Birds can recognize a model's reproduction of their own songs

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lower curves consider only annihilations to W^+W^- or, for lower WIMP masses, to pairs of tau leptons. Those "hard" modes yield the most energetic, therefore most easily detected neutrinos. The "soft" (least visible) modes are annihilations to meson pairs.

For WIMP masses above 35 GeV, IceCube's hard-mode curve is the most stringent upper limit yet. After only one year of observing with DeepCore in place, it already cuts well into the parameter space of MSSMs that had survived earlier null results from recoil and accelerator searches. Collisions in accelerators should create WIMPs, but beam energies impose restrictive mass limits. Even with CERN's Large Hadron Collider, one can't search for WIMPs much heavier than 500 GeV.

The two-dimensional representation of MSSM parameter space in figure 3 is just a projection. More parameters are needed to describe the mixture of annihilation modes predicted by any particular model. So the most stringent IceCube limit in the figure applies only to the many models in which hard modes predominate.

The modifier "spin-dependent" in the ordinate label of figure 3 needs explaining. The χ^0p elastic-scattering cross section has two distinct contributions. The dominant term, plotted in the figure, depends on the spin state of the χ^0p system; the other doesn't. Though the spin-independent contribution is small in the mostly hydrogen Sun, its coherent amplification in scattering off a heavy nucleus makes it important in most recoil searches.

Another kind of WIMP search is gaining attention. WIMP annihilation would also produce positrons. Unlike neutrinos, positrons have short, crooked trajectories; but they're easier to detect. The rising positron fraction with increasing energy above 10 GeV in the cosmic-ray spectrum is suggestive of WIMP annihilation. An eventual abrupt falloff of that rise would reflect the WIMP's mass. Such a falloff hasn't yet been seen. But a spectacularly precise positron spectrum leveling off near 350 GeV, just published by the Alpha Magnetic Spectrometer collaboration,[3] has WIMP watchers waiting for the other shoe to drop.

Bertram Schwarzschild

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Birds can recognize a model's reproduction of their own songs

An interdisciplinary collaboration integrates physical, acoustic, and biological approaches to the study of birdsong.

Just as human babies must learn how to talk, young songbirds have to learn to sing. By listening to others, each bird gradually develops its own voice—an individualized version of its species' song. But despite that behavioral complexity, the physical mechanism of birdsong may actually be very simple. Gabriel Mindlin and colleagues at the University of Buenos Aires have found that they can realistically reproduce the songs of several species by using a dynamical-systems model with just two time-dependent parameters. Now, in collaboration with neuroscientist Daniel Margoliash of the University of Chicago, they've put their model to the ultimate test: What do the birds think?[1]

Of biomechanics . . .

Figure 1 shows a schematic of a songbird's vocal tract. As the bird exhales, it pushes air through the vocal organ, called the syrinx. Under the right conditions, the flow of air can induce vibrations in folds of tissue called the syringeal labia. Those vibrations set up an acoustic wave, which is modified as it passes through the rest of the vocal tract—trachea, oro-esophageal cavity, and beak—and emerges as an audible song.

In Mindlin and colleagues' model, two parameters are under the bird's control. One is the bronchial pressure P_b of the air as it enters the syrinx. The other is the tension, or stiffness, of the syringeal labia, which the bird may control by tightening or relaxing its vocal muscles. (As figure 1 shows, a bird actually has two pairs of syringeal labia. But the model so far accounts for only one.) From there, the researchers treated the syringeal labia as a mass on a damped spring, with the muscle tension playing the role of the spring constant k. They formulated an equation of motion for the labial separation and studied how it behaved in response to different values of P_b and k.

In 2001 they used the model to study canary songs, which are characterized by spectrally pure notes with few overtones. For realistic values of the pressure and tension, they found that the model syringeal labia oscillated sinusoidally at the frequencies at which canaries actually sing. By varying the pressure and tension parameters in time, and by including the filtering effects of the vocal tract, Mindlin and colleagues were able to reproduce the starts, stops, timbre, and continuous changes in pitch of canary song.[2]

But not every species limits itself to single-frequency notes. One of the most widely studied songbird species, the zebra finch, sings some notes with strong fundamental frequencies, but other notes, as shown in figure 2a, are made up of many equally spaced har-

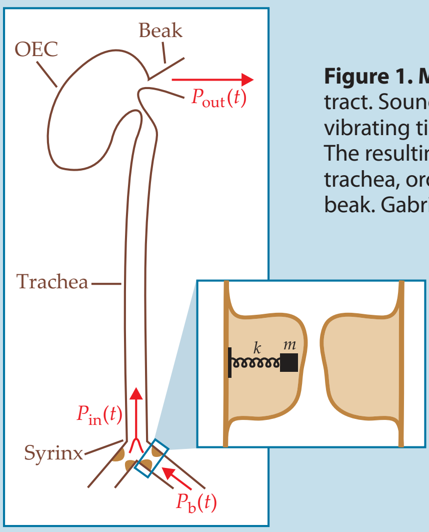

Figure 1. Model view of a songbird's vocal tract. Sound is produced in the syrinx by vibrating tissue folds called syringeal labia. The resulting acoustic wave is filtered by the trachea, oro-esophageal cavity (OEC), and beak. Gabriel Mindlin and colleagues model the syringeal labial position as a mass m on a spring, with the spring constant k and the bronchial pressure P_b under the bird's control. They then compute the pressure P_{in} of the sound wave entering the trachea and the final output pressure P_{out}. (Adapted from ref. 1.)

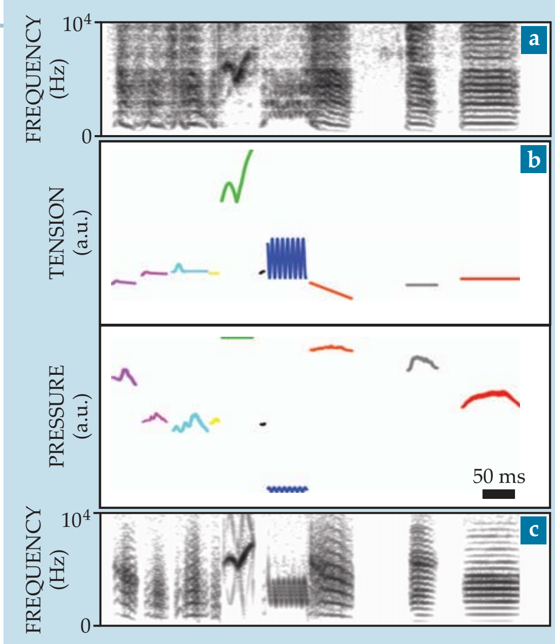

Figure 2. Reconstructing a zebra finch's song. **(a)** A spectrograph of the recorded song, plotting intensity as a function of frequency and time (horizontal axis). **(b)** The best-fit syringeal labial tension and bronchial pressure, broken down into gestures shown in different colors. **(c)** The model-reconstructed song. Sound files for the songs in panels a and c are available with the online version of this story. (Adapted from ref. 1.)

monics, no one of which is dominant. Mindlin and colleagues found that their model, suitably modified, could reproduce those notes as well. By introducing a nonlinear term (but not another controllable parameter) into their mass-on-a-spring equation, they could get the model syringeal labia to exhibit oscillations more complex than simple sine waves.[3]

To reconstruct a whole song lasting half a second or so, they chopped it up into segments of 20 ms or less and searched their parameter space for the best pressure–tension trajectory to fit each segment. The result, such as the one in figure 2b, was a sequence of units, which the researchers call "gestures," bounded by discontinuous jumps in pressure and tension. Real biophysical parameters, of course, must be continuous functions of time, but when the researchers measured the bronchial pressure and syringeal muscle activity in singing birds, they found that both quantities exhibited rapid changes exactly where the model predicted.[4] A spectrograph of the reconstructed song is shown in figure 2c. (Sound files for both the recorded and reconstructed songs are available with the online version of this story.)

. . . and bird brains

"The synthetic songs sounded very good to us," Mindlin recounts, "and they looked good in the spectrograph. But what about for the birds? Were the synthetic copies good enough for them?" The chance to find out soon arose when Ana Amador, one of Mindlin's students who had helped to develop the model, finished her PhD and went to work as a postdoc for Margoliash, a biologist who studied the neurological aspects of birdsong. By surgically implanting tiny electrodes into a bird's head to measure the responses of individual neurons, Margoliash and his group had found in 2000 that when a bird listens to a recording of its own song, neurons in a certain "premotor" part of the brain produce bursts of activity in the same pattern as they did when the bird sang the song in the first place.[5] The effect is specific to the song: When a bird listens to another bird's song, or to its own song played backwards, the premotor neurons don't fire in the same pattern. In fact, they don't fire at all.

Here, then, was a way to test whether the birds recognized the model's reconstructions of their own songs. In Chicago, Amador recorded the songs of nine zebra finches. She sent the recordings to Mindlin in Buenos Aires, where he and his student Yonatan Perl put them through the model. Then Amador played the reconstructed songs back to the birds. She found that the neurons tended to respond at the right times: In about 20 trials per song per bird, the neurons responded to the modeled songs 58% of the time. Says Mindlin, "Given the simplicity of the model and the amazing sensitivity of the birds' auditory system, we were surprised by the model's success." On the other hand, breaking the model—for example, by ignoring the frequency filtering of the oroesophageal—produced songs that the birds couldn't recognize at all.

Overlaying the neuron-activity data with the output from the model yielded another surprise. The neuron bursts always seemed to occur at gesture extrema: either the beginning or the end of a gesture or the local maximum in pressure or tension. That prompted the researchers to look at singing birds' neuron activity, which is more precisely timed than in listening birds. They found an even stronger correlation with gesture extrema.

But it's too soon to tell for sure if neuron bursts always coincide with gesture extrema—or if every gesture extremum is marked by a neuron burst. The researchers' data on singing birds so far include just 15 neurons in three birds. It's relatively easy to gather data for the same neurons over and over, but studying many different neurons is a challenge: After all, it involves performing brain surgery on a bird. And the observed correlation runs counter to the established view, also based on neurons recorded a few at a time, that some premotor neuron or other is always active, and that neuron activity works as a timing signal rather than by controlling any particular features of the song.[6]

In any event, the premotor bursts wouldn't be able to directly control the gesture extrema to which they correspond. It takes about 20 ms for a signal to travel from the premotor part of the brain to the muscles that control singing, and almost as long for a signal from the birds' ears to reach its brain. But the researchers found the neuron bursts to be almost perfectly simultaneous with the gesture extrema, with a delay too brief for them to control or be controlled by any features of the song. That finding is not necessarily a blow to the hypothesis that the two are related. It may ultimately yield important clues about both the neurology and the physics of birdsong. Says Mindlin, "Behavior emerges from the interaction between a nervous system, a biomechanical architecture, and the environment. Its study should be just as integrated."

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