BIRDSONG SCIENCE

Neville Fletcher explains the ways in which birds produce their wide range of songs.

Birds produce a wide range of beautiful, and sometimes not so beautiful, songs. The musical pitch of these songs varies nearly inversely with the square root of the weight of the bird, though there are wide variations around this average. Surprisingly, this general rule extends right down the animal chain to elephants, whose voice pitch is so low we can hardly hear it.

Exactly how do birds sing? Is it different from the way we do it as humans?

Being able to breathe is an important part of singing, and both birds and humans have two lungs, consisting of air sacs and fine tubes that lead out through large tubes, called bronchi, and join up to the trachea or "wind pipe" that leads to the mouth (Fig. 1a). In humans, near the top of the trachea where it enters the mouth, there is a vibrating valve consisting of two small lip-like flaps called vocal folds or labia, which are stretched by embedded muscles known commonly as "vocal chords". These folds can be made to vibrate just as we can make our lips vibrate, and pulses of air from the lungs flow through them and out of the mouth, generating the sound. If we are singing a high note we increase the tension in the muscles to stretch the vocal folds and make them vibrate more rapidly.

Because our vocal folds generally close completely once in each vibration, the air flow through them comes in pulses, and these pulses contain not only the frequency of the basic vibration, called the fundamental, but also other components at frequencies that are whole-number multiples of the fundamental. These are called harmonics.

All these frequencies have to pass through the upper vocal tract, consisting of the top of the trachea, the mouth and the lips, before they escape as sound to the surrounding air. The geometry of this passage can be altered by moving the tongue and lips to produce resonances that reinforce some harmonics while attenuating others, giving peaks in the spectrum called formants. It is adjustment of these formants that makes the vowel "eee" sound different from "aaah" and allows us to produce intelligible speech.

We also add consonants such as "s", "t" or "k" by making hissing or pulsing noises that are independent of the vocal fold vibration.

The vocal folds of humans typically vibrate about 100–200 times per second for men during speech and about twice as fast for women, but singers can change this rate by almost a factor of four to sing much higher notes. The important resonant peaks that distinguish vowel sounds are at about 500, 1500 and 2500 vibrations per second (Hz) for a relaxed open mouth, but the second and third formants can be moved up or down independently by about 500 Hz to produce the different vowels. There are other higher formants but they are not so important.

Although birds have a fairly similar vocal anatomy to humans, there are important differences. Some birds, such as the dove, have a single vocal valve like humans but it is located near the base of the trachea rather than near the top.

In other birds, generally called songbirds, there are actually two valves, one in each bronchus just below the junction with the trachea (Fig. 1b), the whole structure being called the syrinx. This means that songbirds can really sing two different notes at once, and some of them do, though most birds either sing the same note with each valve, use one valve for high notes and the other for low notes, or sometimes do not use one of the valves at all.

The active valve in the syrinx generally vibrates regularly and closes once in each vibration, rather like the human vocal folds, so the air flow up the trachea and out from the beak is again rich in harmonics. Because birds are generally very small compared with humans, the resonances of their vocal tracts are higher by a large factor,

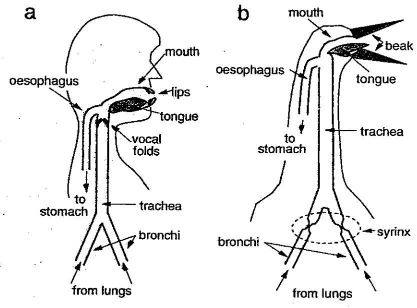


Figure 1. Sketch of the vocal anatomy of (a) a human and (b) a songbird. The lungs supply a steady pressure of air, which causes a pulsating flow through the vocal valve (the vocal folds in a human and the syrinx in a bird). The upper vocal tract, which consists of part of the trachea and the mouth or beak, changes the tone of the sound by producing emphasised formants at particular frequencies.

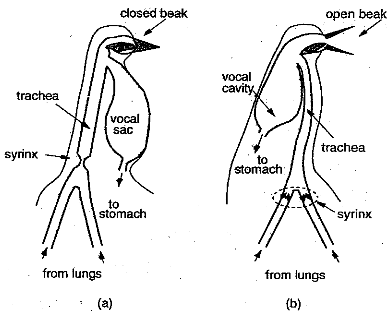
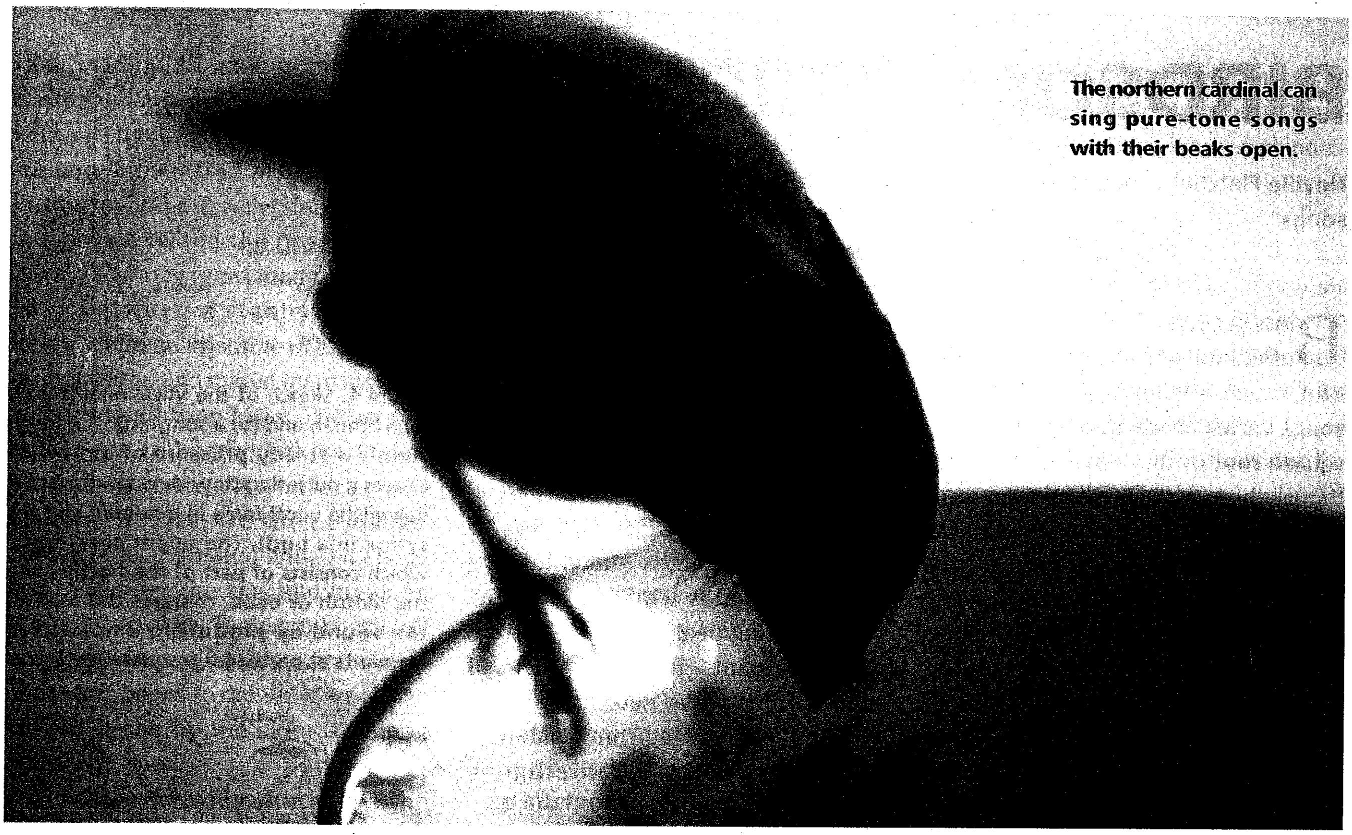


Figure 2. The vocal anatomy of two birds that can sing with a pure, single-frequency tone. In each case there is an inflated cavity involved. (a) The dove, which sings with a closed beak and radiates sound through the vibrating walls of its vocal sac. (b) The cardinal, which sings with an open beak.



The northern cardinal can sing pure-tone songs with their beaks open.

though not as much as might be expected because of the relocation of the vocal valve to the base of the trachea or the bronchi, which gives a greater length of upper vocal tract.

Many birds, however, have rather stiff tongues, and all have beaks rather than lips, so that it is difficult for them to make much change in the strength of the upper harmonics in the way that humans do. The exceptions are some species of parrots, which can mimic human speech by reproducing the second and third formants, though not the lowest one, this making their speech sound like a poor-quality telephone.

Most of this has been known for quite a long time, but there is one significant problem. Some songbirds can produce pure-tone songs with almost no harmonics at all, and it has not been known how they can do this.

In the case of humans, the technique used is the whistle, which is quite different from a normal vocal sound. To do this we purse our lips to a narrow opening and raise the back of the tongue so that our mouth is nearly isolated from the lower parts of the vocal tract. The combination of mouth cavity and small lip opening makes a resonator, and the air jet coming out through our lips makes it oscillate at its resonance frequency, rather like blowing across the top of an empty bottle. The sound is very nearly a pure tone, and we can raise its pitch by pushing the tongue forward and closing the jaw to decrease the mouth's volume.

Do birds do the same thing? It seems impossible, because they have beaks rather than lips, so how do they do it?

Perhaps the most puzzling birdsong is that of the ring dove, the call of which contains "coo" sounds that are very nearly pure tones with a frequency of about 600 Hz. The problem is that doves sing with their beaks closed!

Careful observation shows that the dove puffs up its neck when it is singing, so perhaps this has something to do with it. Careful anatomical measurements and X-ray observations of singing birds show that this puffed-up sac is actually the top part of the oesophagus, which leads to the stomach and joins the trachea near the base of the tongue (Fig. 2a). The sac is covered by a very thin layer of skin and is reasonably large, on the scale of the bird, so that once inflated it can contain quite a lot of exhaled breath.

Because the bird's beak is closed, no sound can come from there, but the walls of the sac are actually so thin that they vibrate like a miniature loudspeaker when the dove sings into the sac. When a calculation is made using the volume of the inflated sac and the mass of the walls, the resonance frequency is found to be just that characteristic of the "coo" song, and the sound will be loud if the bird sings at just this pitch. As the bird sings, this inflates the sac, but the effect of the increased volume is balanced by the fact that the stretched walls become thinner, so that the resonance frequency changes very little. This explains why the "coo" sound is fairly short, only as second or so, why it is nearly a pure tone, and why its pitch is constant. Doves have presumably evolved to use this singing strategy because it gives quite a loud song, which sounds very different from those of other birds.

So what about the birds that can sing

pure-tone songs with their beaks open, and can make their pitch sweep over as much as two octaves (a factor of four in frequency)? The bird we have studied recently is the northern cardinal, which lives in the eastern USA and has a striking scarlet crest and feathers. It also has an inflatable cavity between the top of the trachea and the gastric tract (Fig. 2b), but in this case its walls do not vibrate significantly because of the open beak and the higher frequency of the song. This bird, however, has muscles attached to small bones at the base of its tongue that can expand or contract the cavity just as it wishes, and this makes it an adjustable resonator in conjunction with the aperture out through the mouth and beak. The bird does not, however, rely upon any sort of whistle but sings a note at the exact pitch of the resonance, an exercise made easier by the action of the resonator back upon the vibrating vocal folds of the syrinx.

As well as pure-tone songs, other truly outstanding song characteristics belong to some Australian birds. Two that have attracted particular attention are the lyrebird, which can imitate the sound of almost any other bird and even some mechanical devices, and the sulphur-crested cockatoo, which surely has the loudest and most raucous shriek of any known bird, a characteristic that does not match its beauty but fits well with its destructive behaviour!

I am not aware of any studies of the acoustics of lyrebird behaviour, but it seems likely that its virtuoso performance is a matter of bird psychology rather than of different anatomy. I have studied the call of the cockatoo in some detail, however, and found it to be chaotic in the scientific sense. This means that it is not simply a random high-pitched noise, but is governed by very complex rules, like the motion of a flag flapping in the wind. The call is far from simply harmonic, but contains a broad band of frequencies with a maximum near 3000 Hz. This is close to the frequency at which human hearing is most sensitive, which explains part of the perceived loudness of the call, but the cockatoo does put a great deal of effort into its song so that it is physically loud as well.

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So there we have the story as it stands at present. Ornithologists studying the biological aspects of bird behaviour have amassed a great deal of detail about birdsong and bird anatomy for many different species. As a physicist and mathematician, I have collaborated with biologist colleagues in the USA and Europe in research on the particular birds described here. My colleagues study the anatomy and behaviour of the bird of interest, and I am able to devise simplified mathematical models that explain exactly how the whole system functions and that can predict the observed song with good accuracy.

To work out what is really going on in much of biological science requires this sort of collaboration between biologists and physicists, and in this way the whole complex structure can be progressively understood. In the case of birdsong, there are two motivations for this research. The first is simply curiosity about the way things work, but the second is that birds and birdsong provide important models for animal learning in general, since songbirds and parrots are among the few groups of vertebrates known to learn their songs.

Similar collaborations by other scientists on, for example, the sounds made by termites, echolocation by bats and the vision of honeybees, are already leading to valuable applications. In many cases the application does not become apparent until the work has been completed, so the future for birdsong is yet unsung.

After 20 years as professor of physics at the University of New England and 5 years as director of the CSIRO Institute of Physical Sciences, Neville Fletcher is now a visiting fellow in the Research School of Physical Sciences and Engineering at the Australian National University.