LEARNING TO LISTEN

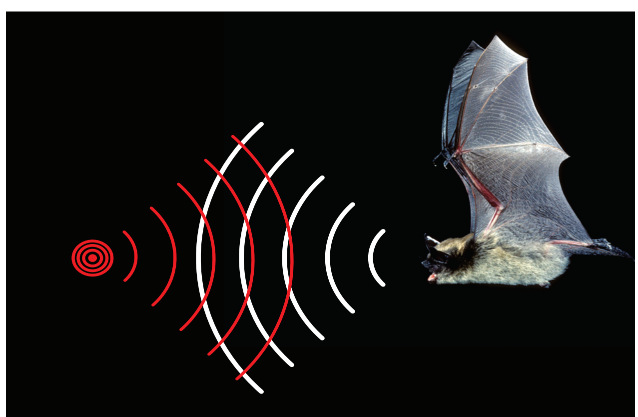
How some vertebrates evolved biological sonar

BY SID PERKINS

The aggressor swoops low over the treetops, piercing the night with a barrage of sonar pulses and searching for telltale data bouncing back. Some prospective targets perceive the ultrasound, take evasive action, and escape. Others, the unwary ones, are fair game. When the prowling aerialist senses the faint echoes bouncing off one of these prey, he turns toward the target, quickens his chirp rate, and homes in for the kill.

This isn't a duel between modern fighter pilots, but an aerial battle that's been raging nightly for millions of years. It's bat versus insect. Bats are members of one of the most diverse groups of mammals, and the echolocation capability that enables some bat species to detect, track, and catch insects on the wing—even ones as small as mosquitoes—is a crucial part of bats' success.

Sonar use has evolved independently among widely disparate groups of creatures. For aquatic mammals, such as porpoises and whales, the sequence of adaptations that led to echolocation is well preserved in the fossil record of their ancestors. But no such trail exists for bats, a group whose oldest known remains indicate that echolocation was already in use.



HOMING IN — The distance between pressure pulses in a bat's ultrasonic chirps and echoes (represented by white and red wave outlines, respectively) determines how small a target the predator can detect.

M. TUTTLE/BAT CONSERVATION INTL./S. NORCROSS

In the handful of bird species that use sonar, the origin of that ability is even murkier. Some echolocating species have close relatives that apparently possess the anatomical means to echolocate but don't use it, implying that avian echolocation is a behavior that some species simply haven't learned. For insights into how echolocation evolved in birds and bats, scientists are turning to DNA, a modern source of information about ancient biological relationships.

Although tiny bats and toothed whales may seem to be as different as night and day, they do have something in common. A few species of their respective prey can detect high-frequency sonar and have developed a variety of techniques that increase their odds of escape and survival in the ever-escalating arms race of evolution (*see sidebar, page 315*).

LISTEN UP Sonar systems on modern submarines were inspired by the principle behind biological sonar: Send out a short burst of sound and then listen for the echo. The direction from which the echo arrives and the time it takes to come back reveal a target's location and distance. In general, the higher the frequency of the emitted sound, the better echolocation works: High frequencies correspond to short wavelengths, and the rules of physics require short wavelengths to detect small objects.

For whales, the evolution of efficient biological sonar took about 30 million years. Around 50 million years ago, mammals known as pakicetids—the land-dwelling ancestors of modern whales—foraged in the rivers and streams of what is now Pakistan (*SN: 9/22/01, p. 180*). Those creatures, like most land mammals, could hear well in air but poorly underwater, says Zhe-Xi Luo, a vertebrate paleontologist at the Carnegie Museum of Natural History in Pittsburgh.

Fossils of pakicetid descendants that lived during the next 10 million years show a gradual improvement in their hearing underwater. During that period, the role of the outer ear in funneling sound to the middle ear was minimized, and the lower jawbone became the animal's main sound receptor.

Members of these aquatic-adapted species weren't echolocators, however, because they didn't have structures in their breathing passages that would enable them to make high-frequency sounds, says Luo. Those sound-generating organs, which in modern whales are chambers in the nasal passages, evolved later, during a period when nostril position changed from far forward on the nose in older species to high on the head in more-recent ones, he notes.

Then, a little more than 30 million years ago, the whale family tree split into two major lineages. One branch, the toothed whales, today includes porpoises, killer whales, and sperm whales. This branch evolved organs to produce high-frequency chirps and inner ear structures to detect them. By 18 million years ago, the ancestors of today's dolphins had an ear structure that suggests that they could echolocate as well as their modern relatives can.

If only the fossil record for bats' progenitors were as rich or as revealing as is that of the whales. The oldest bat fossils, belonging to an extinct lineage, were unearthed from rocks about 54 million years old, but the creatures that they represent aren't dramatically different from living bats, says Mark S. Springer, an evolutionary biologist at the University of California, Riverside.

Hallmark features of these creatures include the elongated fingers that support the wing membranes and the extensive coiling of bony structures in the inner ears, a sign that they were capable of detecting the high-frequency chirps used in echolocation. The few bat fossils unearthed to date don't include the soft tissues, such as sound-producing organs, that could show whether the creatures had the ability to produce high-frequency sounds. But some fossil bats' stomach contents, which include large numbers of flying insects, strongly suggest that the ancient animals could echolocate.

The fossil record of bats is sparse mainly because of the animals' small size and the delicacy of their bones. Scientists haven't yet found creatures that form an evolutionary link between bats and their presumably rodentlike, earthbound ancestors. Nevertheless, DNA studies of modern-day bats shed some light on when the night flyers might have originated.

Springer and his colleagues analyzed 17 genes from the cell nuclei of bats from 30 different genera, or groups of species. DNA differences among the modern bats, along with estimates of long-term rates of genetic mutation, suggest that the common ancestor of modern bats probably lived about 64 million years ago, a period just after the hypothesized asteroid or comet impact on Earth that wiped out the dinosaurs and triggered rapid mammalian evolution.

The DNA evidence further suggests that modern bats fall into four major lineages that arose between 52 million and 50 million years ago, a time when average global temperatures jumped 7°C and stimulated an explosion in the variety of plants and insects. Bats diversified and took advantage of this new ecological bounty, the researchers speculated in the Jan. 28 *Science*.

Ancestral bats were in the right place at the right time, says Nancy B. Simmons of the American Museum of Natural History in New York. As predators capable of catching insects on the wing, bats would have had few competitors for the sudden wealth of airborne prey, she comments in the same issue of *Science*.

DUMB COUSINS Today, there are more than 1,100 species of bats, a tally that accounts for more than 20 percent of living mammal species. Scientists typically split bats into two large groups. The 800-or-so species that use sonar are called microbats. In general, members of these species are much smaller than those in the second group, called megabats, which don't echolocate prey. The megabats include the large tropical species known as flying foxes. These fruit-eating animals weigh up to 1.5 kilograms and have a wingspan that rivals an eagle's.

Recent DNA analyses by Springer and his colleagues show that the single evolutionary lineage containing all the megabats also includes several microbat species that can echolocate. These studies alone, says Springer, don't indicate whether the use of sonar evolved only once, and was then lost in megabats, or whether it arose separately within various lineages. On the other hand, the limited anatomical information from the fossils of extinct bats suggests that the capability to echolocate arose just once in an ancestral bat, he notes.

However high-frequency sonar arose, modern bats use it for more than just detecting and tracking prey. The winged mammals use echolocation to navigate as they enter and leave their roosts. Some bats use the same squeaks for communication, says Karry A. Kazial of the State University of New York (SUNY) at Fredonia.

Laboratory tests conducted by Kazial and her colleagues suggest that females of *Eptesicus fuscus* or big brown bat, a species that ranges from southern Canada to northernmost South America, can recognize the sex of another adult of its species by listening to its ultrasonic chirps.

Although scientists haven't isolated characteristics of the calls that differ between the sexes, bats in the wild may use such variations to identify possible mates at a distance, Kazial and her colleagues speculate in the March 2004 *Animal Behavior*.

FLYING BLIND Mammals can hear higher frequencies than other creatures can because of the characteristic arrangement of tiny bones in their ears (*SN: 5/26/01, p. 324*) as well as the structure of their cochlea, or inner ear. Even among mammals, however, hearing ability varies widely. Among people, most young adults can detect sounds with frequencies between 20 hertz, or cycles per second, and 20 kilohertz (kHz). But even that highest tone is low by echolocation standards: The typical bat's sonar chirps exploit frequencies as high as 120 kHz, and bottlenose dolphins' calls include frequencies that range up to 150 kHz or so.

Birds, however, can't produce or hear the high-pitched, short-wavelength sounds needed to track insect-size targets. The few birds that can echolocate use lower frequencies, and they do so only to navigate in the dark, says J. Jordan Price, a biologist at St. Mary's College of Maryland in St. Mary's City. Even that limited capability provides a benefit, however, because it enables

Biological Arms Race

Predators evolve better ways to hunt, then prey work out escape plans

Although echolocation provides some bats and whales with an extraordinary capability to detect and track their prey, a few of those creatures' favored meal items have developed techniques to counter that advantage.

A diverse group of insects, including beetles, katydids, lacewings, and a host of moth species, have body structures that vibrate when struck by the ultrasonic frequencies used by echolocating bats, says M. Brock Fenton of the University of Western Ontario in London. Equipped with these sonar detectors, the insects can engage in a variety of countermeasures.

The easiest—and typically most effective—move is simply to turn tail and fly away before detection. For example, some moths can perceive a bat's ultrasonic chirps from a distance of 40 meters, about four times the distance at which the bat can detect the moth, Fenton notes.

When sonar signals get stronger, suggesting that a prowling bat is close, insects may fly upward in a spiral, flutter their wings chaotically, or fold their wings and dive to the ground. Some moths use all these tricks, says Karry A. Kazial of the State University of New York at Fredonia. Randomly using different techniques adds a further measure of unpredictability to a moth's behavior, she notes.

Some insects have evolved to emit high-pitched squeaks of their own, signals that may disrupt the bat's sonar. Kazial says that she considers that possibility unlikely, however, because tests suggest that such a jamming technique would work only if the defensive chirp were emitted just as the bat's sonar pulses were bouncing off a moth, for instance. Instead, the defensive squeaks may serve as a warning that the moth is distasteful—an audible version of the protective coloration of some bitter-tasting butterflies and poison frogs.

Some fish, in an attempt to foil the dolphins that prey on them, have developed similar techniques, says Arthur N. Popper of the University of Maryland in College Park. Lab tests show that *Alosa sapidissima*, the American shad—a small fish related to herring—can hear frequencies as high as 180 kilohertz. Most fish can't detect frequencies above 3 kHz or so.

Shad in a lab tank will turn and swim away from a device emitting low-volume frequencies between 70 kHz and 110 kHz, which are characteristic of foraging dolphins, says Popper. As the sound intensifies, the shad form a tight school at the far side of the tank. At sound levels typical of a dolphin at close range, the fish scatter in a panic and even leap from the water.

Dolphins and porpoises, not surprisingly, have developed their own responses to these countermeasures. Groups of the predators often corral schools of fish or chase their prey into bays or other dead ends. —S.P.

members of those species to nest in caves and other places that aren't readily accessible to predators.

With one exception, all birds known to echolocate are swiftlets. Birds in this group catch insects on the fly just as a bat does, but they do so in the daytime and track their prey by sight, says Price.

Scientists have typically relied on characteristics beyond size, shape, and color to distinguish the members of one swiftlet species from those of another, simply because the birds have so few distinguishing features, he notes. Until recently, all swiftlets known to echolocate fell within the genus *Aerodramus*. Then, Price and his colleagues found a swiftlet in another genus—the pygmy swiftlet, *Collocalia troglodytes*—sitting on its nest, in complete darkness, about 30 m inside a cave on an island in the Philippines.

Members of this species had not been known to use sonar, but the researchers removed the bird from the cave, recorded the sharp, clicking noises that it uses to navigate, and then conducted the definitive test: They turned it loose in a completely dark room. The bird passed with flying colors: Unlike birds from the two other species in its genus, the pygmy swiftlet can fly around in a darkened room without slamming into the walls.

DNA studies conducted by Price and his colleagues supported the original placement of the pygmy swiftlet in the *Collocalia* genus. Their analyses further suggest that birds in the two swiftlet genera last shared an ancestor 2 million to 3 million years ago, says Price. The researchers reported their findings in the March 2004 *Journal of Avian Biology*.

TRAIL OF EARS — Fossils of aquatic mammals that lived during a 30-million-year span of time record the evolution of ear features that enable dolphins and their kin to echolocate prey and obstacles.

PHOTODISC

The team's results complicate the debate about how and when the use of sonar evolved in swiftlets. Now, there are two options. The first is that echolocation appeared only once, in a common ancestor of *Aerodramus* and *Collocalia* swiftlets and then disappeared in some modern swiftlets. The second is that echolocation evolved at least twice, once in each of the genera. Current data don't permit researchers to know which option is correct, says Price.

There aren't any significant anatomical differences in ear structure or other features that distinguish the swiftlets that echolocate from those that don't, says David W. Steadman of the Florida Natural History Museum in Gainesville. Therefore, analysis of swiftlet fossils probably won't reveal how and when sonar use evolved in that group. However, because the oilbird, a nocturnal bird of South America that is unrelated to swiftlets, also developed echolocation, that capability has evolved in birds more than once.

Echolocation's evolution several times in groups of vertebrates as disparate as birds, bats, and whales is a testament to its biological usefulness. Another powerful endorsement is science's continuing quest to develop electronic equipment for submarines and aircraft that imitates animals' sophisticated sonar. ■

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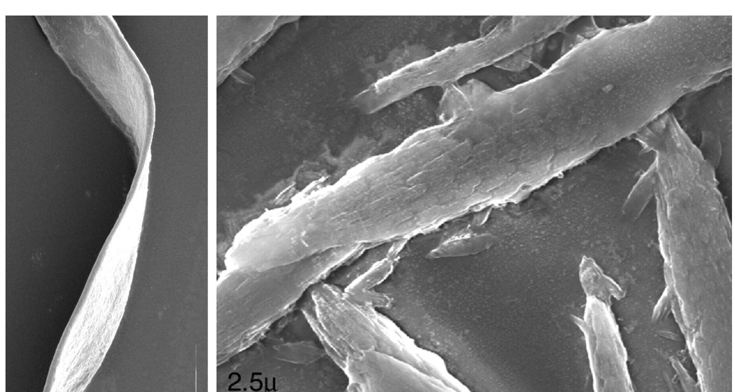
ventional fillings such as polymer resins and metal alloys, don't stick properly to small cavities or damaged surfaces.

In the Feb. 24 *Nature*, the researchers describe experiments on an extracted human molar bearing a new cavity. Shortly after the scientists applied the paste, a minute amount of the molar's enamel dissolved, but it was quickly replaced by synthetic enamel, which filled the cavity and integrated with the natural material.

When viewed under a transmission-electron microscope, the microstructure of the filling was virtually indistinguishable from that of real enamel, and there was no obvious gap between the synthetic material and the natural enamel surrounding the cavity, says Yamagishi. That's important, she says, because existing filling materials have crystal structures different from that of enamel and therefore rarely adhere seamlessly to the natural tissue.

Yamagishi says that her group is gearing up to begin clinical trials. If all goes well, the dental paste could find its way into the dentist's office in the next 2 to 3 years, she says. So far, the material works only for small, early-stage cavities, not the deeper cavities of later-stage tooth decay.

Even so, such advances might ultimately help researchers build whole teeth from scratch to replace diseased or damaged teeth. To that end, the National Institute of Dental and Craniofacial Research plans to establish a center within the next 2 years, where a team of biologists, engineers, materials scientists, and clinicians will bring their expertise to bear on the problem. The replacement teeth that they envision would last longer than the dental implants available today.



BANDS THAT BOND — During tooth development, a small protein called amelogenin spontaneously assembles into a microribbon structure (left). These protein ribbons serve as templates for the growth of hydroxyapatite crystals (right), the main ingredient in tooth enamel.

SCIENCE

The institute's strategy most likely will combine materials science–based approaches for making synthetic enamel and cell-based methods for growing other dental tissues. With a biomaterial that mimics the properties of natural enamel, researchers could bypass the need for enamel–producing cells. For instance, scientists might create a crown out of synthetic enamel and use it as a mold, says Robey. Inside the mold, researchers would then place all the necessary cells for regrowing the rest of the tooth, she says.

That 's the vision. It may take more than a decade before researchers realize such a goal. However, if successful, it would represent a major feat in bioengineering—not to mention a major boon for patients, who won't have to run back to the dentist so often for repairs on false teeth.

Dental science has certainly come a long way since the days of George Washington, whose sets of false teeth were fashioned not from wood, as legend has it, but from gold, hippo ivory, and horse teeth. ■