Behavior as the result of an interaction between the nervous system and biomechanics

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Laboratorio de sistemas dinamicos

Laboratorio de Sistemas Dinámicos

Behavior emerges from the interaction of a nervous system, a biomechanical periphery and the environment.

We are interested in how the biomechanics (and its nonlinearities) conditions some behaviors.

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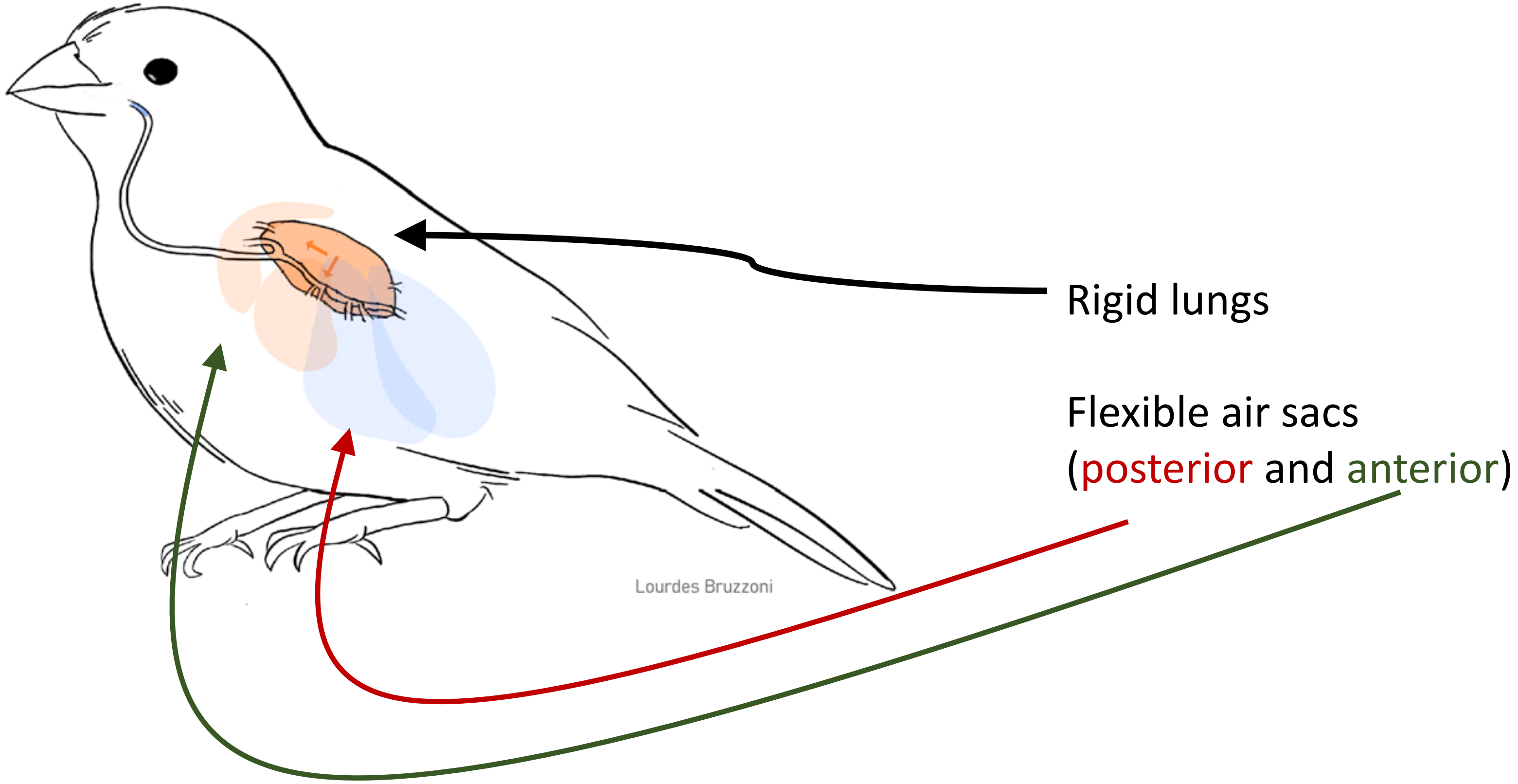
Behavior emerges from the interaction of a nervous system, a biomechanical periphery and the environment.

Two examples of temporal scales conditioned by biomechanics

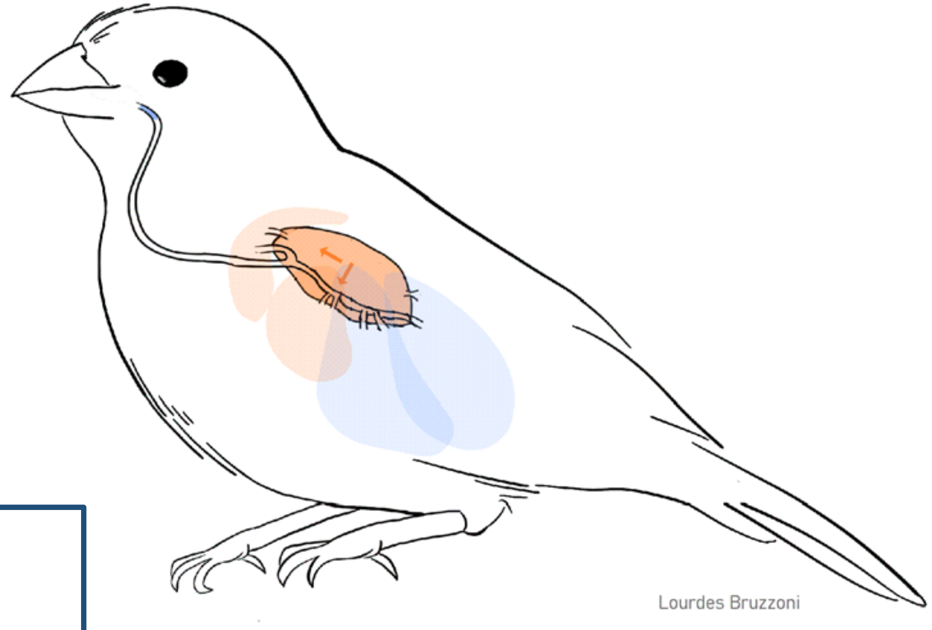
1. At which rates do birds breathe? (syllabic frequencies)

2. How much of the acoustics is determined by the brain, and how much by the biomechanics? (sound frequencies)

First example: the avian respiratory system



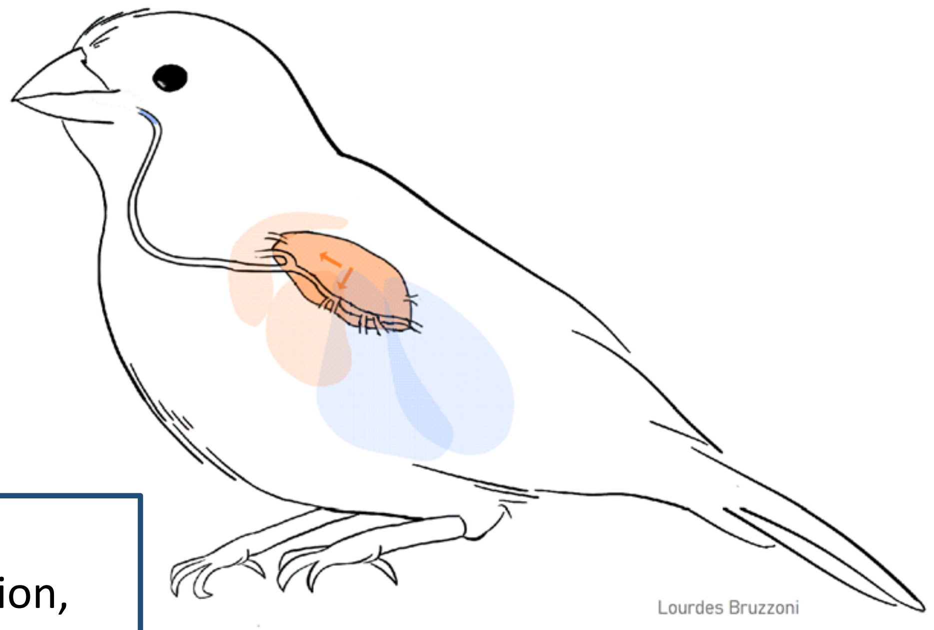
The avian respiratory system



The complete circulation of air throughout the respiratory system takes two motor cycles.

The gif shows the states of two "puffs" of air: the "brown" and the "blue"

The avian respiratory system

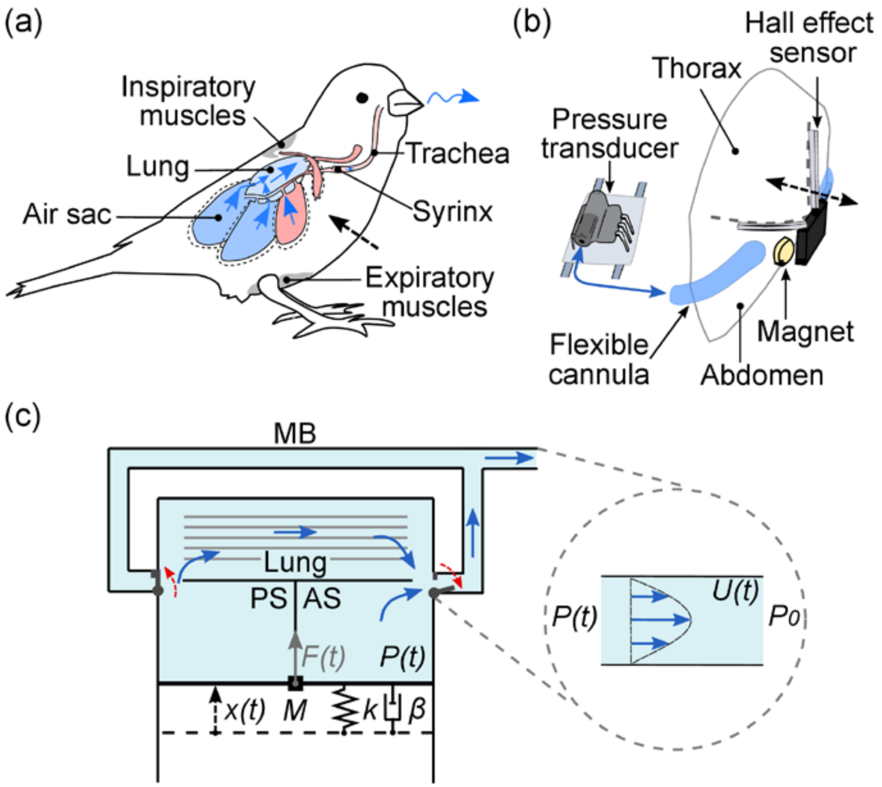


This mechanism guarantees oxygenated air flowing through the lungs.

In the first expansion, air enters the posterior sacs. In the first contraction, the air in the anterior sac is sent to the lungs.

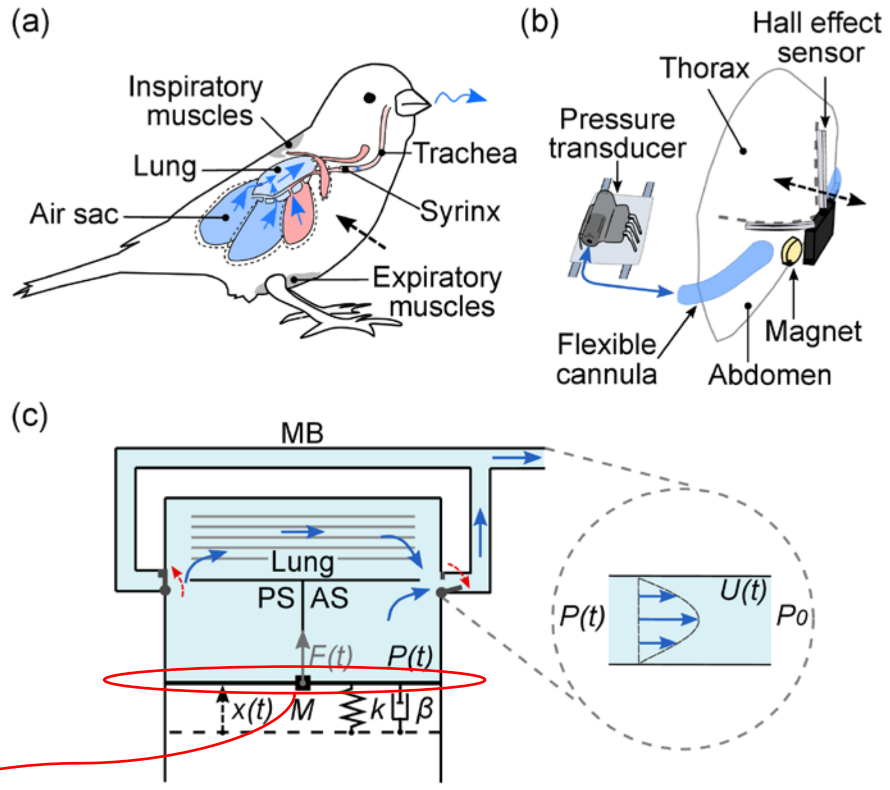
In the second expansion, the air in the lungs is sent to the anterior sacs, and in the second contraction the air in the anterior sacs is expelled.

A model for the aviar respiratory system and the measurement of its variables



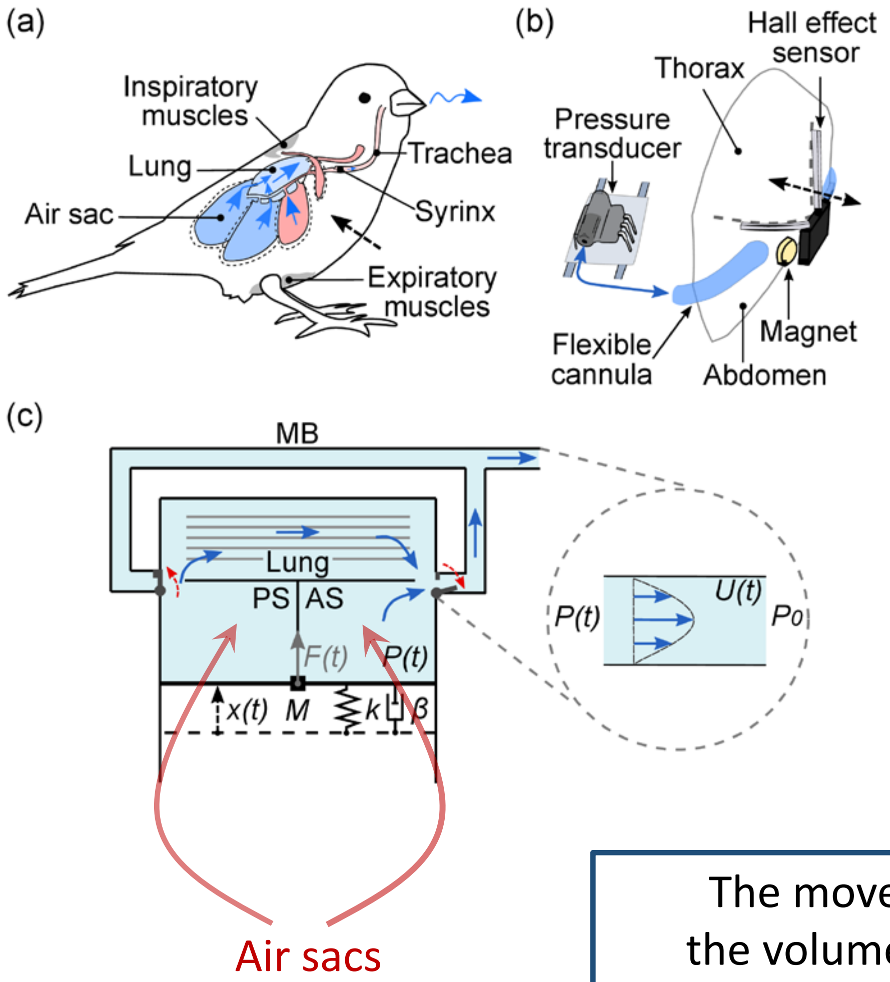
A cylinder with three subdivisions: the lung, and the two air sacs

A model for the aviar respiratory system



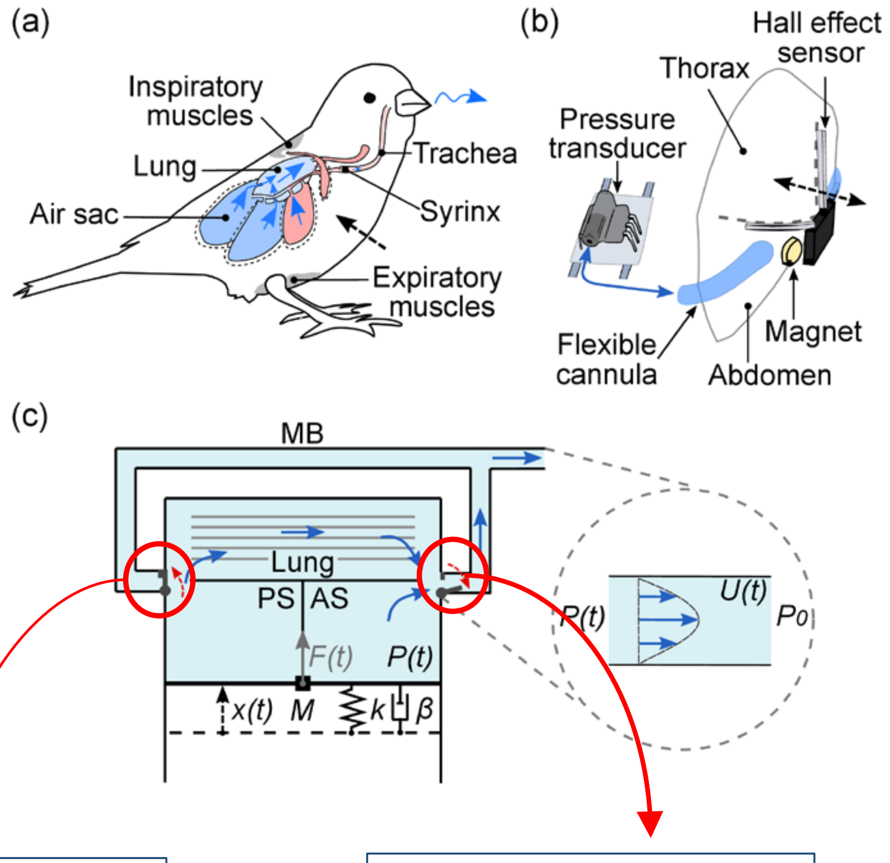
the piston represents the sternum,
the rib cage and the overlying muscles

A model for the aviar respiratory system



The movement of the piston changes the volume of two of the three cavities, representing the anterior and posterior air sacs

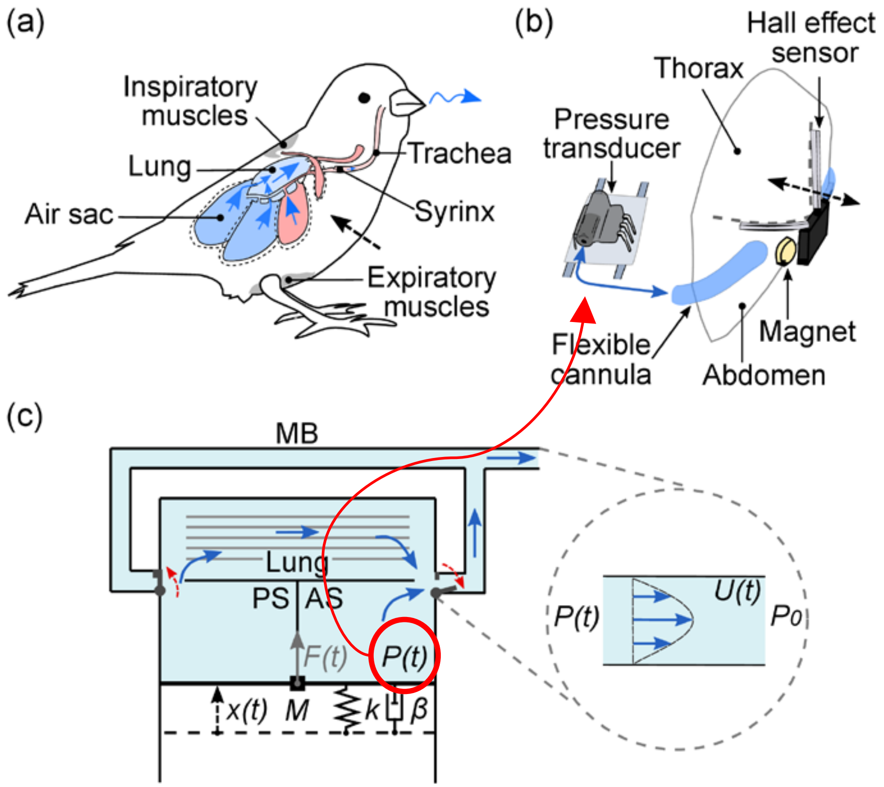
A model for the aviar respiratory system



Aerodynamic valve 1 (air flows in, only)

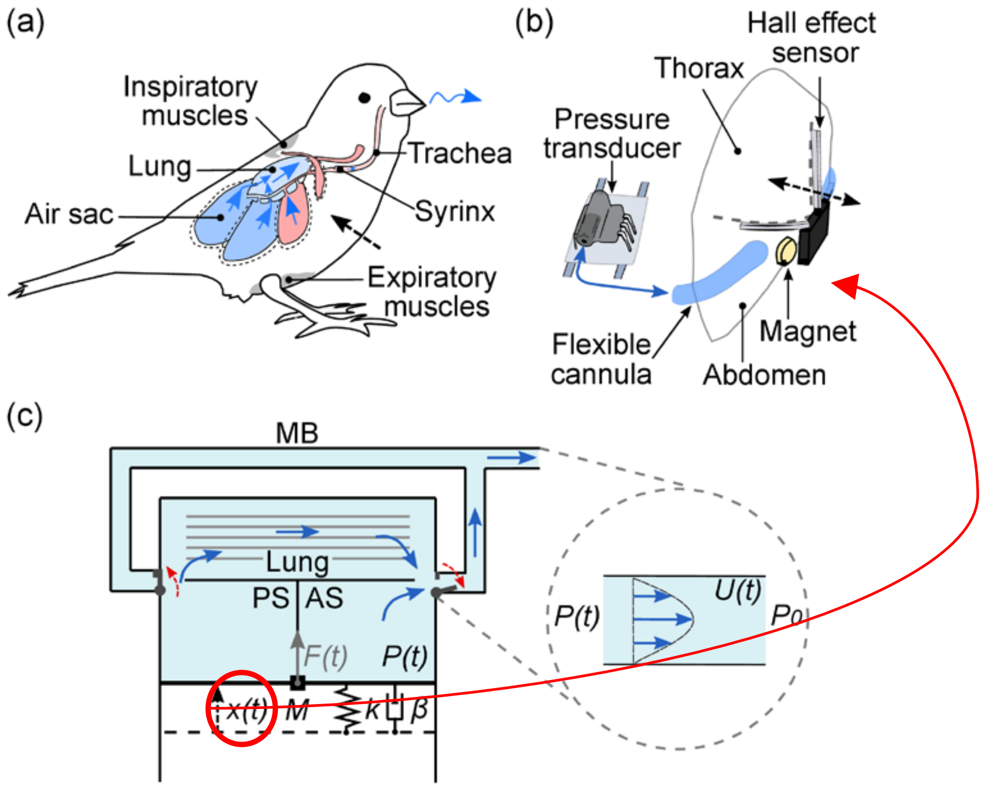
Aerodynamic valve 2 (air flows out, only)

A model for the aviar respiratory system



We measure the pressure
in the air sacs with a pressure transducer

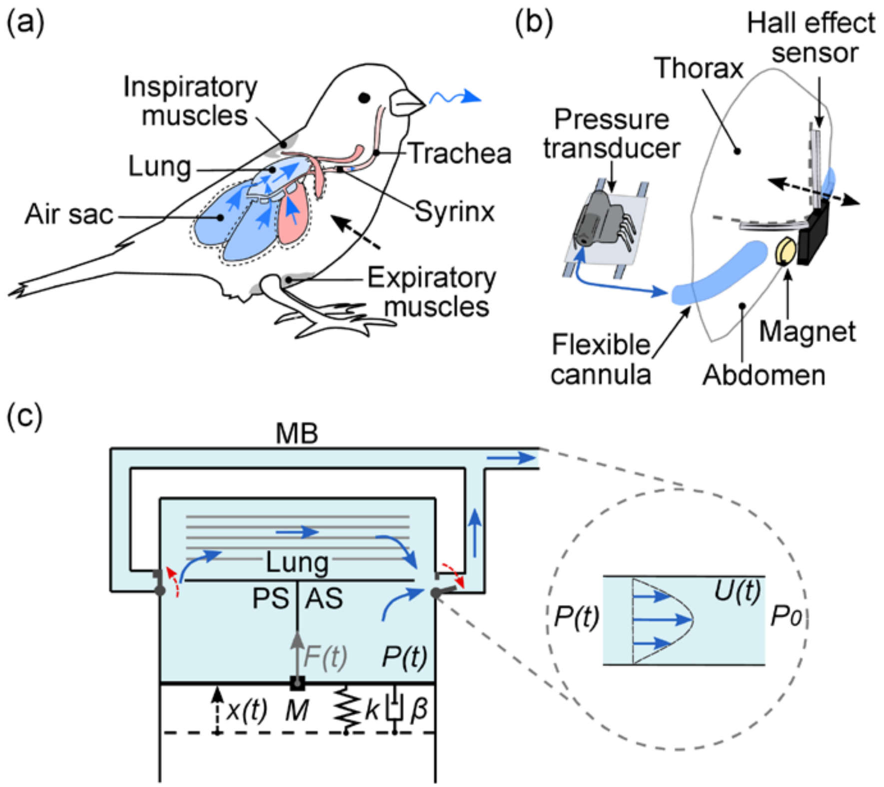
A model for the aviar respiratory system



We measure the volume variations with a small magnet and a Hall transducer

The dynamics of the piston

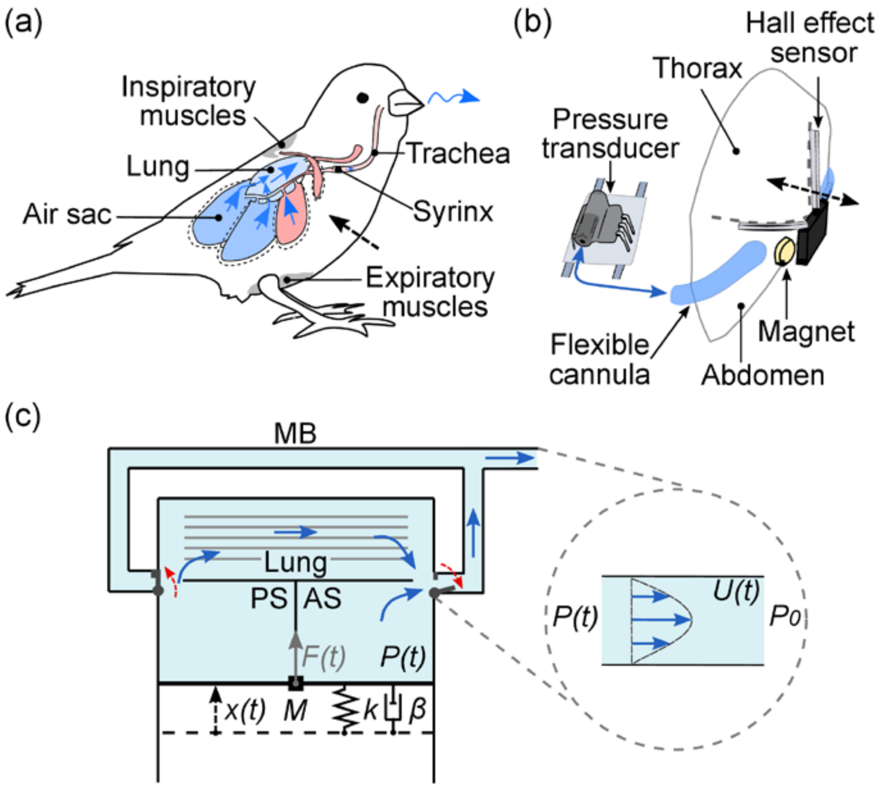
$$M\frac{d^2x(t)}{dt^2} = -kx(t) - \beta\frac{dx(t)}{dt} - A(P(t) - P_0) + F(t).$$



where

$F(t)$ Accounts for the forces made by expiratory and inspiratory muscles

$$M\frac{d^2x(t)}{dt^2} = -kx(t) - \beta\frac{dx(t)}{dt} - A(P(t) - P_0) + F(t).$$



State equations to relate pressure with the geometric variable *x*

$$\begin{cases} P\,V = Nk_BT \\ V(t) = V_0 - Ax(t) \\ dN = -\rho U dt \approx -\rho_0 U dt, \\ U = \left(\alpha_{ps} - (\alpha_{ps} - \alpha_{as})S(\Delta P)\right)\Delta P(t), \end{cases}$$

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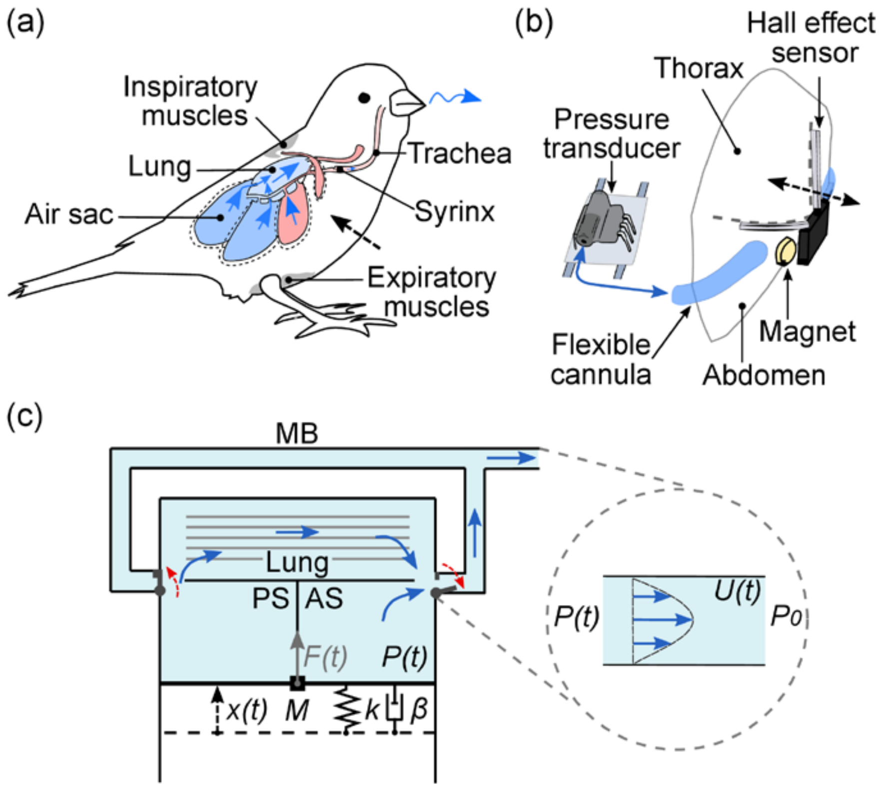

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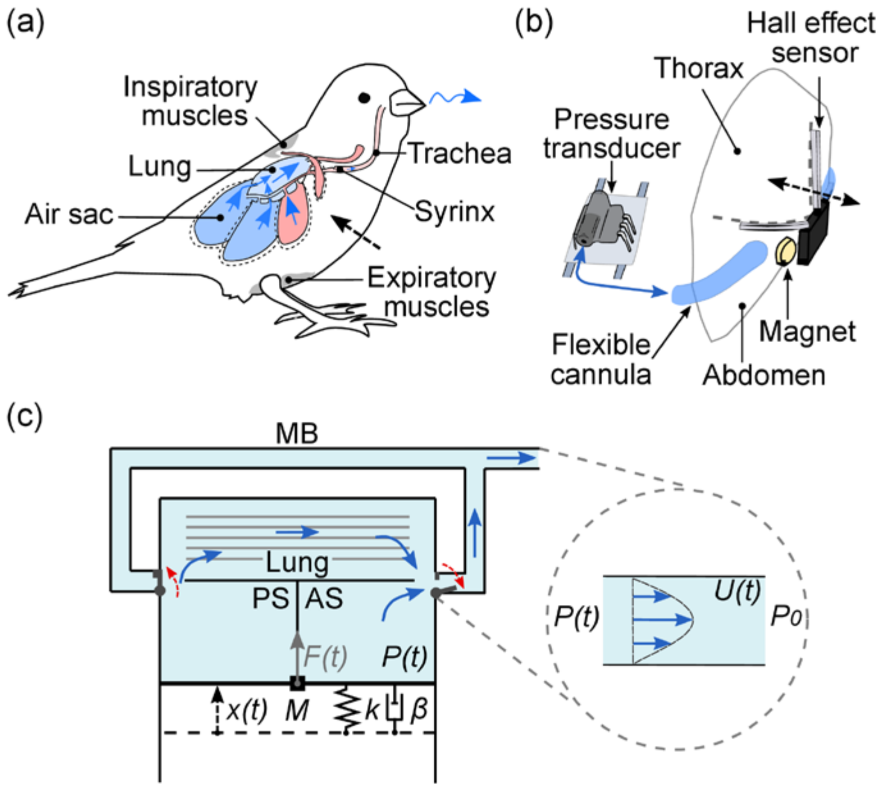
Sigmoideal function

The relationship between U and P depends on the aperture of the valves, and in different regimes α_{ps} and α_{ps} can be equal or different.

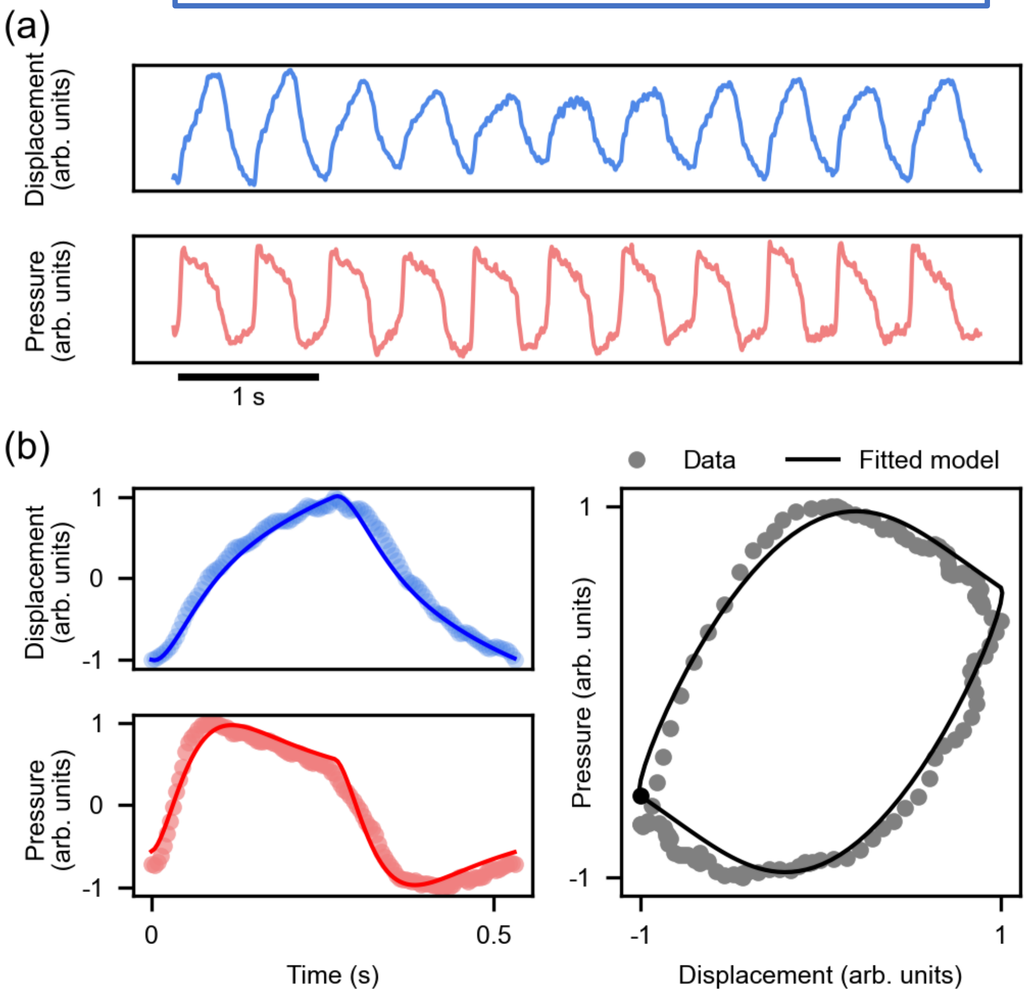
$$M\frac{d^2x(t)}{dt^2} = -kx(t) - \beta\frac{dx(t)}{dt} - A(P(t) - P_0) + F(t).$$



$$\begin{cases} P\,V = Nk_BT \\ V(t) = V_0 - Ax(t) \\ dN = -\rho U dt \approx -\rho_0 U dt, \\ U = \left(\alpha_{ps} - (\alpha_{ps} - \alpha_{as})S(\Delta P)\right)\Delta P(t), \end{cases}$$

$$\frac{d(\Delta P(t))}{dt} = \frac{P_0}{V_0}A\frac{dx(t)}{dt} - \frac{P_0}{V_0}\left(\alpha_{ps} - (\alpha_{ps} - \alpha_{as})S(\Delta P)\right)\Delta P(t).$$

Measurements during quiet respiration



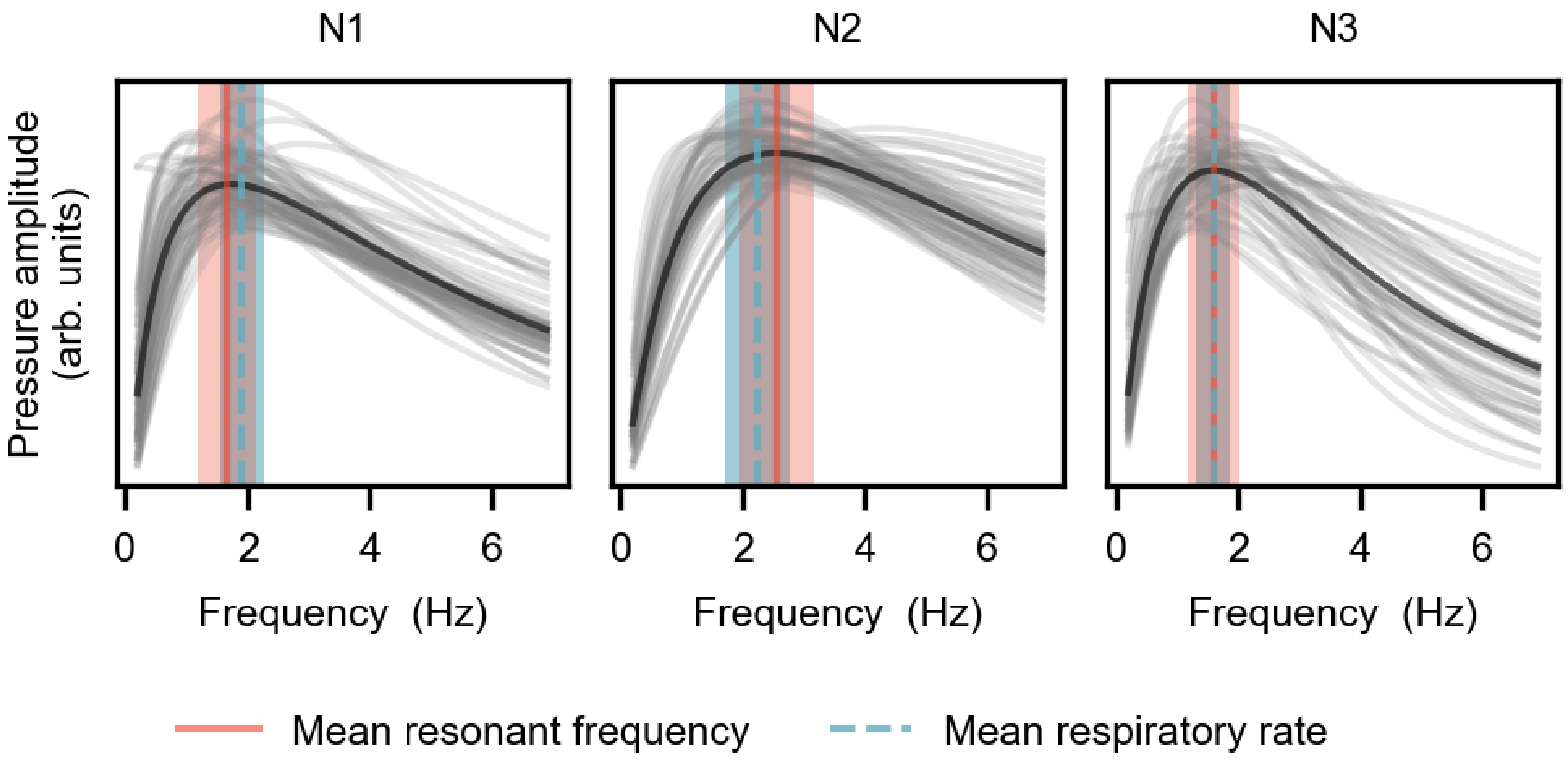
$$\alpha_{as} \approx \alpha_{ps} \equiv \alpha$$

$$\frac{dx}{dt} = y$$

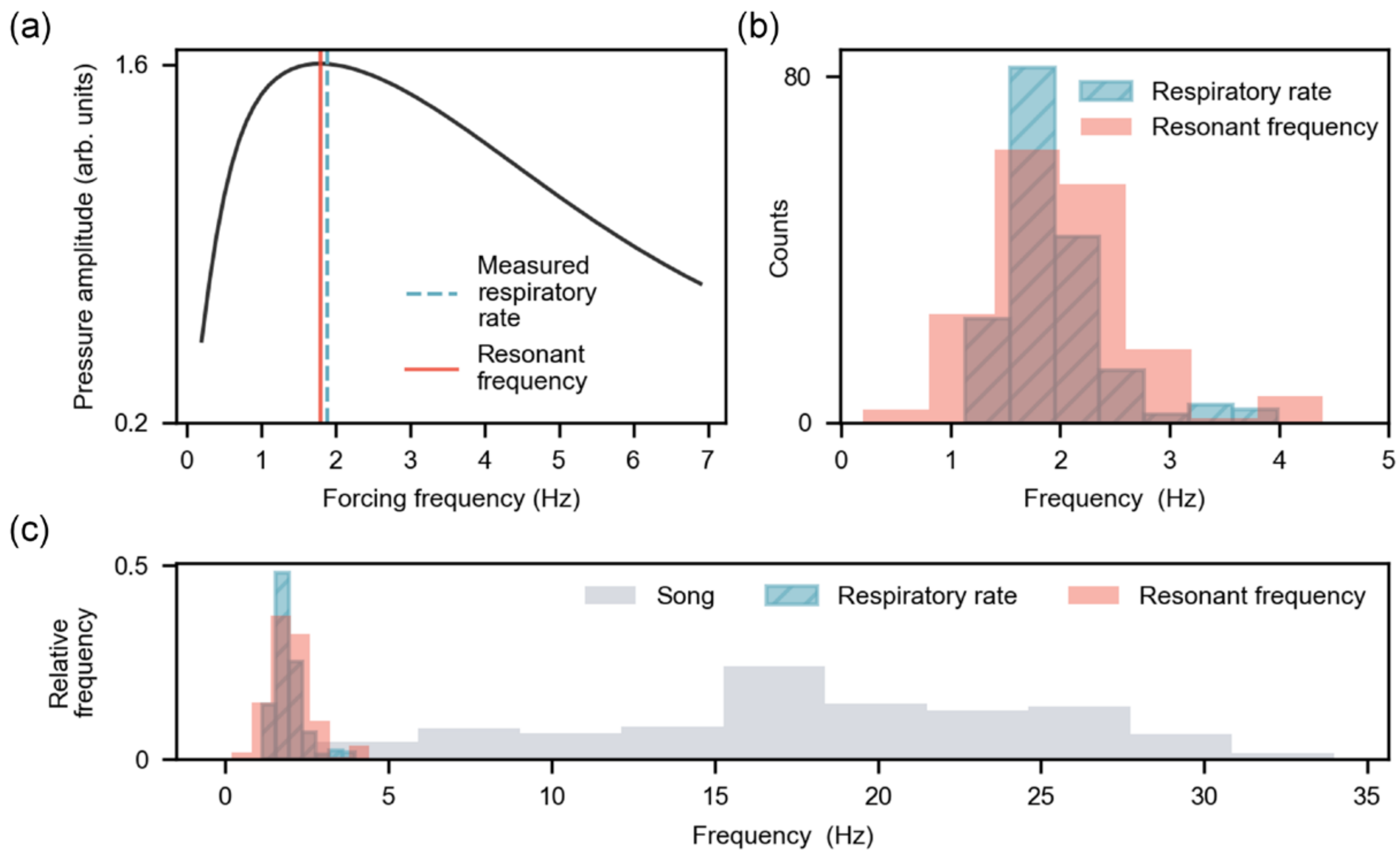
$$\frac{dy}{dt} = Bx + Cy + Dp + Ef(t)$$

$$\frac{dp}{dt} = Fy + Gp$$

$$(B, C, D, E, F, G) = \left(-\frac{k}{M}, -\frac{\beta}{M}, -\frac{A}{M}, \frac{f_0}{M}, \frac{P_0}{V_0}A, -\frac{P_0}{V_0}\alpha\right).$$

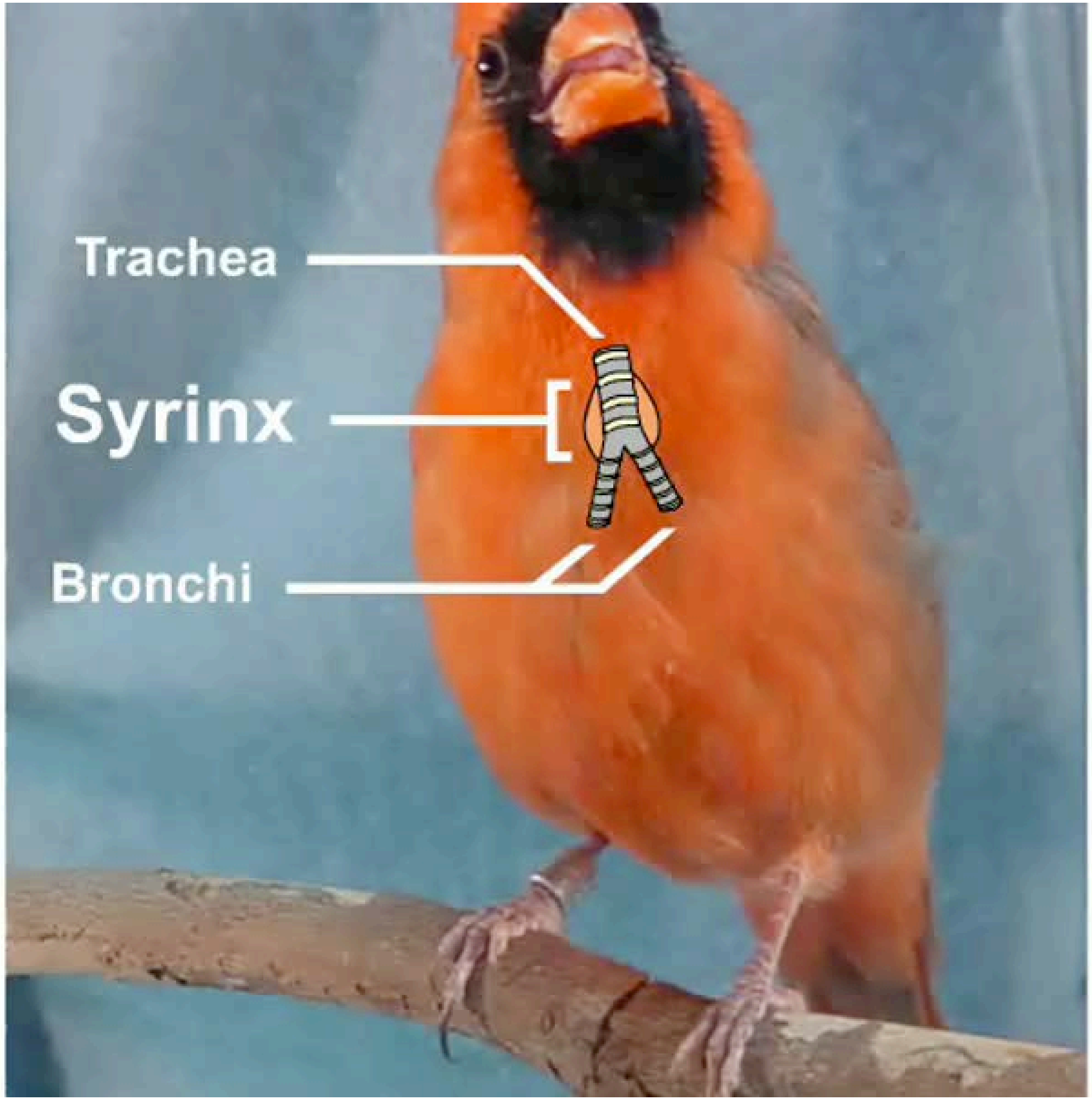


N1
N2
N3
Pressure amplitude
(arb. units)
0
2
4
6
Frequency (Hz)
Mean resonant frequency
Mean respiratory rate

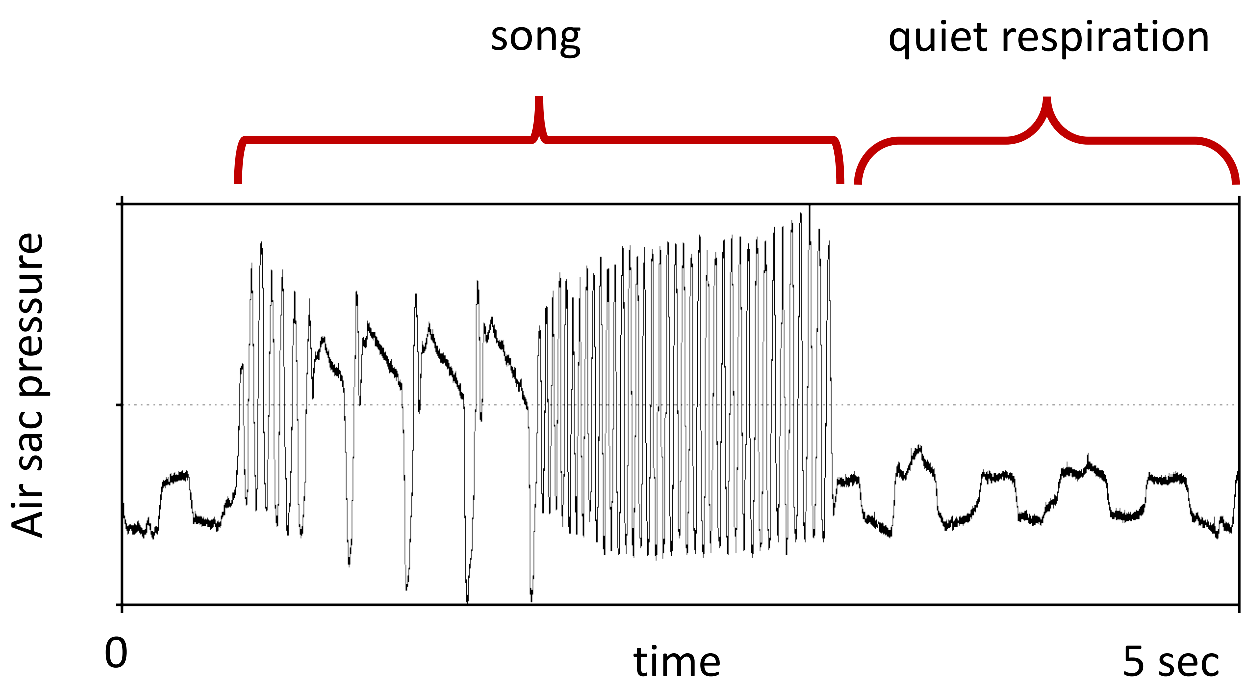


We fitted the biomechanics, and the model displays resonances …
at the breathing frequency

What happens in the body, during singing?



As seen in the movie, the singing requires pressing the labia against each other, increasing the labial resistance

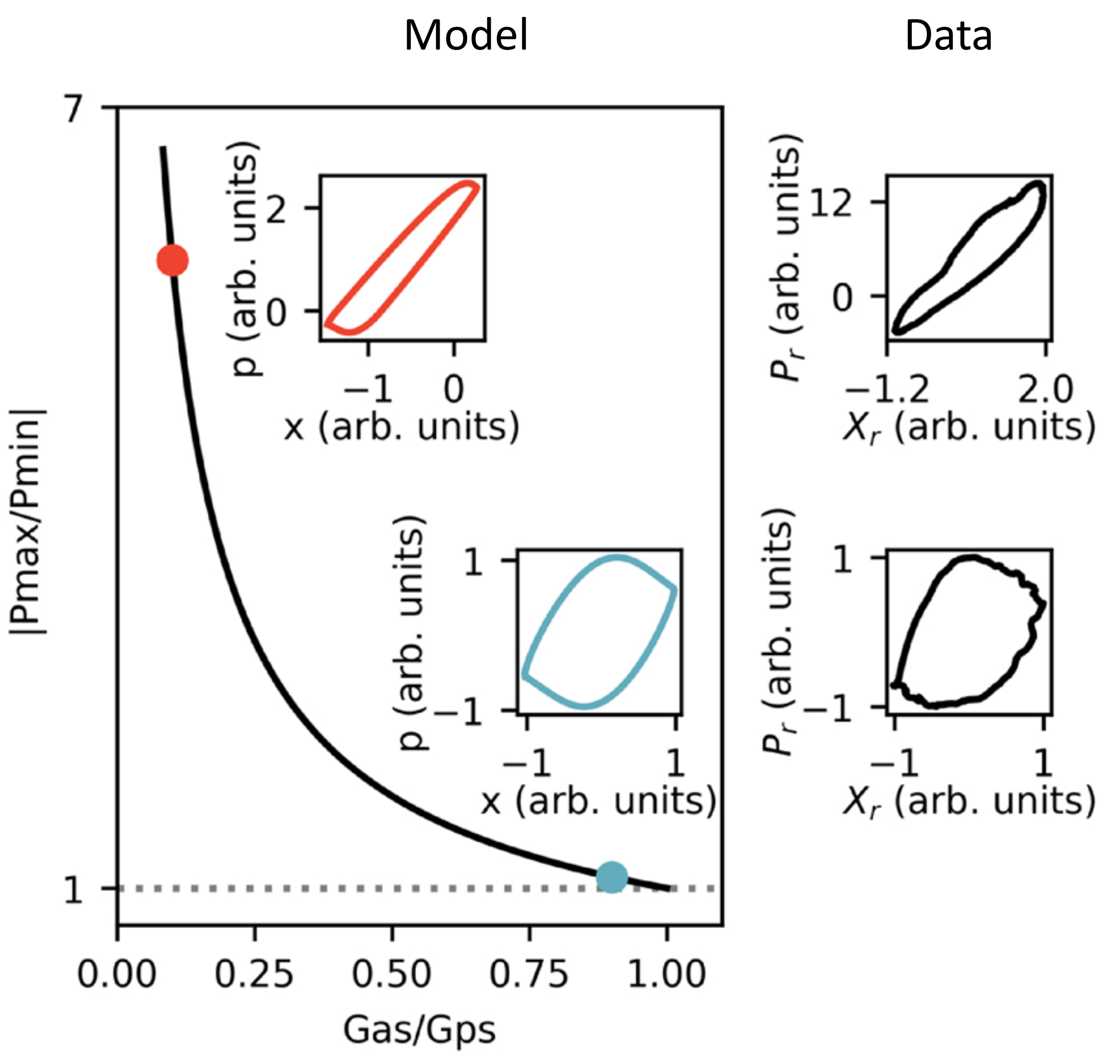


Syringeal valve very Small during expiration

open valves

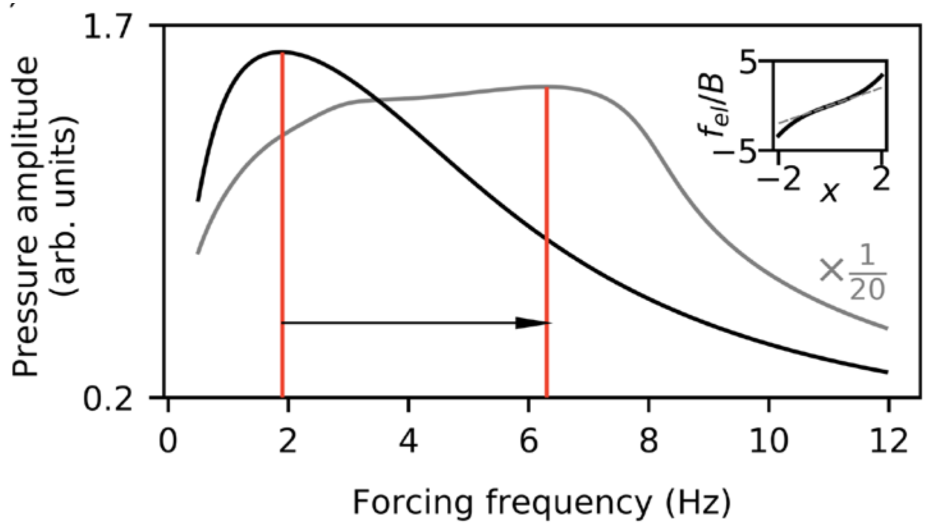
A first prediction for singing: the asymmetry of the respiratory gesture

A second prediction, the phase difference between the two variables will be smaller during singing



To study resonances in the singing regime, we observe that for higher forcing, the elastic term is no longer linear

Considering the nonlinear restitution



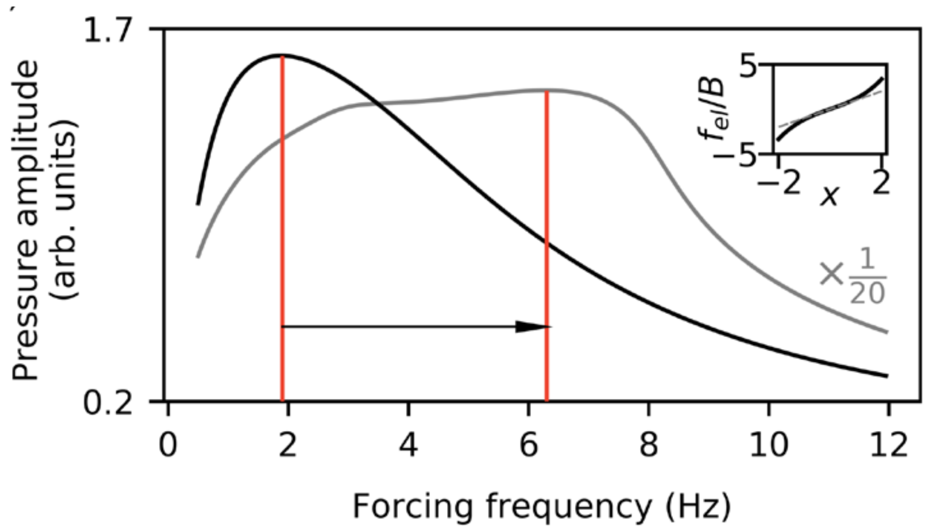
$$\begin{cases} \dfrac{dx}{dt} = y \\ \dfrac{dy}{dt} = Bx + Cy + Dp + Ef(t) \\ \dfrac{dp}{dt} = Fy + \left(G_{ps} - \left(G_{ps} - G_{as}\right)S(\Delta P)\right)p \end{cases}$$

$$f_{el}(x) = B\left(1 + \varepsilon x^2\right)x$$

And the resonances do shift towards higher values.

That means, not only birds do breathe at resonances; they might sing at resonances as well

Considering the nonlinear restitution

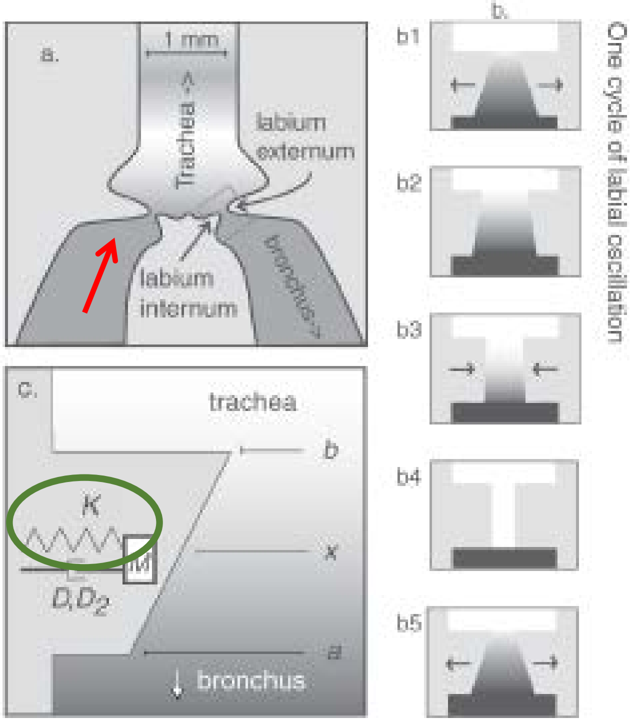


$$\begin{cases} \dfrac{dx}{dt} = y \\ \dfrac{dy}{dt} = Bx + Cy + Dp + Ef(t) \\ \dfrac{dp}{dt} = Fy + \left(G_{ps} - \left(G_{ps} - G_{as}\right)S(\Delta P)\right)p \end{cases}$$

$$f_{el}(x) = B\left(1 + \varepsilon x^2\right) x$$

Second example: sound frequencies in birdsong

On Monday I presented a simple model of birdsong production

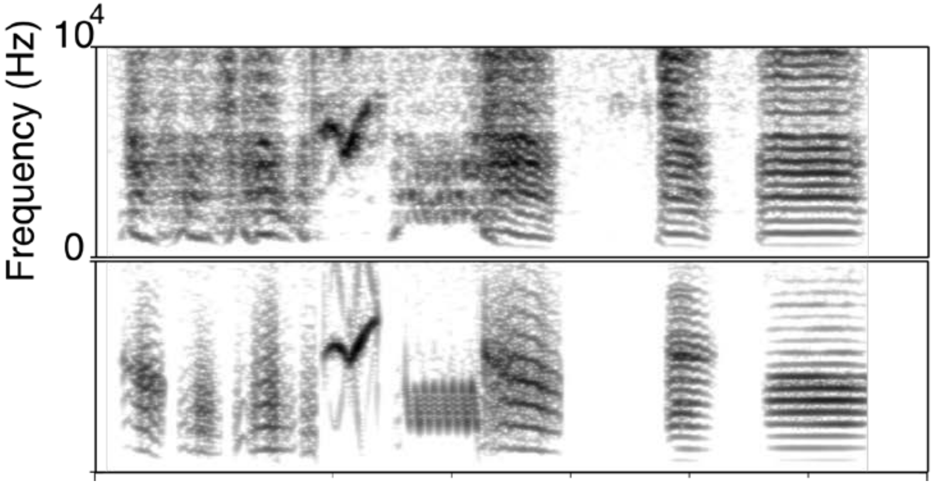


$$\frac{dx}{dt} = y,$$

$$\frac{dy}{dt} = (1/m)\left[-k(x)x - b(y)y - cx^2 y + a_{lab} p_s \left(\frac{\Delta a + 2\tau\tau}{a_{01} + x + \tau y} \right) \right].$$

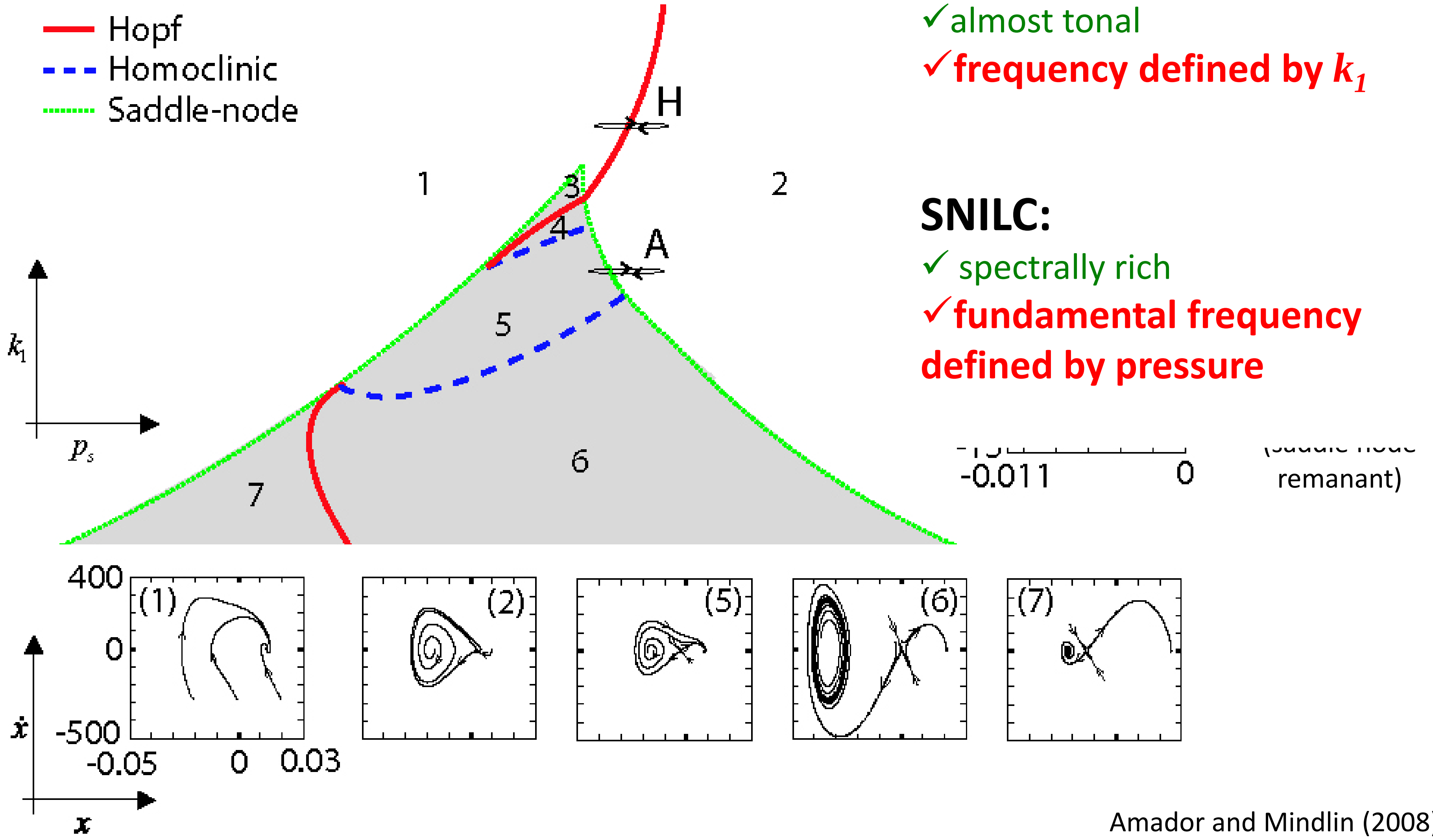
Tension

Pressure



The model allowed generating quite realistic sounds

Dynamical analysis of the model



Hopf:

✓almost tonal

✓**frequency defined by k_1**

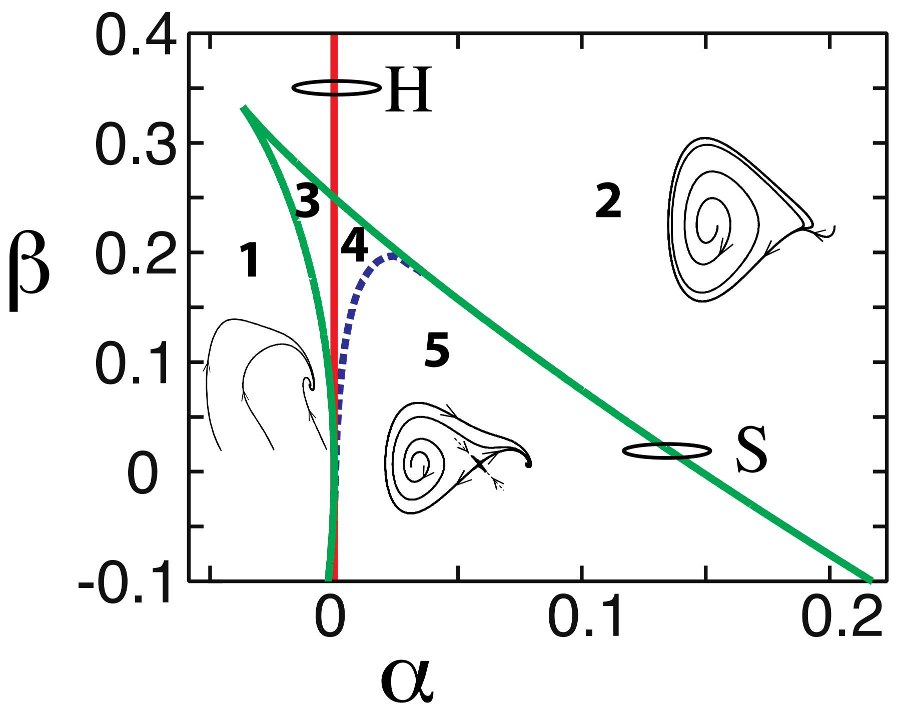
SNILC:

✓ spectrally rich

✓**fundamental frequency defined by pressure**

Amador and Mindlin (2008)

The relationship between these acoustic features depends on the dynamics: the normal form* captures the relevant aspects of the problem

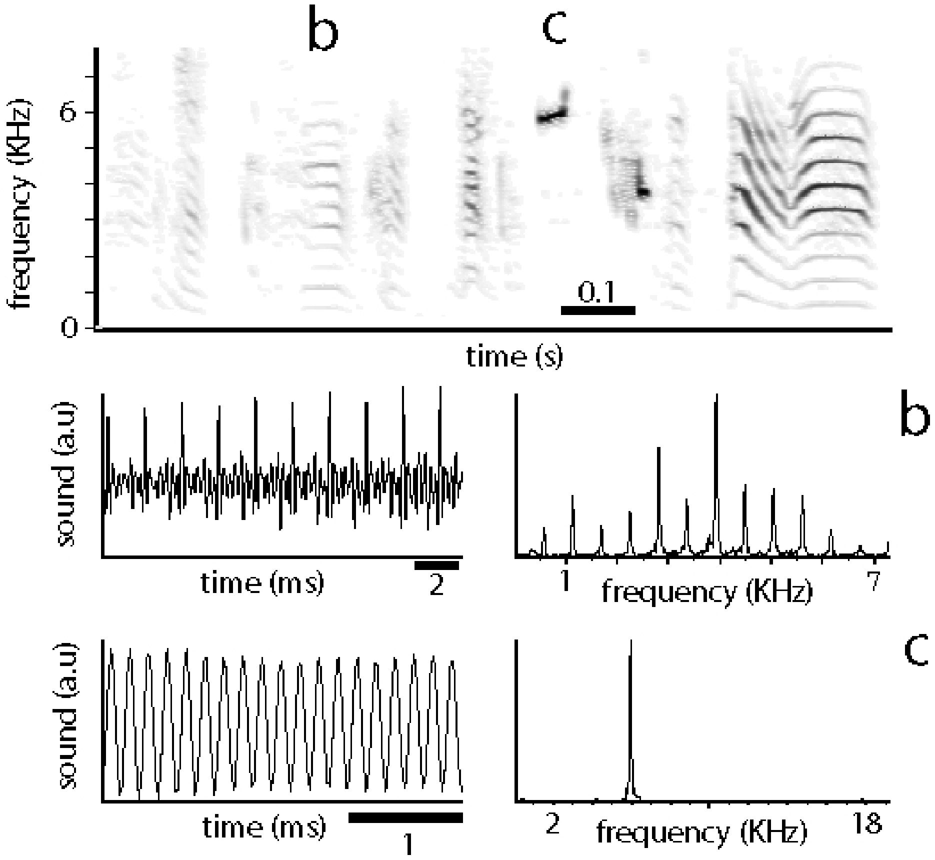


$$\frac{dx}{dt} = y$$

$$\frac{dy}{dt} = -\alpha(t)\gamma^2 - \beta(t)\gamma^2 x - \gamma^2 x^3 - \gamma x^2 y + \gamma^2 x^2 - \gamma x y$$

*** Normal form reduction**
Algorithmic procedure that
Allows to obtain the simplest
Dynamical system with
equivalent dynamics

Why should we care about different bifurcation types?



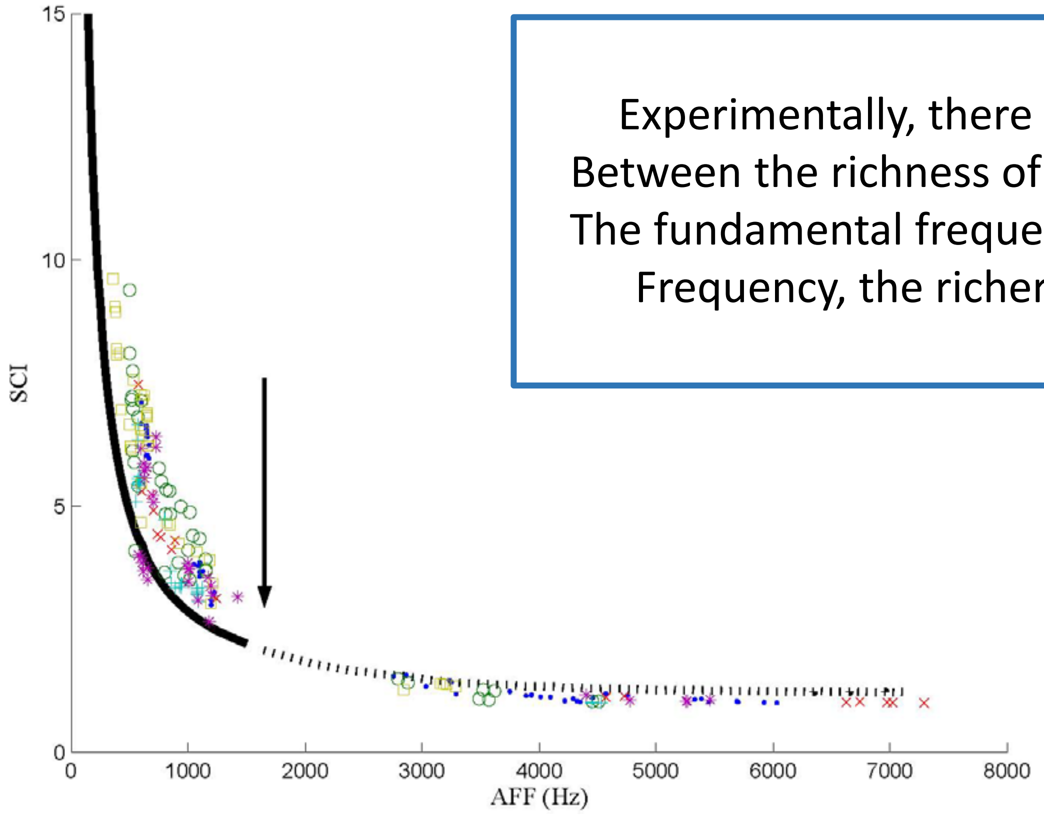
Zebra finch song

Spectrally rich notes

Almost tonal notes

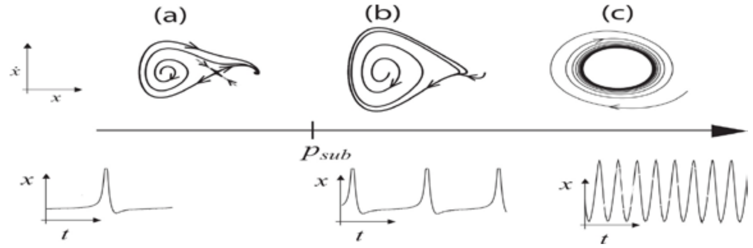
The spectral Index Content (SCI) is defined to Reflect how the energy is distributed in the spectrum compared to the energy in the Fundamental frequency component

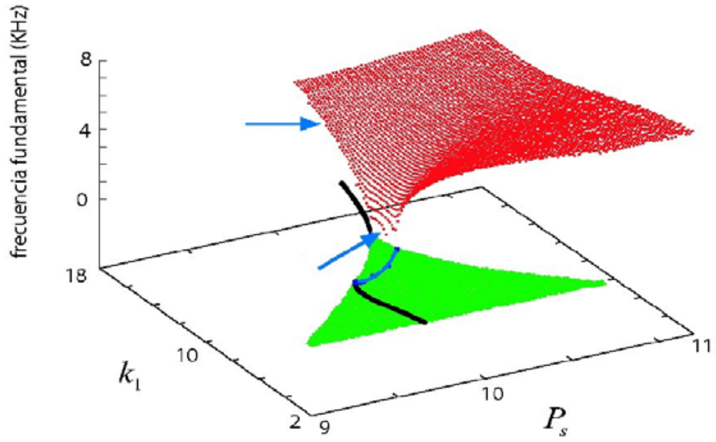
$$SCI = \left(\sum_i \omega_i \varepsilon_i / E\right) \Big/ AFF$$

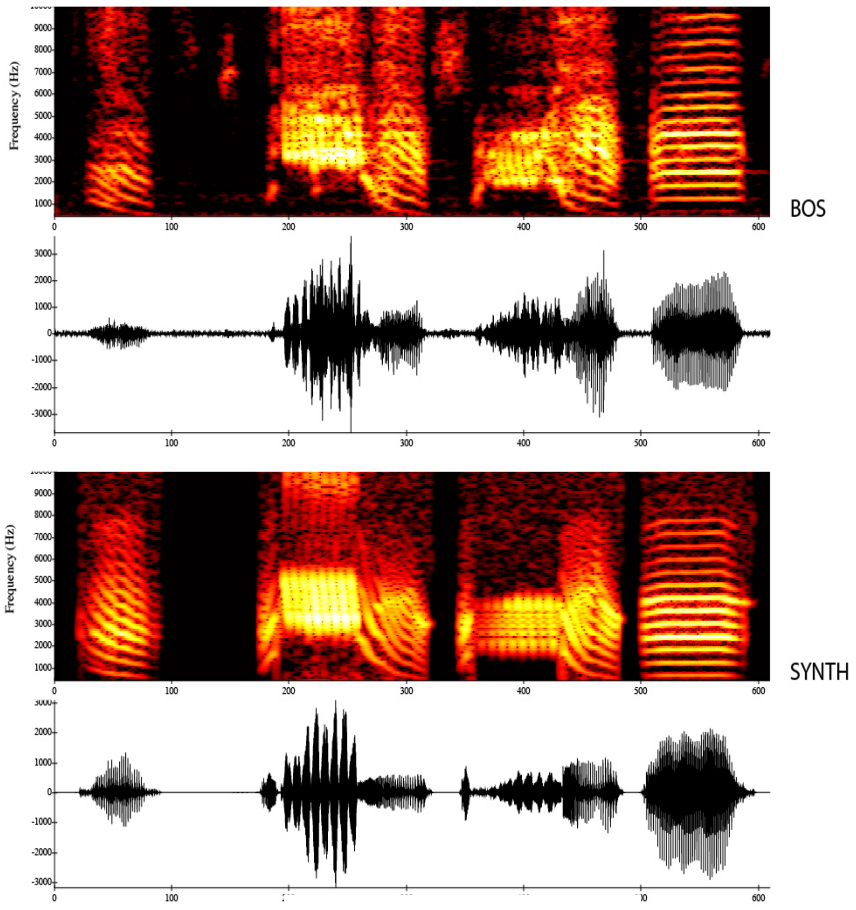


Experimentally, there is a relationship Between the richness of the spectrum and The fundamental frequency: the lower the Frequency, the richer the spectrum.

Signature of a snilc?







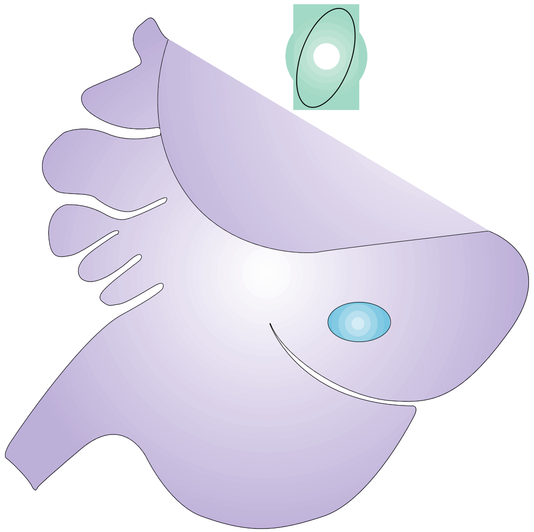
sonido sintetico

Testing the model

In order to estimate the relevance of this work, we used neurophysiological measurements

Neural selectivity in HVC

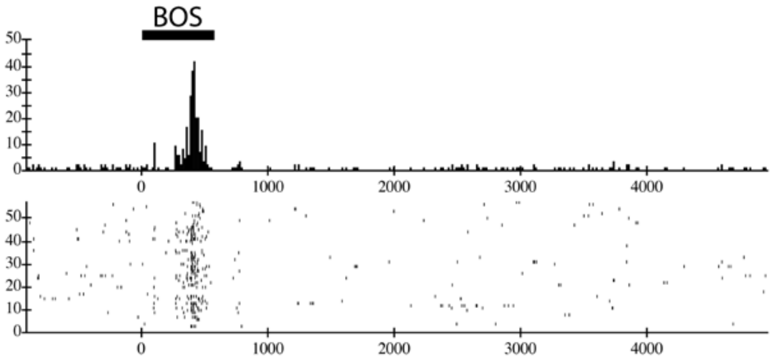
Neurons in HVC respond to the auditory presentation of the bird's own song (BOS) with a distinctive pattern. No other auditory stimulus elicits any response.

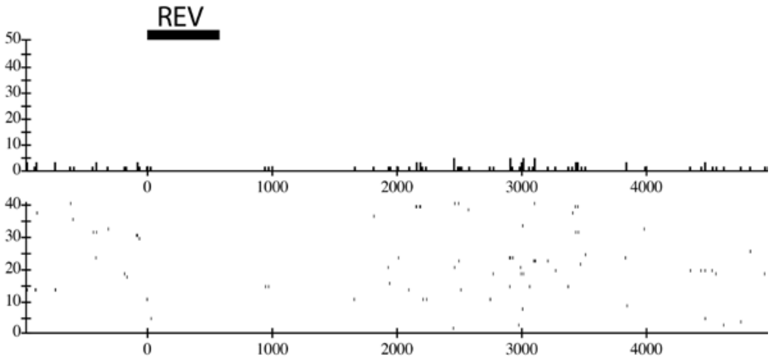


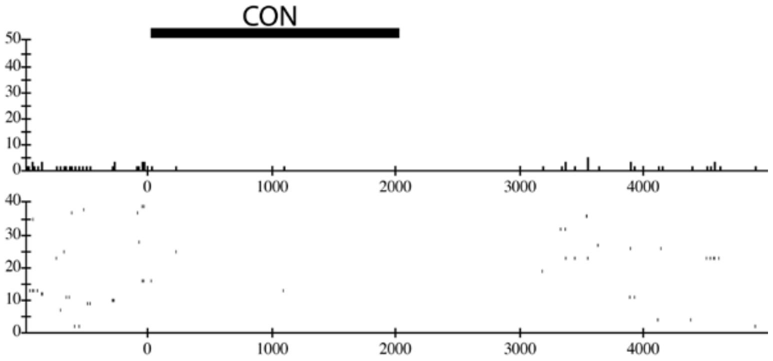
Dan Margoliash, priv.

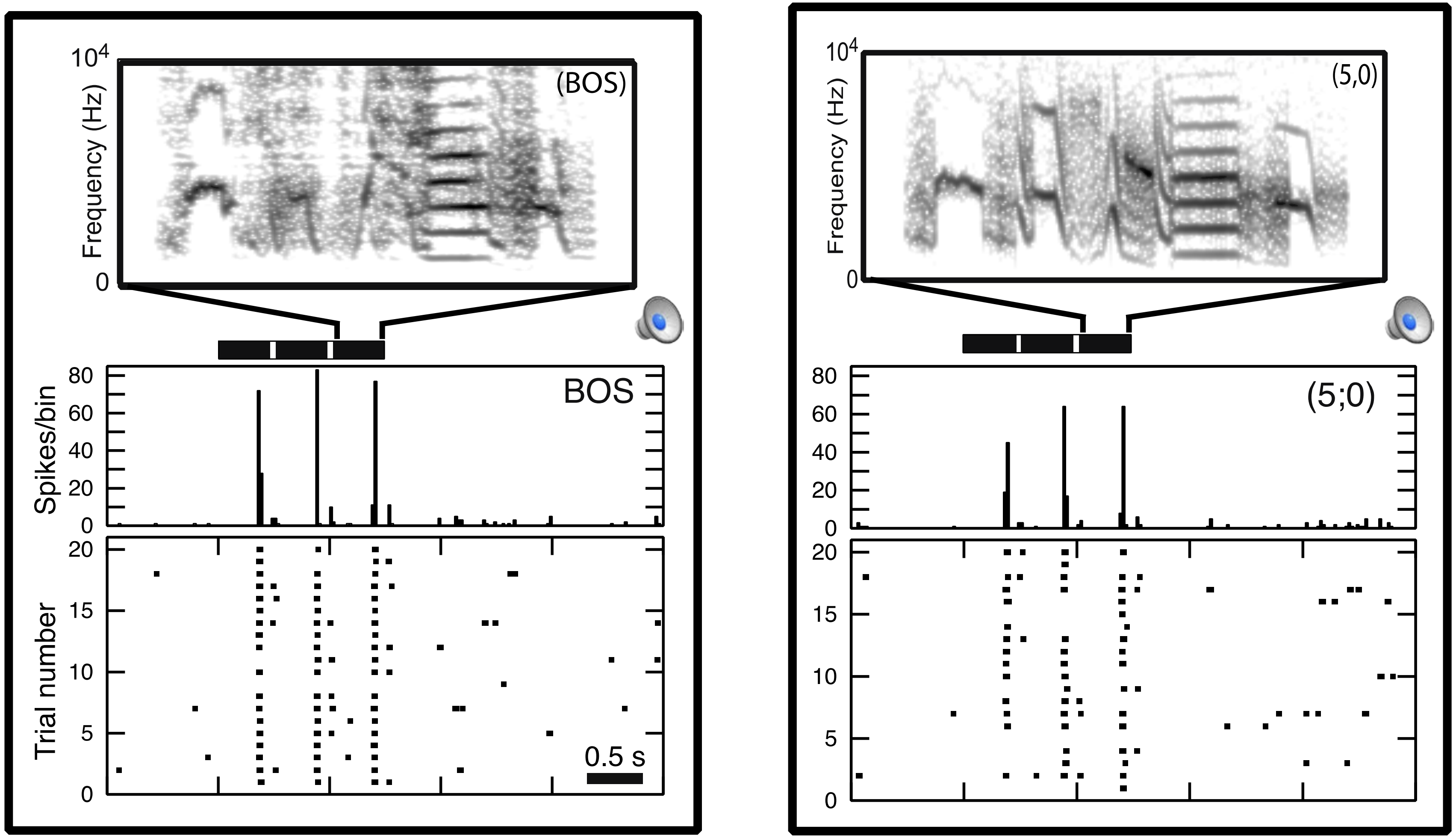
Testing the model

Neurons in HVC respond selectively to the bird's own song (BOS)



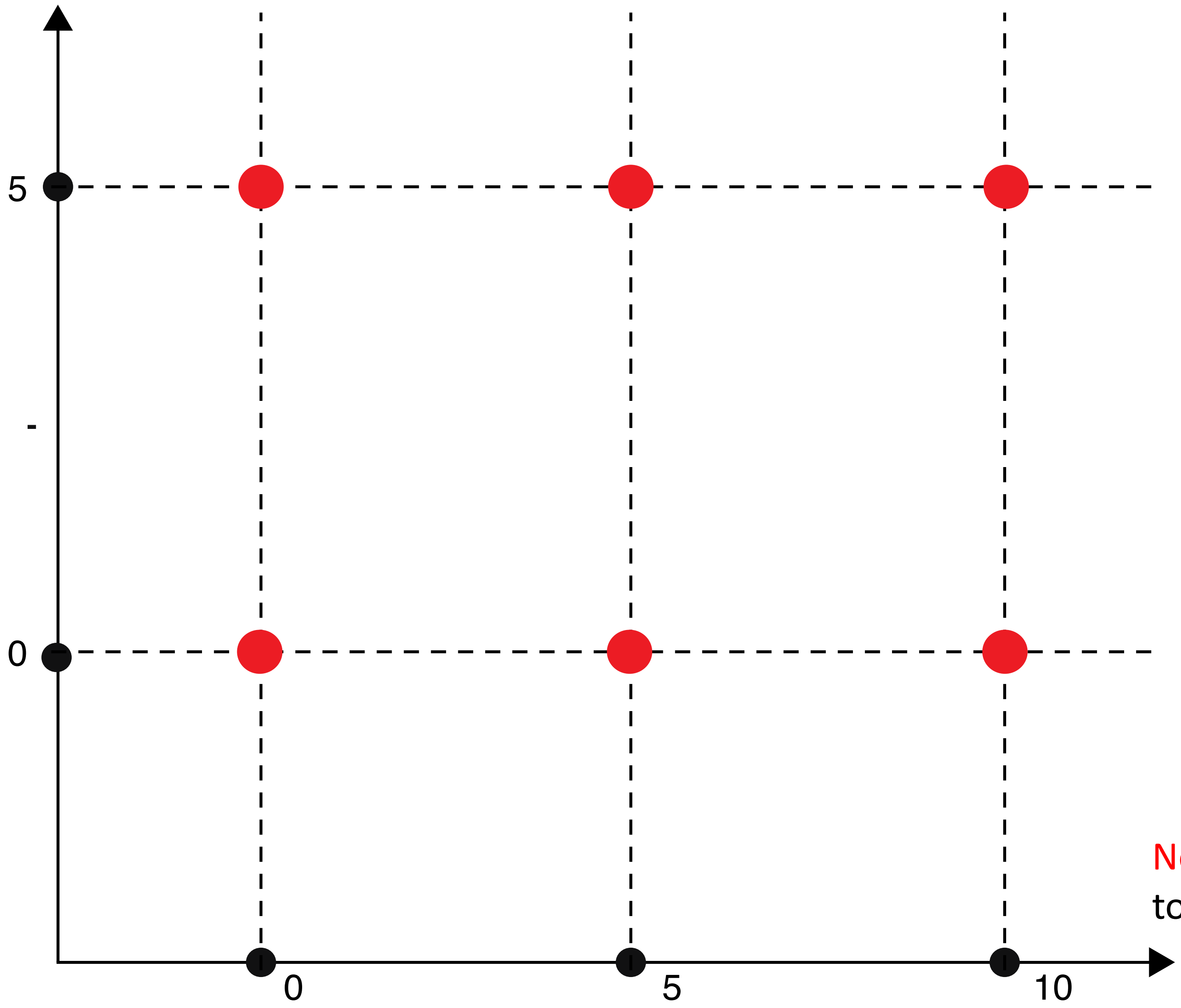






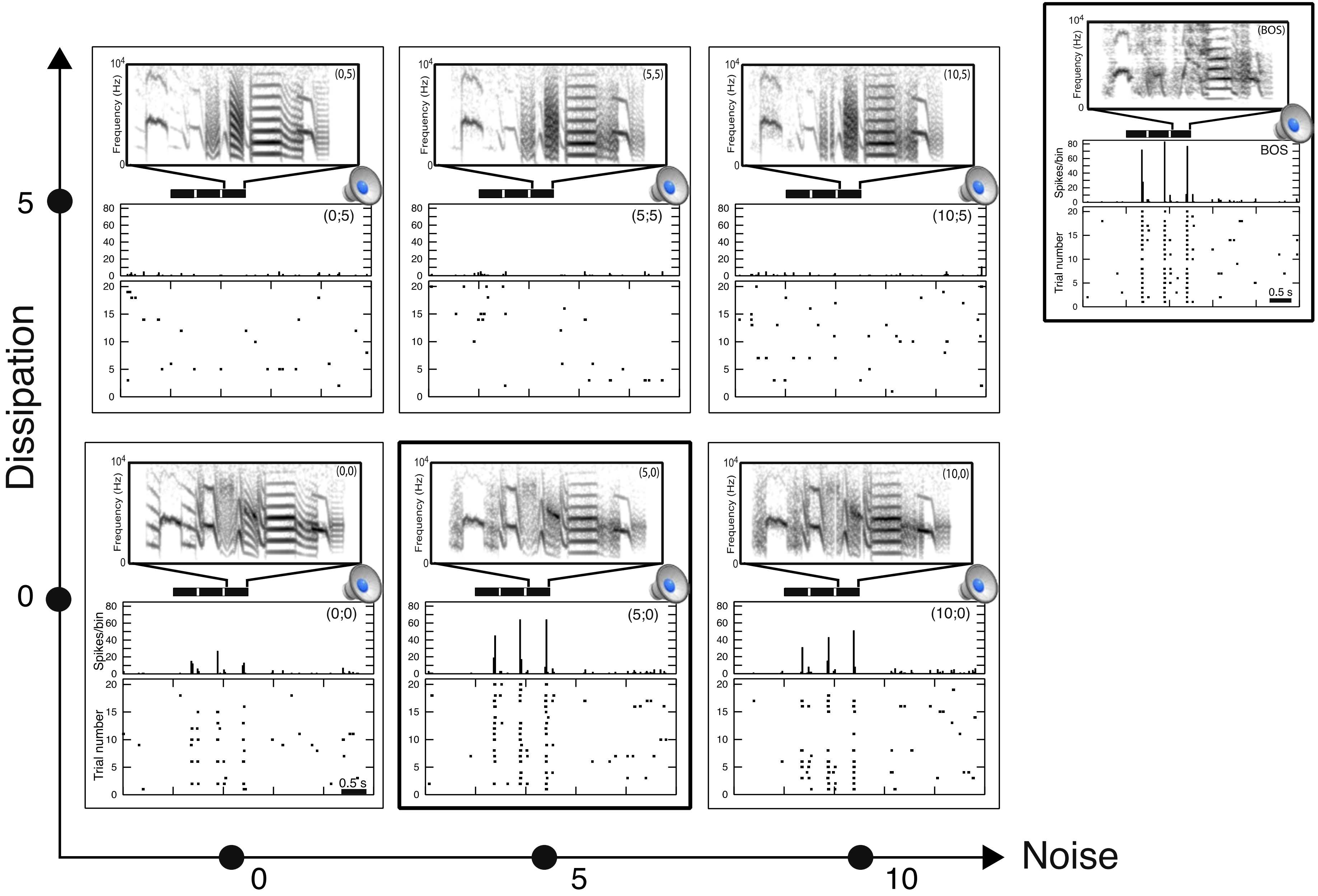
The synthetic song elicits the same neural response than the bird's own song

Dissipation of the oropharingeal cavity: increasing dissipation => decreasing presence of the cavity.



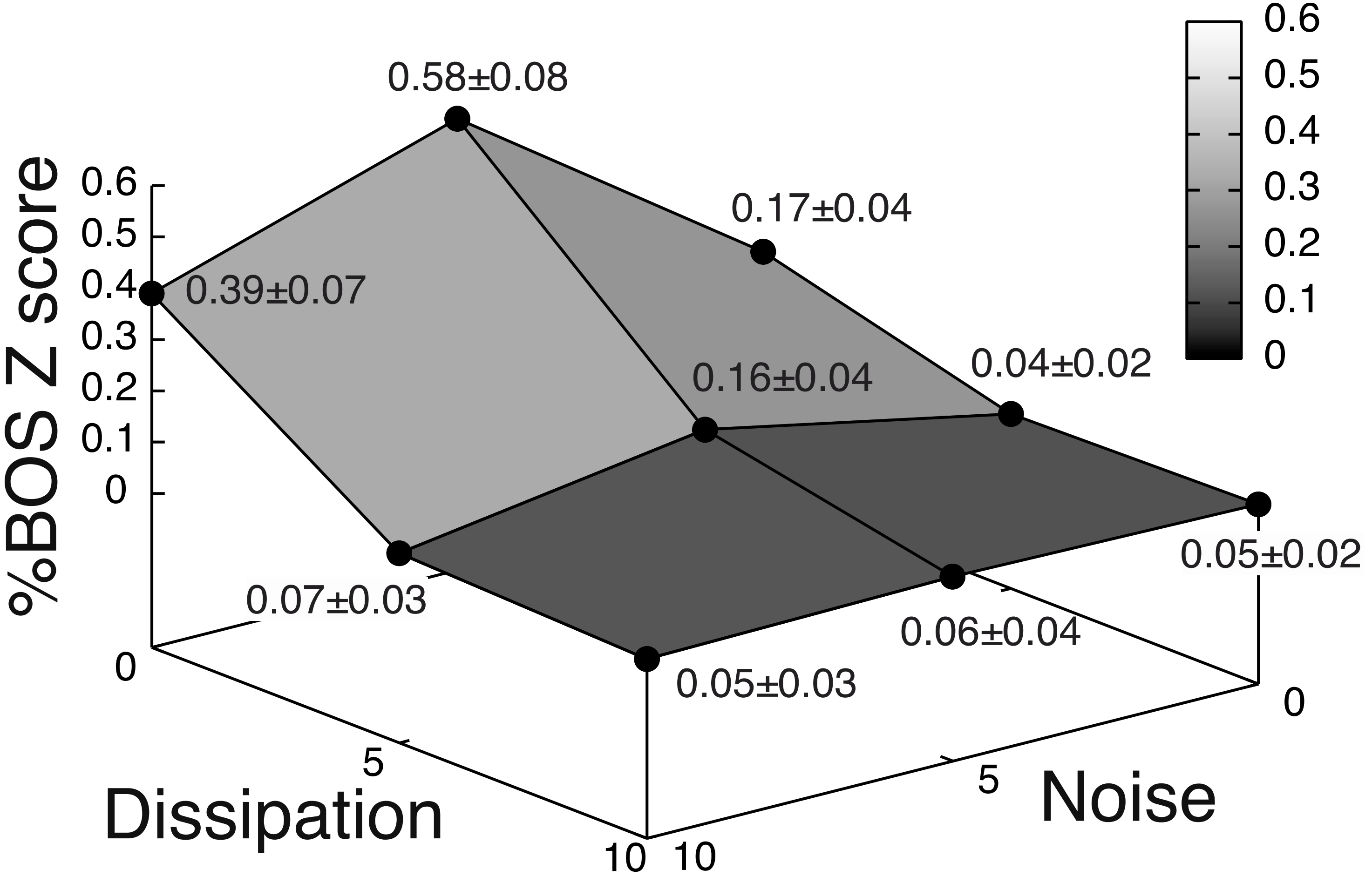
Noise: white noise added to β (tension)

A strategy for studying a hierarchy of importance for the elements in the model



Tuning surface

Grouped data: 5 birds



conclusions

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- Birds breathe at resonances of the respiratory biomechanics (the secret syllabic frequencies)
- The spectral features of the song, strongly conditioned by the dynamics of the biomechanics (the secret behind the spectral properties of the sounds)
- Both examples illustrate the deep relationship between nervous system and biomechanics at the origin of behavior.