "map sense."

To understand the difference between compass sense and map sense, consider the dismal situation you would confront if you were blindfolded, flown by helicopter to a clearing in a forest too enormous to walk out of, given a compass and told to meet your return flight in an hour at another clearing, which is located exactly at the center of the forest. By using the compass, you could maintain a straight course, but this ability alone could not guide you directly to your destination in time. You would first need to know where you were with respect to the central clearing—whether, for example, you were located east or north of it. A compass, then, would not be enough. You would also need a map, or a map sense.





WAVE DIRECTION ordinarily provides a good orientation cue: during the hatching season, waves typically move toward the coast (*above*). The swimming directions of hatchlings dropped into the ocean during unusual weather conditions confirm that the turtles use waves to guide their offshore migration. They swim into waves even if the direction leads them back to shore (*left*).

Relatively little is known about the map sense of animals. Detailed investigations have been carried out only on birds, and experts do not agree on either the precise nature of the map or the cues used. In both birds and sea turtles, however, the ability to detect magnetic fields is theoretically well suited for determining position.

Several geomagnetic parameters vary in a consistent and predictable manner according to latitude, such as the field-line inclination (the angle at which magnetic field lines intersect the surface of the earth, sometimes called the dip angle) and the field intensity in the horizontal and vertical directions. Any of these features could be used as one component of a map for determining position with respect to a goal.

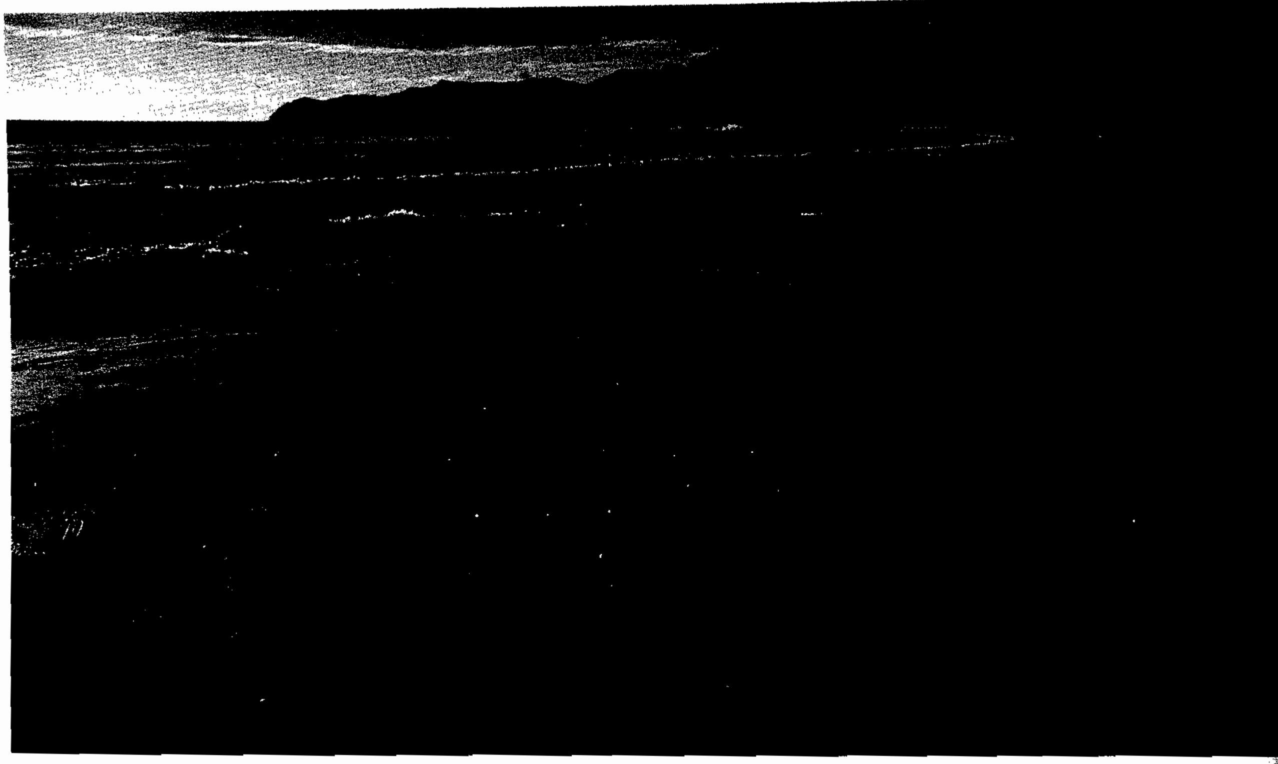
An additional source of magnetic information potentially available to sea turtles exists in the form of the magnetic maxima and minima stripes on the ocean floor. Such stripes occur in seafloor-spreading zones, that is, areas where continental plates diverge. The plates move apart at a rate of a few centimeters per year. Molten material here continually seeps out along the ocean floor. As the material cools, it acquires a magnetization parallel to the direction of the geomagnetic field.

Because the polarity of the earth's magnetic field has reversed at irregular intervals over geologic time (at least 23 times in the past five million years alone), stripes of ocean floor formed during periods of opposite geomagnetic polarity are magnetized in opposite directions. As the seafloor spreads, the plates diverge further, eventually resulting in a series of alternating stripes along the ocean floor. The magnetic signal of each stripe either adds to the local geomagnetic field, enhancing the total field slightly (creating magnetic maxima), or opposes the present earth's field, decreasing it (resulting in magnetic minima).

These stripes of maximum and minimum magnetic intensity are detectable over large regions of the open ocean. Studies by Joseph L. Kirschvink and his colleagues at the California Institute of Technology have shown that whales and dolphins often become stranded on beaches where magnetic minima intersect land, suggesting that cetaceans may follow such pathways during migrations. These pathways might also provide migrating sea turtles with directional information.

Just as the nature of the map sense remains mysterious, so too are the compass cues used by adult turtles to guide them as they migrate. The magnetic field is one clear possibility. Wave propagation direction is another; in many parts of the open ocean, waves and swells provide a consistent directional cue for much of the year. Ocean swells reflect wind patterns that prevail over huge expanses of open water and endure for considerable periods. Thus, because the propagation direction of swells in a given area is determined by prevailing wind conditions hundreds or thousands of miles away, swell direction is largely independent of local weather patterns and varies little over weeks or months. The seasonal constancy of swell direction has long been recognized; Polynesian navigators, for example, employed it in their long-distance voyages.

Whether adult turtles use waves as a cue is not known. During migrations, adults almost certainly swim in directions other than straight toward waves. Thus, the tendency of hatchlings to



HATCHLING SEA TURTLES scamper down Nancite Beach, in Santa Rosa, Costa Rica, to the relative safety of the ocean. Researchers think the few of these olive ridleys that rea adulthood will navigate back to the same beach to nest.

swim directly into waves might be supplanted in juveniles and adults by the ability to hold courses at fixed angles to waves (a wave compass).

Chemosensory cues might also be used by sea turtles in at least some migrations. Several researchers have theorized that the Ascension Island green turtles might home in on their nesting beach by detecting dissolved chemicals unique to the island (a chemical signature) from hundreds of miles away. Calculations by Arthur L. Koch and his colleagues at the University of Florida have suggested that the concentration of natural chemicals entering the sea at Ascension Island might dilute surprisingly little—only about 100 to 1,000 times—before reaching Brazil.

Several considerations, however, cast doubt on the hypothesis that turtle navigation is based solely on chemical cues. Green turtles near the coast of Brazil almost certainly cannot detect a chemical gradient originating at Ascension without sampling and comparing the water in locations separated by many miles. Moreover, the ability of green turtles that nest at Tortuguero (and elsewhere) to converge on specific nesting beaches from widely dispersed feeding grounds (both upstream and downstream) argues for navigational mechanisms that are not strictly chemosensory.

Orientation based on the positions of the stars also seems unlikely. Although many migratory birds use star patterns in orientation, anatomic studies of sea turtle eyes by Koch, now at Indiana University, and his colleague David W. Ehrenfeld of Rutgers University have revealed that adult sea turtles are extremely myopic when their heads are above water. They are therefore almost certainly unable to discern star configurations at night.

The extraordinary navigational abilities of sea turtles have no doubt contributed to their evolutionary success, enabling them to exploit feeding grounds far removed from nesting sites. They are an ancient group of animals, relatively unchanged in the fossil record for millions of years.

Yet despite their long history, sea turtles now face unprecedented threats to their survival. Years of relentless turtle fishing and egg harvesting have wiped out some nesting populations entirely. Many other populations—faced with widespread loss of nesting beaches from human encroachment, growing marine pollution and accidental drowning in fishing nets—are also in jeopardy. Two of the three species of sea turtle that nest in Florida (the leatherback and the green turtle) are now classified as endangered, and the third (the loggerhead) is considered threatened. Moreover, the strong fidelity for the nest site exhibited by many sea turtles means that depleted populations a not likely to be replenished by indiv uals from other areas.

Some hope exists. Knowledge of t orientation cues hatchlings use now e ables workers to release laborato reared turtles under conditions th maximize their chances of successfu migrating offshore. Conservationists a also trying to exploit the turtles' na gation prowess by moving eggs to pr tected beaches. The turtles hatching the safe havens may return there nest. Understanding how adult turtl navigate may one day enable returni females to be tricked into nesting protected beaches. Studying the orien tion mechanisms of sea turtles not o provides insight into one of the mo sophisticated navigation systems e to evolve, it may also help save the animals from extinction.

FURTHER READING

SO EXCELLENT A FISHE: A NATURAL HIS TORY OF SEA TURTLES. Revised editio A. Carr. Charles Scribner's Sons, 1984.

RIPS, FADS, AND LITTLE LOGGERHEADS Archie Carr in *Bioscience*, Vol. 36, page 92–100; February 1986.

MAGNETIC ORIENTATION BY HATCHLIN LOGGERHEAD SEA TURTLES. K. J. Loh mann in *Journal of Experimenta Biology*, Vol. 155, pages 37–49; Januar 1991.