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PREDATOR AND PREY: Life and Death Struggles
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Before the appearance of bats, more than sixty million years ago, the night was a relatively safe time for insects to move about, free from most hungry birds and mammals. The eyes of most nocturnal vertebrate predators were poorly designed for the dark, and as a result, many insects like moths, caddisflies, and beetles evolved a nocturnal lifestyle.

Staying alive during the day is a complicated affair for insects. Many use visual defenses, such as camouflaging themselves or packing their bodies with noxious chemicals and then advertising their distastefulness with bright colors. One of the best ways of remaining uneaten is simply to be very still. This tactic, however, presents problems when it comes to finding food, mates, or places to rear young. Becoming nocturnal initially solved these problems, but once bats evolved their sonar into the sophisticated tool it is, the night was no longer safe.

Different insects adopted different strategies to cope with such efficient nocturnal predators. Some insects moved back into the day, and others remained nocturnal, but evolved a new sense: a way of hearing the echolocation calls of hunting bats. The anti-bat ear was born. Today, ears that serve as bat detectors are found in certain moths, lacewings, and preying mantises and are suspected in some beetles. The ears of moths were the first to be discovered and still amaze us with their exquisite design. Depending upon what family they belong to, moths have ears on their waists, their abdomens, or their faces, and they equip them with only one to four nerve cells. Our ears, by contrast, have over 15,000 sound receptor cells each, but we use our sense of hearing for more complicated tasks. When we listen, our ears pick out thousands of subtle changes in the pitch of the voices we use for communication.

When it comes to social communication, moths, for the most part, have little use for sophisticated ears. They usually communicate to members of the opposite sex, or to others, using chemicals called pheromones. Some moths do use sounds in their mating behavior, but the relative rarity of this suggests that bat-detection is the most common purpose for their ears. The nonsocial use for hearing has resulted in moth ears being tone-deaf, though this limitation apparently has not hindered the moths much. Moths that can hear the approach of a bat and respond to its attack stand a 40% less chance of being consumed.

It was the work of Kenneth Roeder and his students and colleagues (notably Asher Treat) in the 1950s and 1960s that provided the initial insights into the hidden lives of moths and bats. Since then, researchers around the world have continued to fill in the picture.

This is what we think is happening. When a flying moth first hears a bat's echolocation calls, the sounds are faint and affect only one of the moth's ears. This lets the moth know from which side the bat is approaching and how far away it is. The moth acts on this information by adjusting its wingbeat to fly away from the bat. This early-detection system works well for the moth because its ears are so sensitive. North American moths can hear the sonar calls of a big brown bat (*Eptesicus fuscus*), one of their most common predators, when it is almost 100 feet away. Even the most optimistic echolocation researcher will admit this is much further than the distance at which the bat hears its own echoes from the moth. The moth can out-hear the sonar system of the bat in much the

same way as a radar detector in your car warns you of a police car in wait.

Why then, do any moths ever get eaten? This dilemma always confronts people working on evolutionary questions: If a defense is so good, why does it sometimes not work? The answer is in the unpredictability of the real world. The military hardware that works superbly on the drawing board often fails when it has to perform in the uncertain conditions of a battlefield; similarly, the defenses of the moth are also imperfect. For instance, when a bat feeds around trees, the trees become obstacles to the moth's ability to hear the bat's echolocation signals. The moth, therefore, may not have early warning of the bat's approach and must use short-range defenses. For this purpose, some moths have a back-up system in the form of a single nerve cell in each ear that alerts the moth only to very close bats.

One of the ways that this cell alerts the moth that a bat is close is based on the kind of sonar the bat uses. When a bat begins its final approach, it speeds up its rate of echolocation pulsing (often called a "feeding buzz"). This sonar gunfire appears to activate a special part of the moth's flight circuitry, which instructs the moth to begin a series of wild, looping aerial maneuvers designed to out-fly the heavier and less agile bat. If these aerial acrobatics fling the moth outside of the bat's narrow echolocation beam, the bat seems to give up its pursuit to search for less troublesome prey. If, however, the bat locks onto the echoes off its intended prey, real problems begin for the moth since the bat's greater speed works in the bat's favor.

The final tactic for the moth is to fold its wings and dive toward the ground. Some moths have more elaborate defenses. Certain tiger moths have one last salvo they can launch at the bat. At the last possible moment of the bat's final attack phase, when it is very close and flying at its highest speed, the tiger moth blasts back streams of high-pitched clicks. Some scientists think these sounds are advertisements of the moth's bad taste, while others feel the clicks are the moth's way of saying "Boo!" to the bat and startling it. We will never know exactly what goes on in the mind of the bat during these critical last few milliseconds in pursuit of a meal. More often than not, the harried tiger moth flies away, alive, to resume its search for mates or places to lay its eggs.

The evasive flight of the moth, as effective as it is, may not be the last word in this aerial warfare. Some tropical bats, especially those of the Old World leaf-nosed family, emit echolocation calls so high-pitched that even the sensitive ears of moths cannot detect them. This kind of echolocation may function mainly to allow the bats to avoid collision within dense vegetation, but another advantage to this sonar is that it has rendered them acoustically invisible to moths. What, if anything, a moth does to defend itself from these chiropteran stealth fighters is unknown.

In our lab we are particularly interested in how bat-detector ears evolved. As effective as ears that can detect bats are, some moths do not have them, and how they avoid bats is a mystery. Luna and Cecropia silk-worm moths, for example, may simply rely on their large size to protect them from most bats. One of my students, Jayne Yack, found that earless moths in the upper Northeast region of North America emerge as adults very early in summer, before most bats have returned from their overwintering hibernation sites. Moths have a very short adult life span (they are essentially flying reproduction machines), and limiting their flying life to times when bats are not active may be one way to live without ears.

Another student, Scott Morrill, tested Ken Roeder's idea that deaf moths co-exist with bats by flying low to the ground away from where bats normally hunt. Scott found that deaf moths, overall, fly less often and when they do, they fly in areas that bats generally avoid, such as deep forests.

Other possible defenses exist for earless moths. Some moths are almost as large as the bats that hunt them and could, in an aerial dogfight, pose serious problems to a bat's ability to stay aloft. Since it is very likely that the echolocation signals bats emit can determine the size of their prey, they may simply ignore large moths. These moths may not have been subjected to the evolutionary pressure to evolve a way of detecting bats. Of course, not all echolocating bats are small; some species in the tropics have wingspans close to foot and a half. What deaf moths do to avoid these giants is yet another tantalizing question.

One type of bat that poses real headaches for moths is the kind that has evolved faint echolocation calls. Gleaning bats snatch their prey either directly from vegetation or from the ground instead of while in flight. Early investigators called them "whispering bats," because their echolocation calls were so faint. Gleaning bats hunt by using the sounds insects make as they walk among foliage, fan their wings, or sing for mates. We have found that moths in north temperate areas likely never hear the ultra-quiet, high-pitched sonar emitted by such bats as they fly in for the kill.

Studying the simple ears of moths and how they have been modified to meet the needs of the moths that possess them can tell us much about the mechanisms of evolution. The simple, yet critically important, behaviors these sensory structures govern in moths can give us insight into the ways in which our own nervous systems work. Ultimately, though, the most fascination comes from simply watching the life and death struggles of moths and bats as they try to out-maneuver each other. It tells us that mortal battles rage continuously in the natural world of animals--a reminder, perhaps, that our own warfare may be only a modern version of these evolutionarily ancient conflicts.

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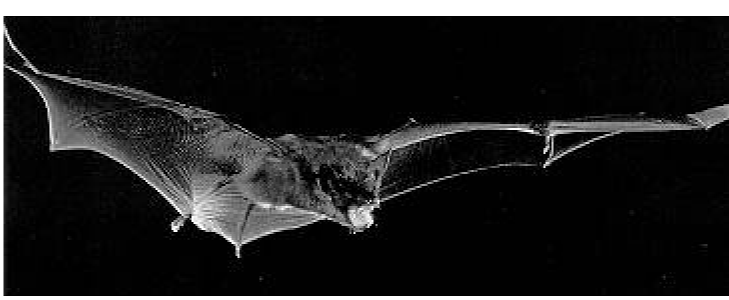
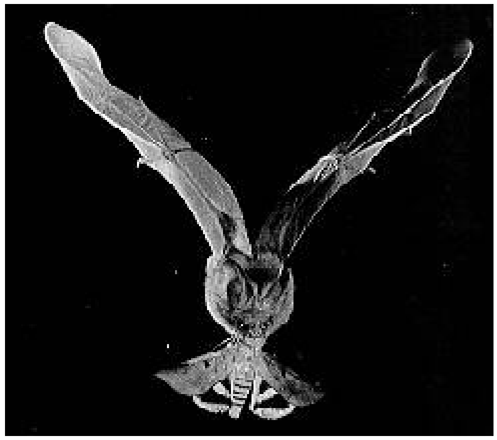
To avoid being eaten by bats, some moths have evolved sensitive hearing that warns them of a bat's approach. Still, even the best defenses are imperfect and many moths are eaten.



North American moths can hear the sonar calls of a big brown bat (above) when it is as far away as 100 feet, much further than the distance the bat hears its own echoes from the moth. In contrast, some Old World trident-nosed

bats (below), hold the record for high-pitched echolocation calls at 212 kHz. Even the sensitive ears of moths cannot hear them and, consequently, a high proportion of moths are included in the diets of these bats.



"Whispering bats" pose a real problem for moths trying to avoid them. Even though the moth has ears, it could not hear the faint echolocation calls of the bat and was captured.

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