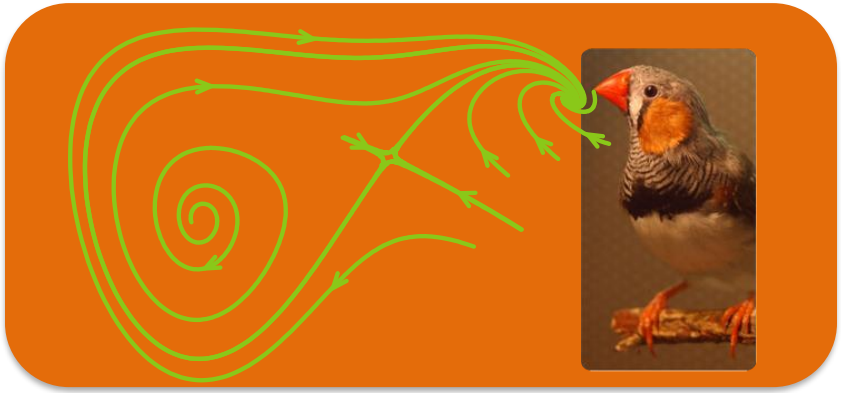


The physics of birdsong

Bengaluru 2017

Gabriel Mindlin

Physics Department, Universidad de Buenos Aires

Argentina

Buenos Aires

Laboratorio de sistemas dinamicos,
Depto Fisica, FCEyN, UBA

Buenos Aires

10 temporada

Why birdsong?

- Animal model to study mechanisms of vocal learning

- Shared properties with humans:
  - Similar learning stages
  - Similar sound production mechanisms

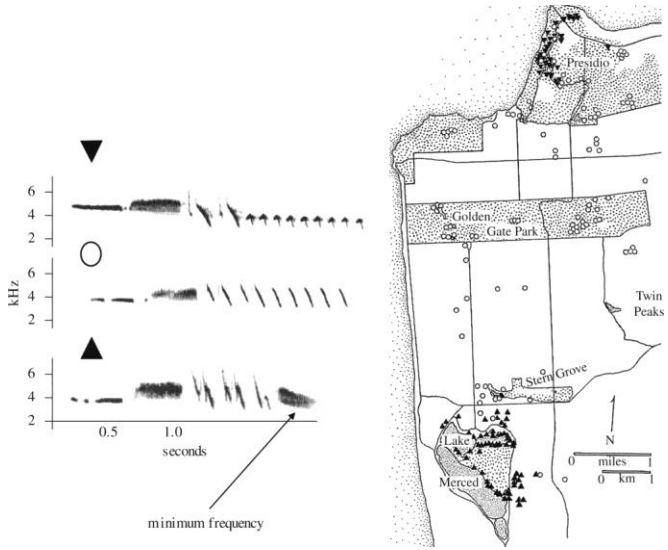
- Vocal learning is not common in mammals
  (just humans, cetaceans, bats)

Why birdsong … for a dynamicist?

1. How much of the "complex features" observed in behavior is due to the **Nonlinear nature** of the peripheral system?
2. Is it pertinent to reduce dimensionalities in biology?
3. Can we translate from physics the idea of "progressive" modeling?

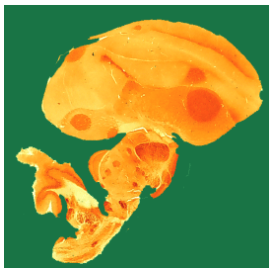
Landmarks in study of Birdsong

50’s



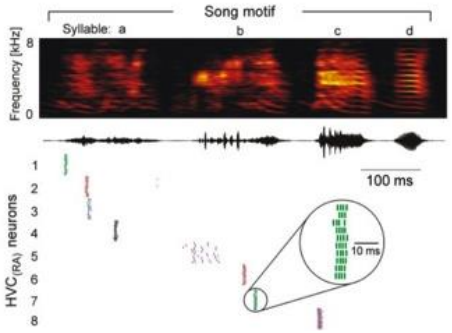
Dialects

70’s



Vocalizations reflected
The operations of a definable
Collection of neural structures

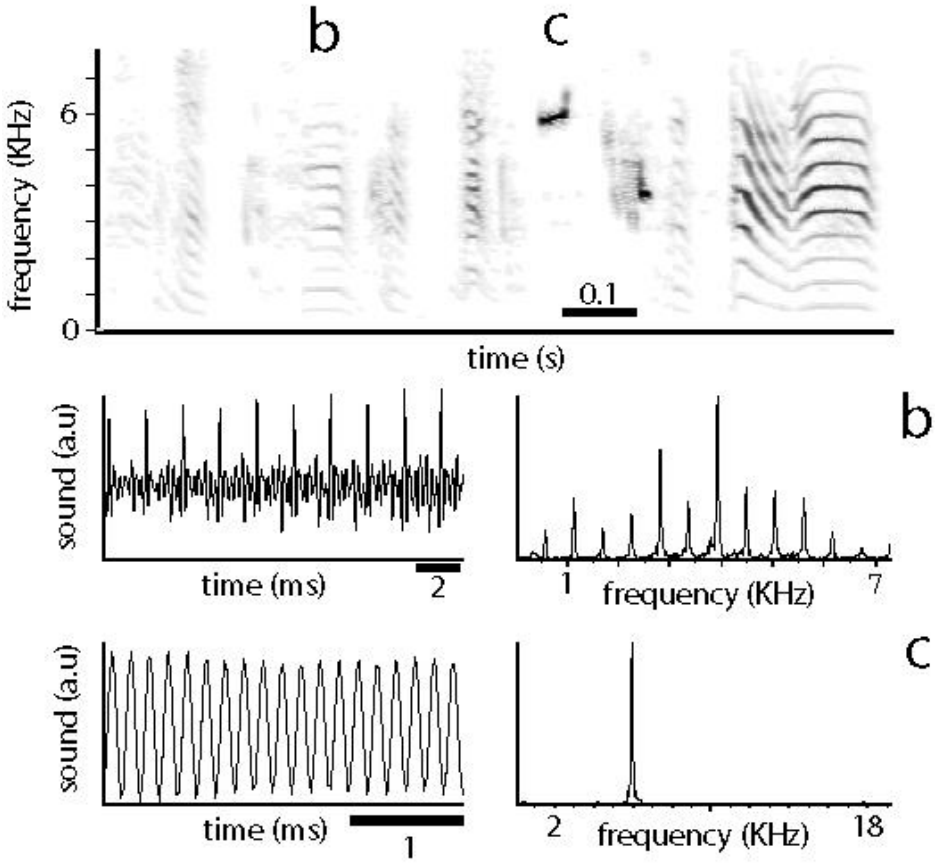
00’ s



The ability to monitor
Neural ability in awake
Singing birds.

"How much of the complex features observed in behavior is due to the **Nonlinear nature** of the peripheral system?"

Example of a "complex feature"

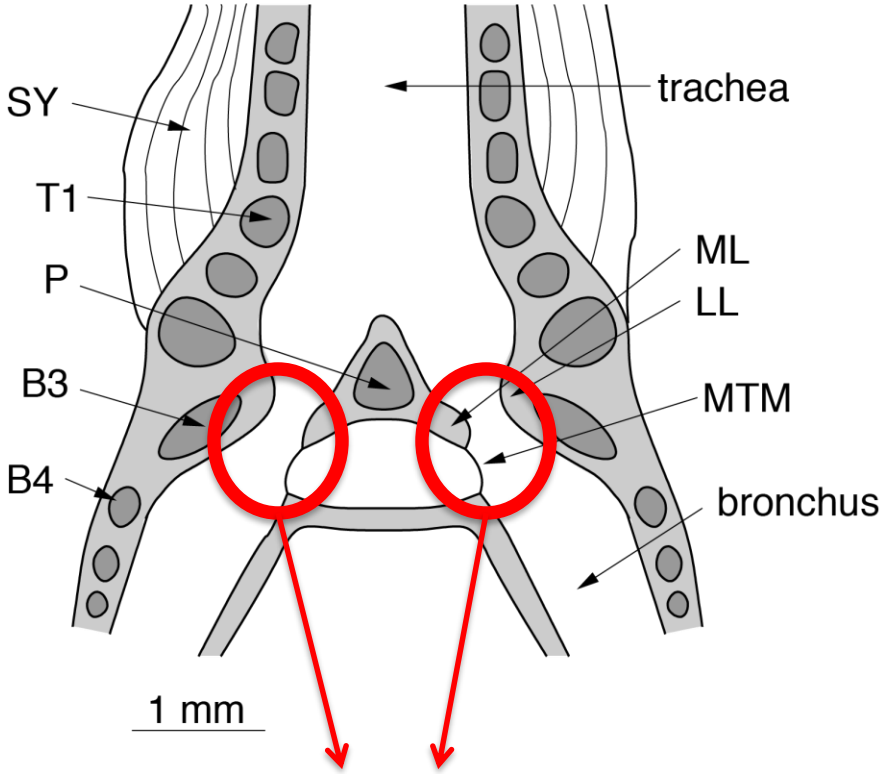


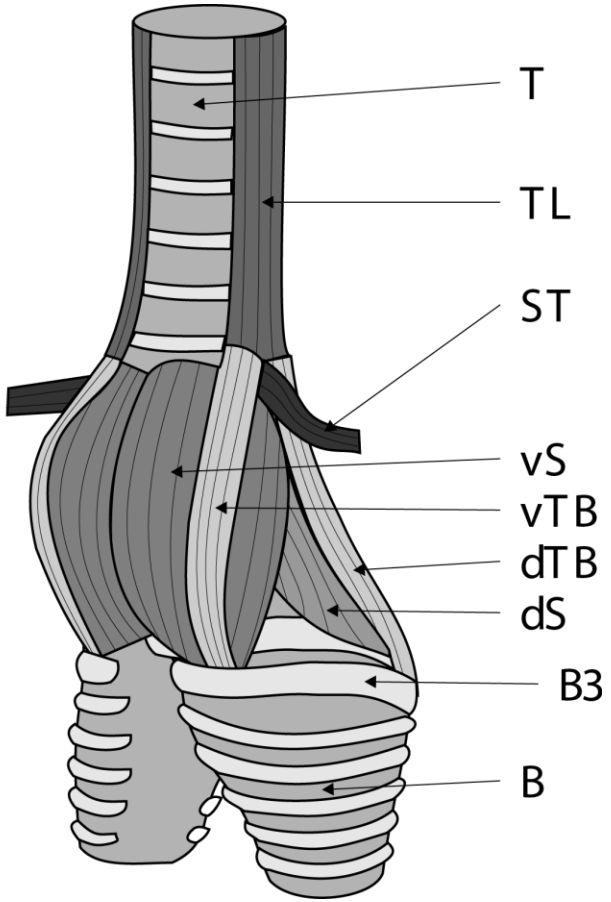
Zebra finch song

Spectrally rich notes

Almost tonal notes

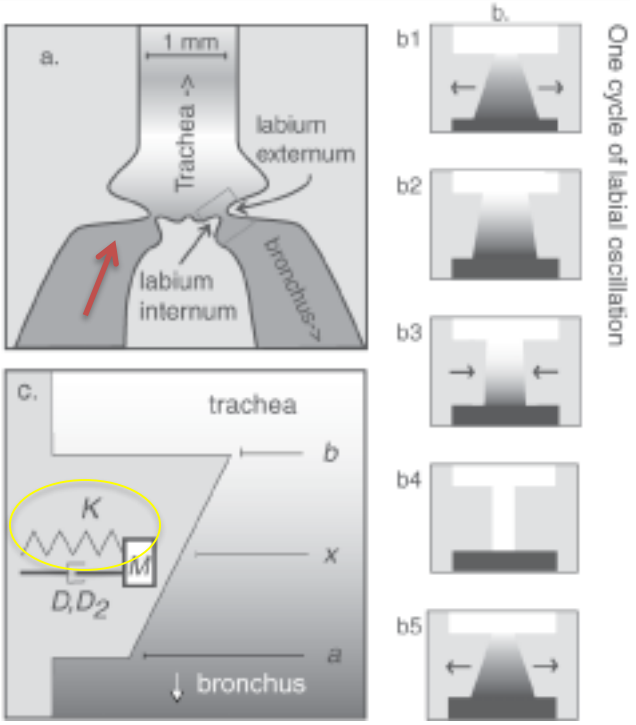
Between the song and the neural architecture, the avian vocal organ: the **syrinx**





Two independent sound sources

Our first steps in the field: the basic mechanics of labial motion

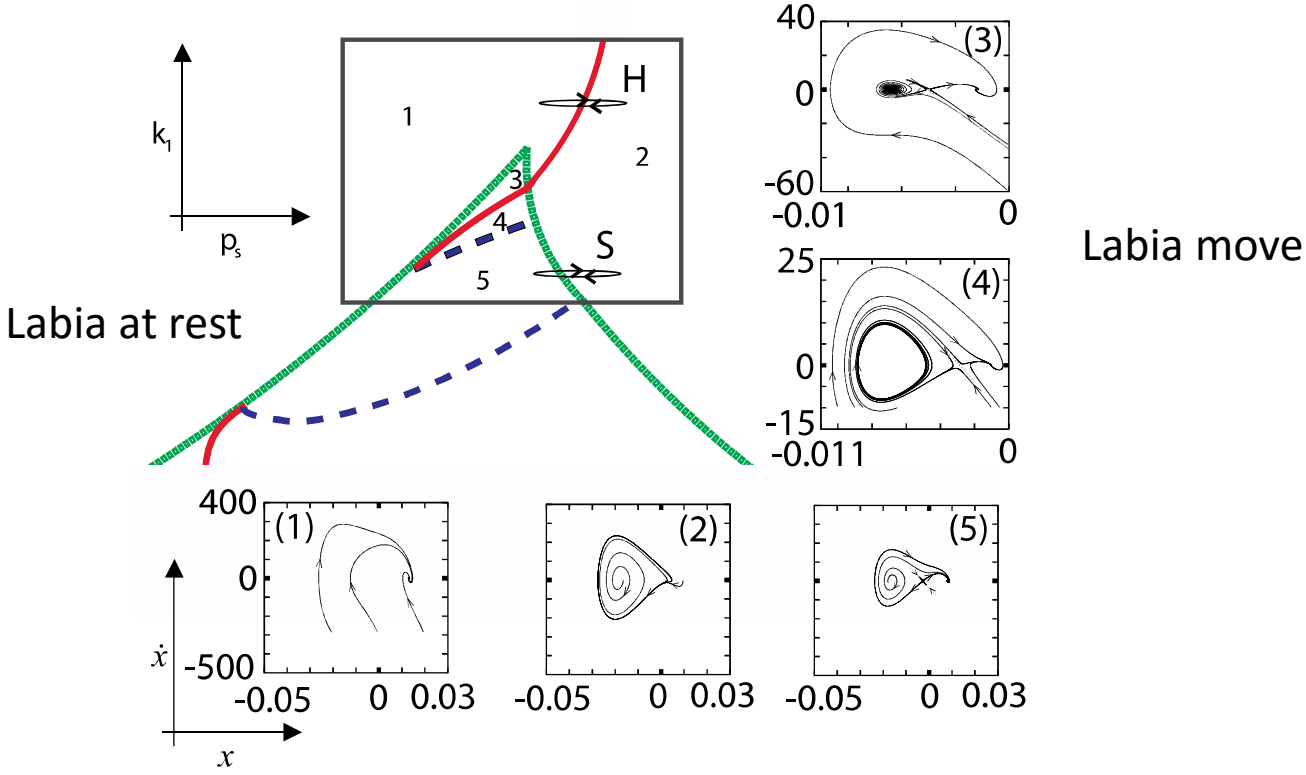


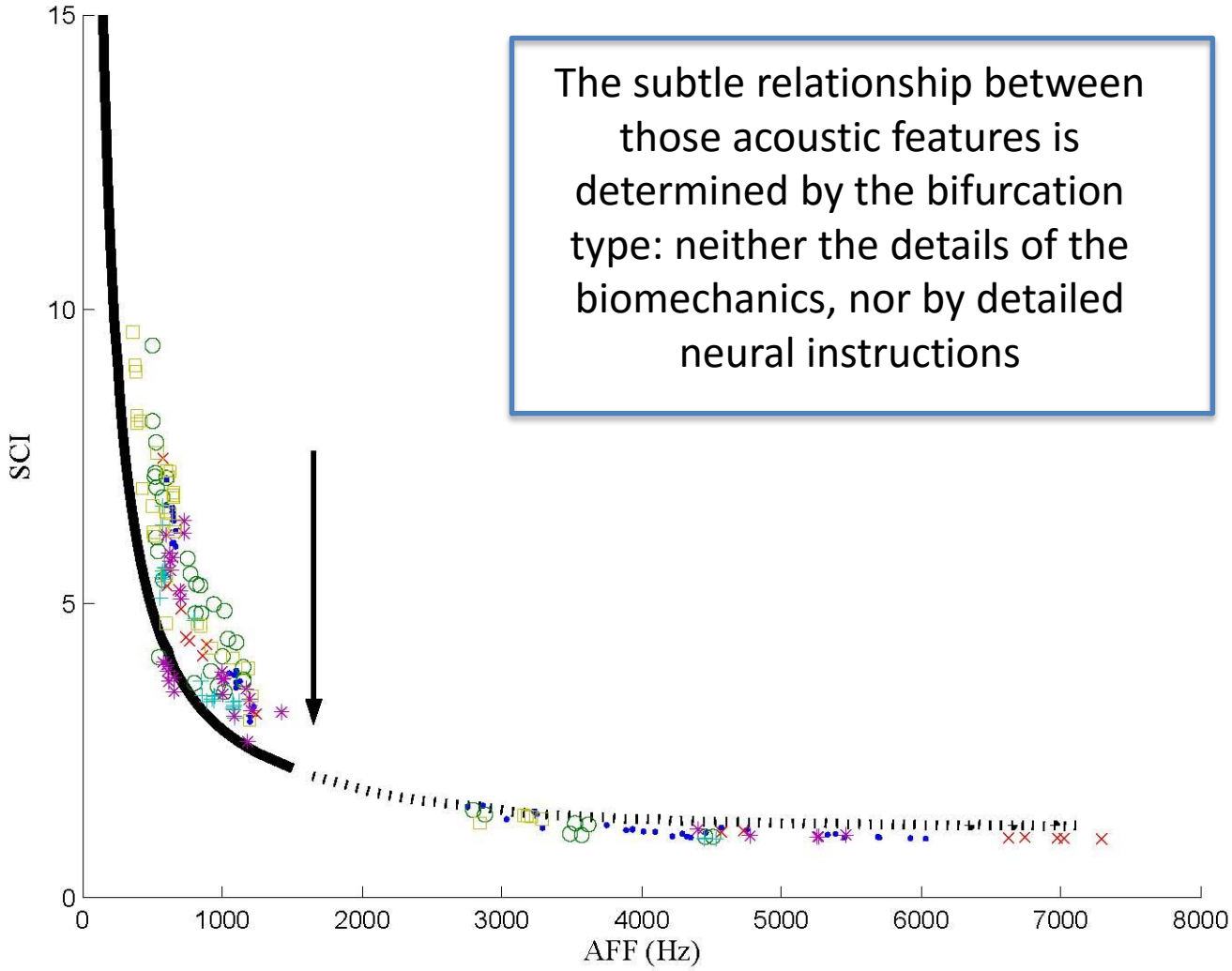
$$\frac{dx}{dt} = y,$$

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

Two time dependent parameters
Control many features of the vocalizations:
air sac pressure and s.v. tension

Dynamics of the model

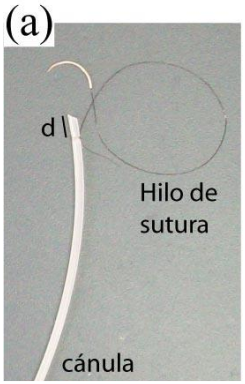


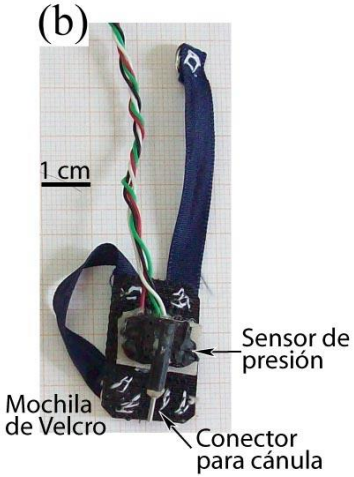


The subtle relationship between those acoustic features is determined by the bifurcation type: neither the details of the biomechanics, nor by detailed neural instructions

Jaco's thesis

Direct mesurement of pressure and muscle activity



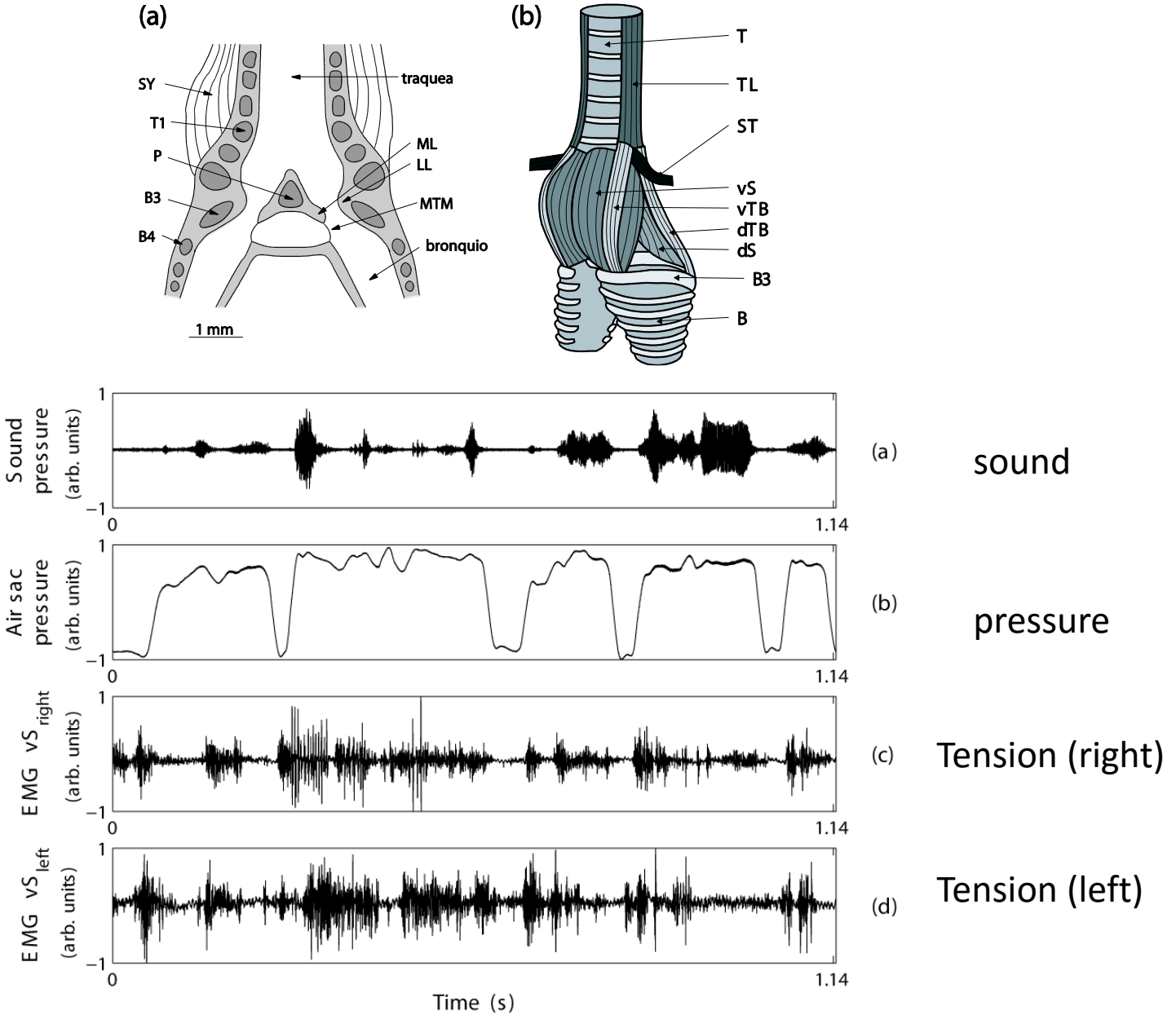


Air sac Pressure

Tension
(activity of vS muscle)

With Franz Goller, 2003-present

Not that simple, these instructions…



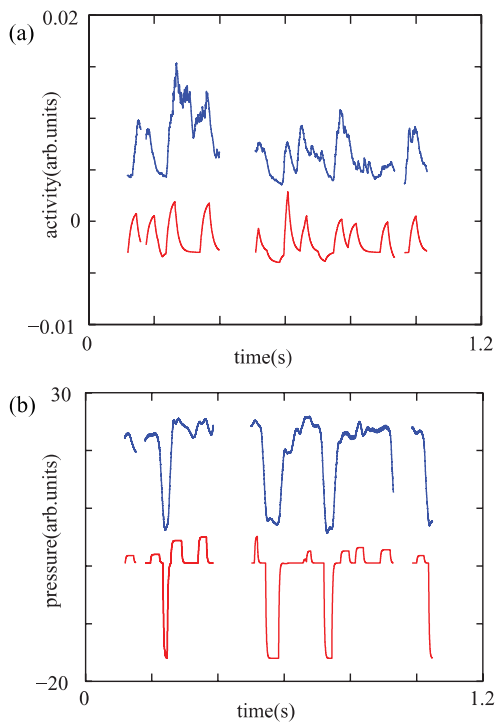
sound

pressure

Tension (right)

Tension (left)

1. Reconstructed Instructions, Compared with the measured ones

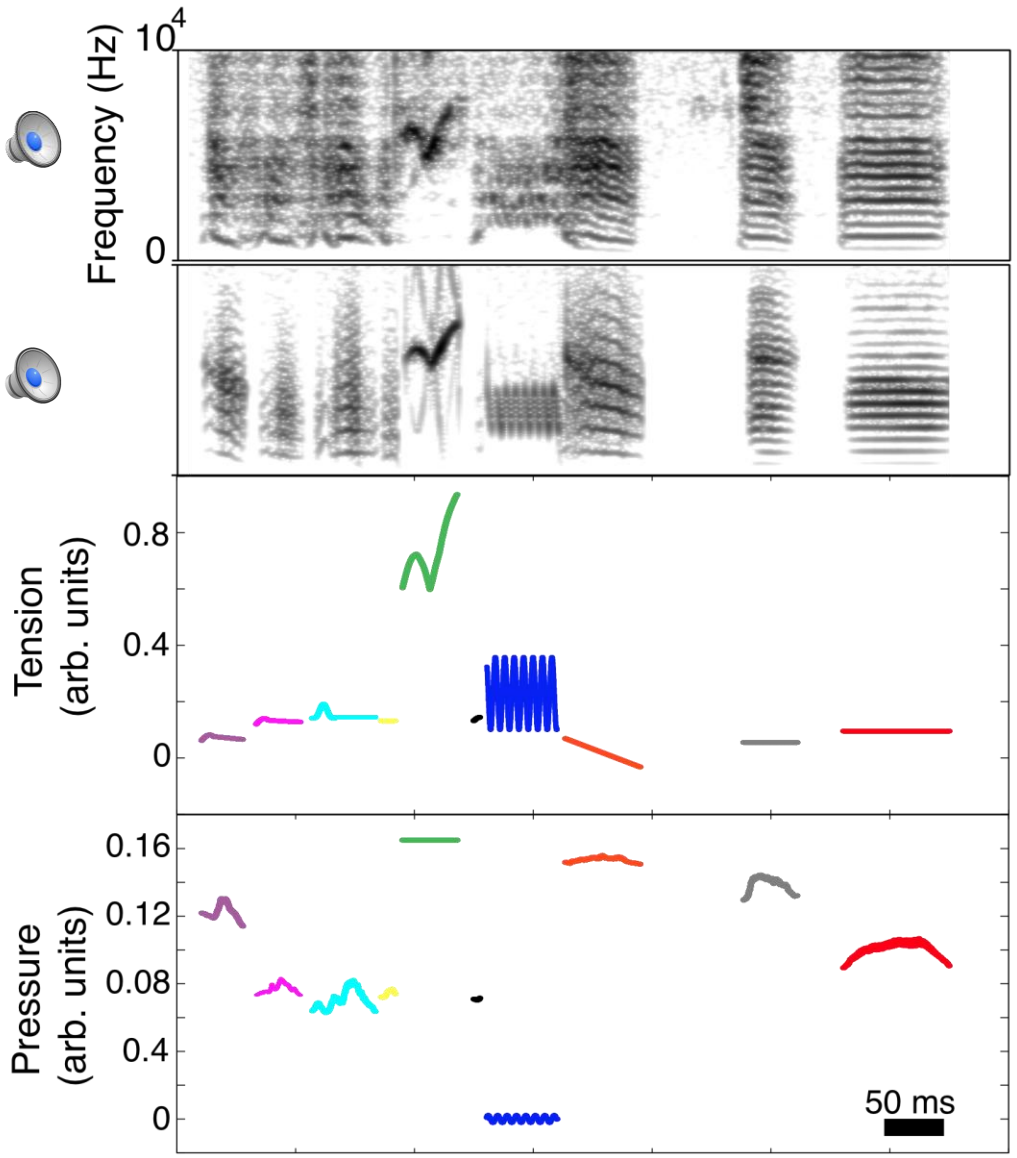


we fit α (pressure) and β (tension) in the normal form model so that BOS and SYN share spectral features (Fundamental, Spectral content)

2. Synthesize song with the model

BOS

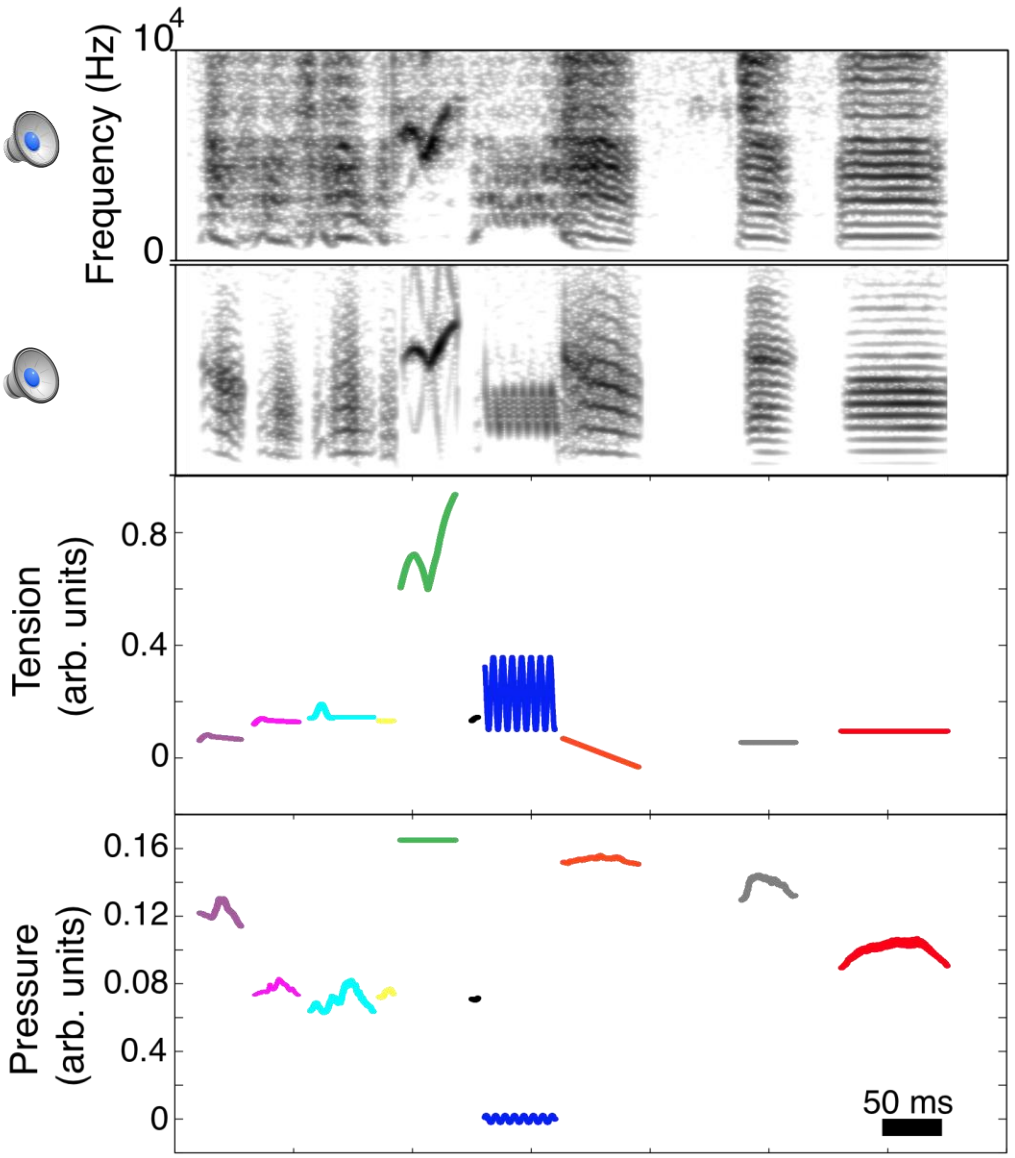
SYN



2. Synthesize song with the model

BOS

SYN



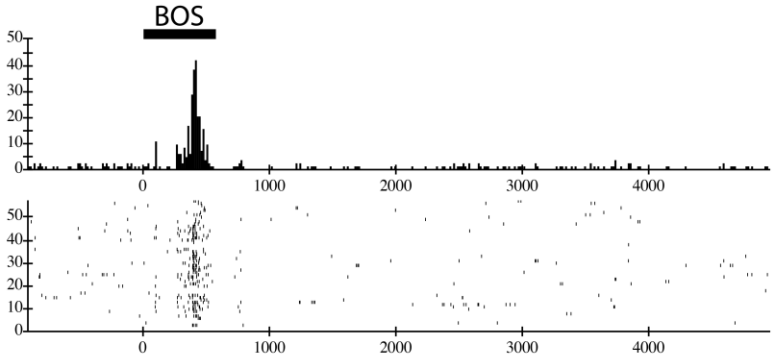
But… can we ask the bird?

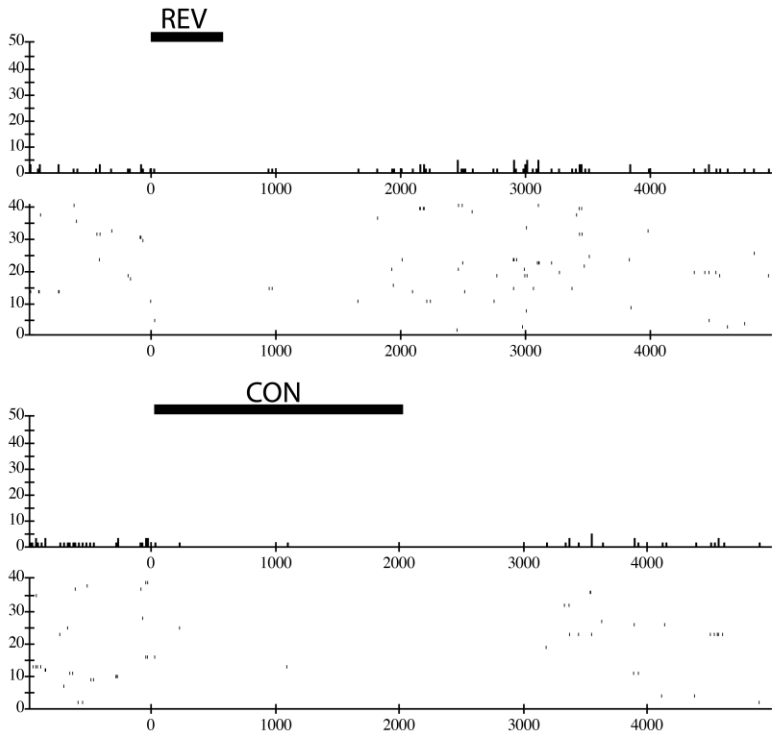
From Dan’s Lab

From Dan’s Lab

Testing the model

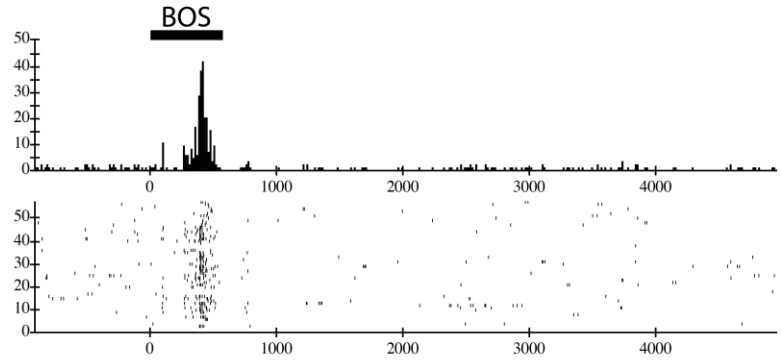
Neurons in HVC respond selectively to the bird's own song (BOS)

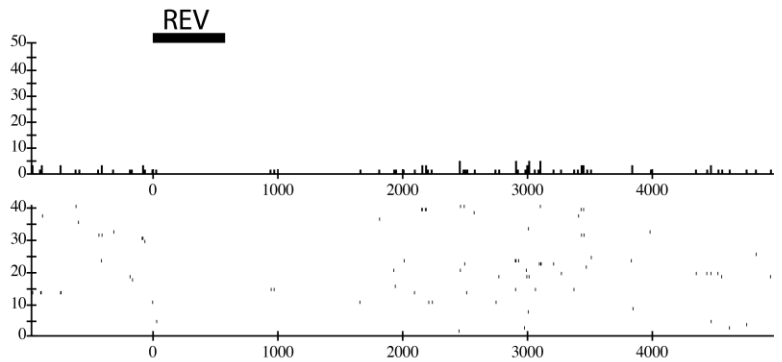


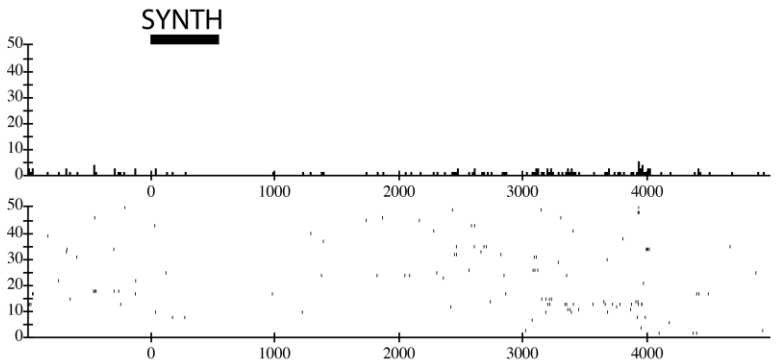


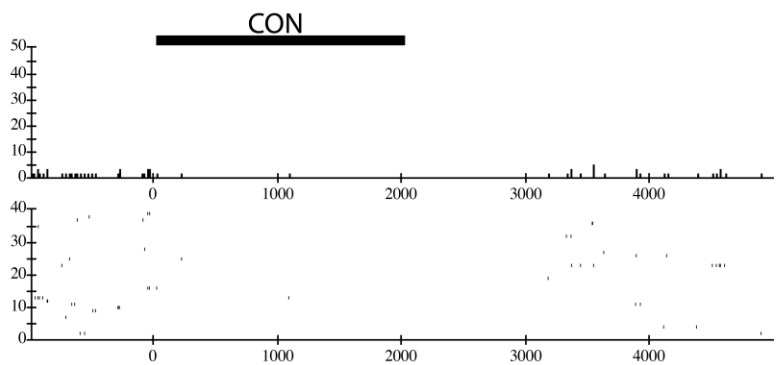
Testing the model

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

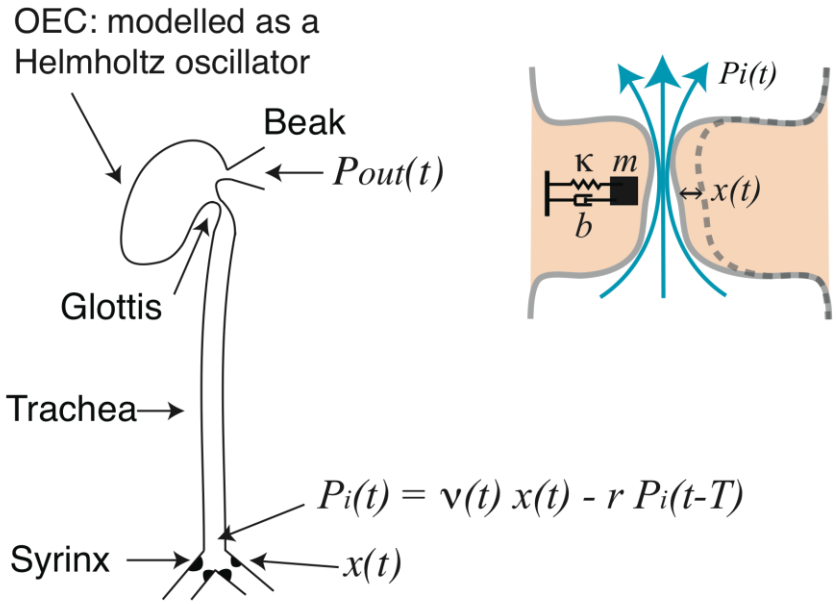






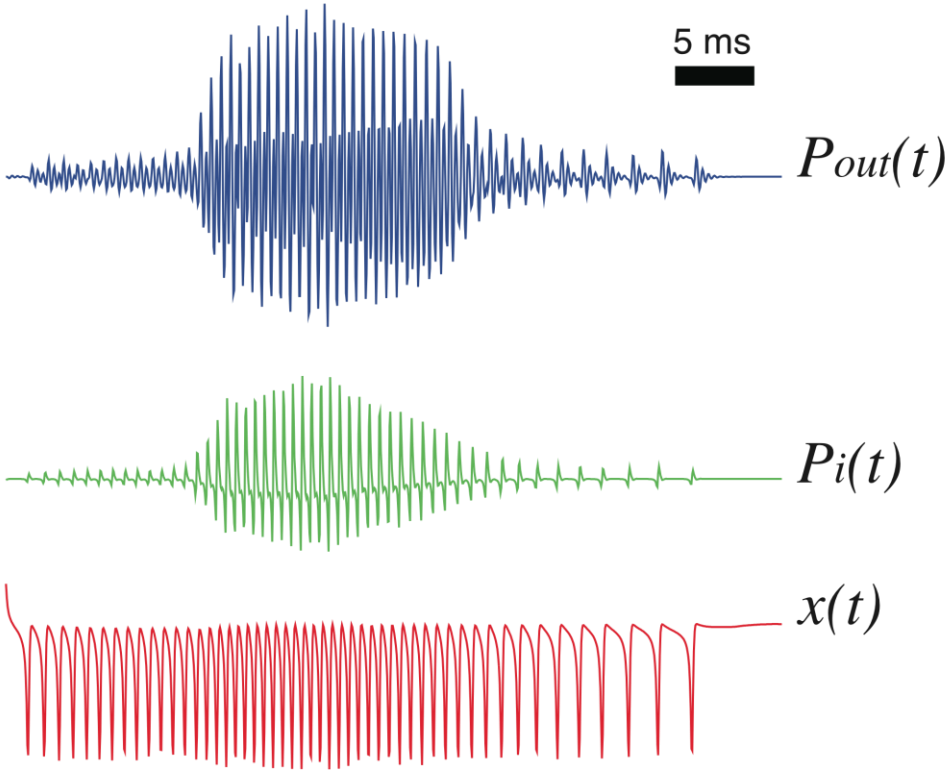


A more detailed modeling



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

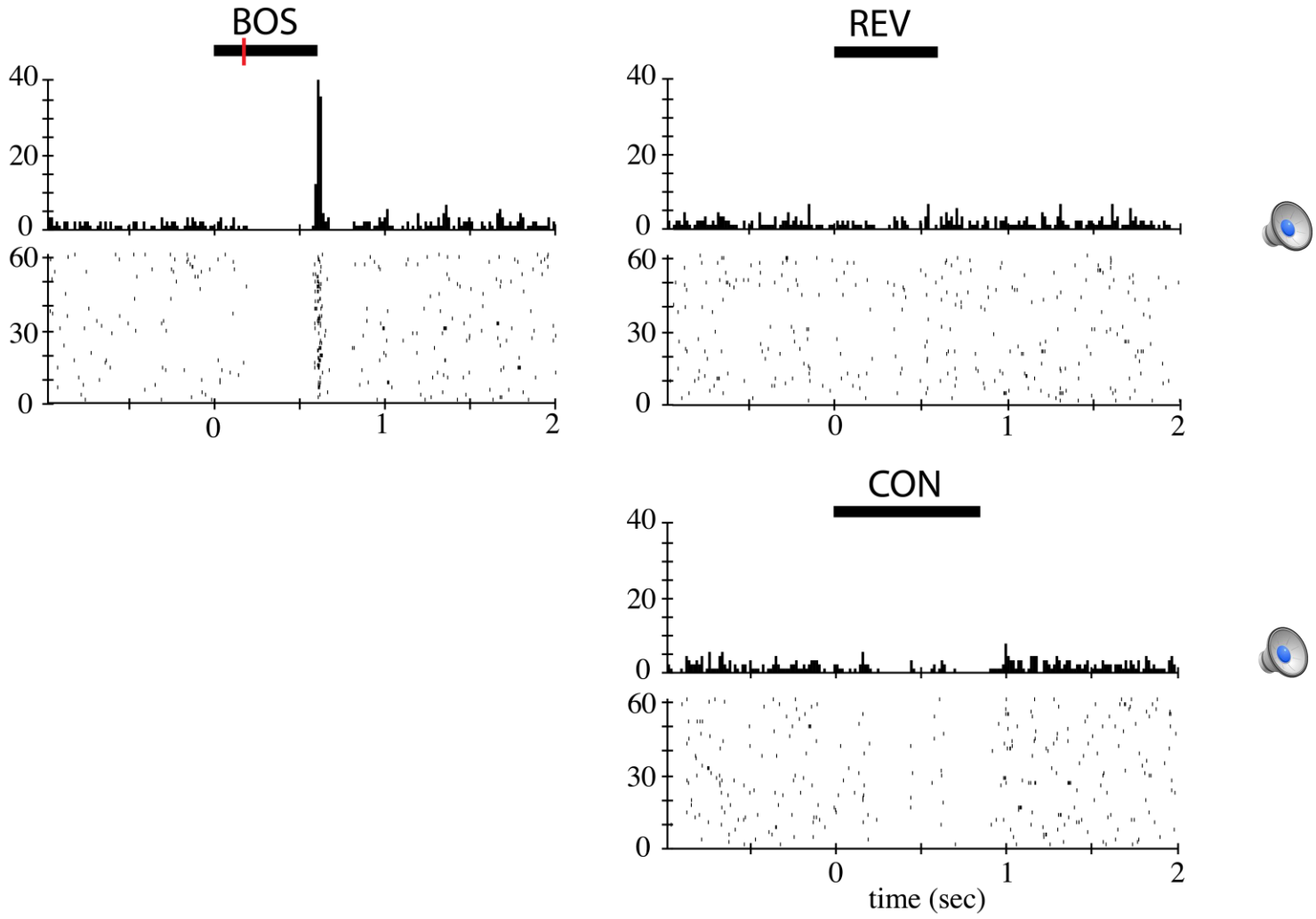
$$\frac{dy}{dt} = -\alpha(t)\gamma^2 - \beta(t)\gamma^2 x - \gamma^2 x^3 - \gamma x^2 y + \gamma^2 x^2 - \gamma x y$$



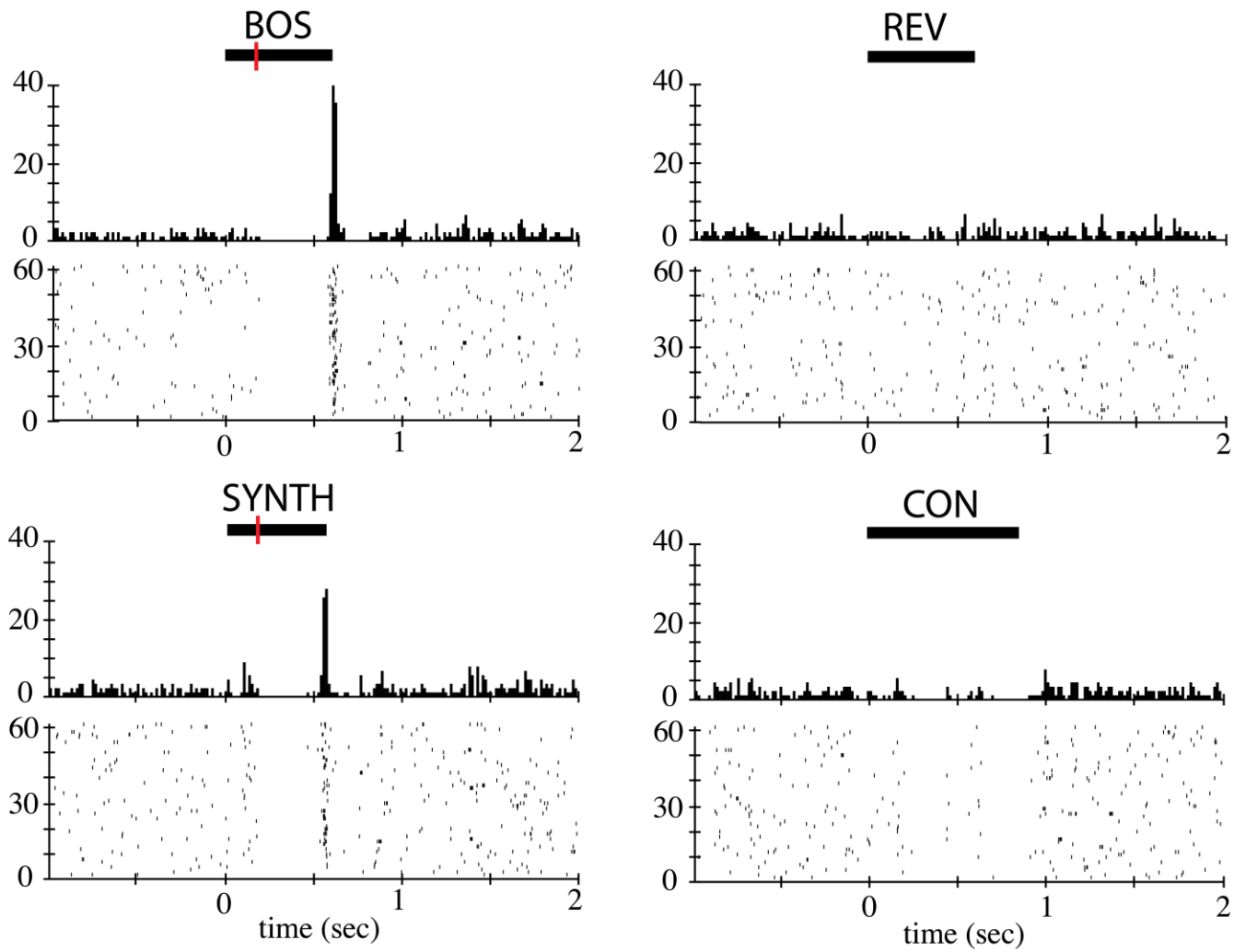
✓ More detailed modeling of the vocal tract (not just 3 tubes). Oropharingeal cavity as a resonator

✓ Intrinsic noise in the activity of the syringeal muscles

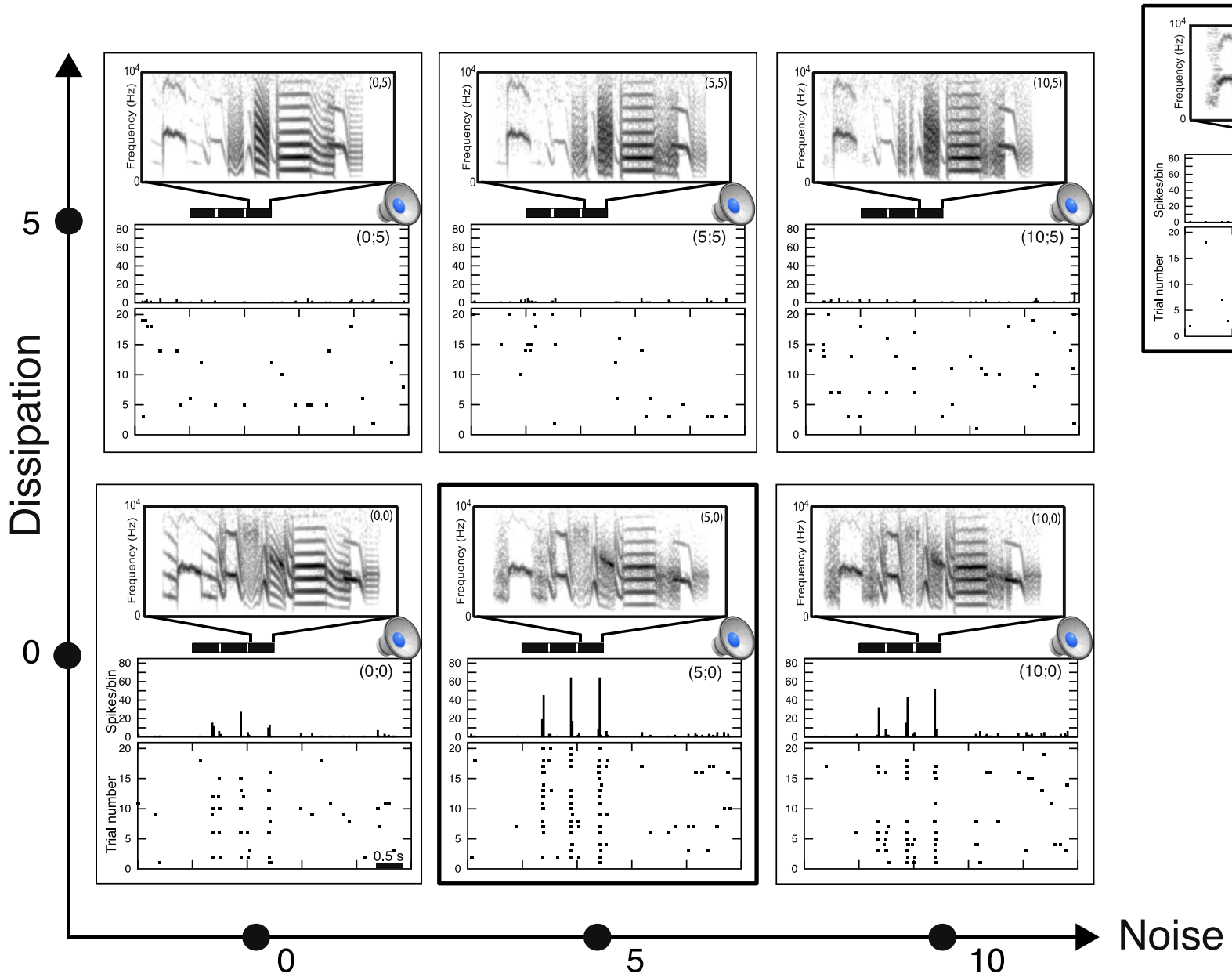
A more detailed modeling



A more detailed modeling



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

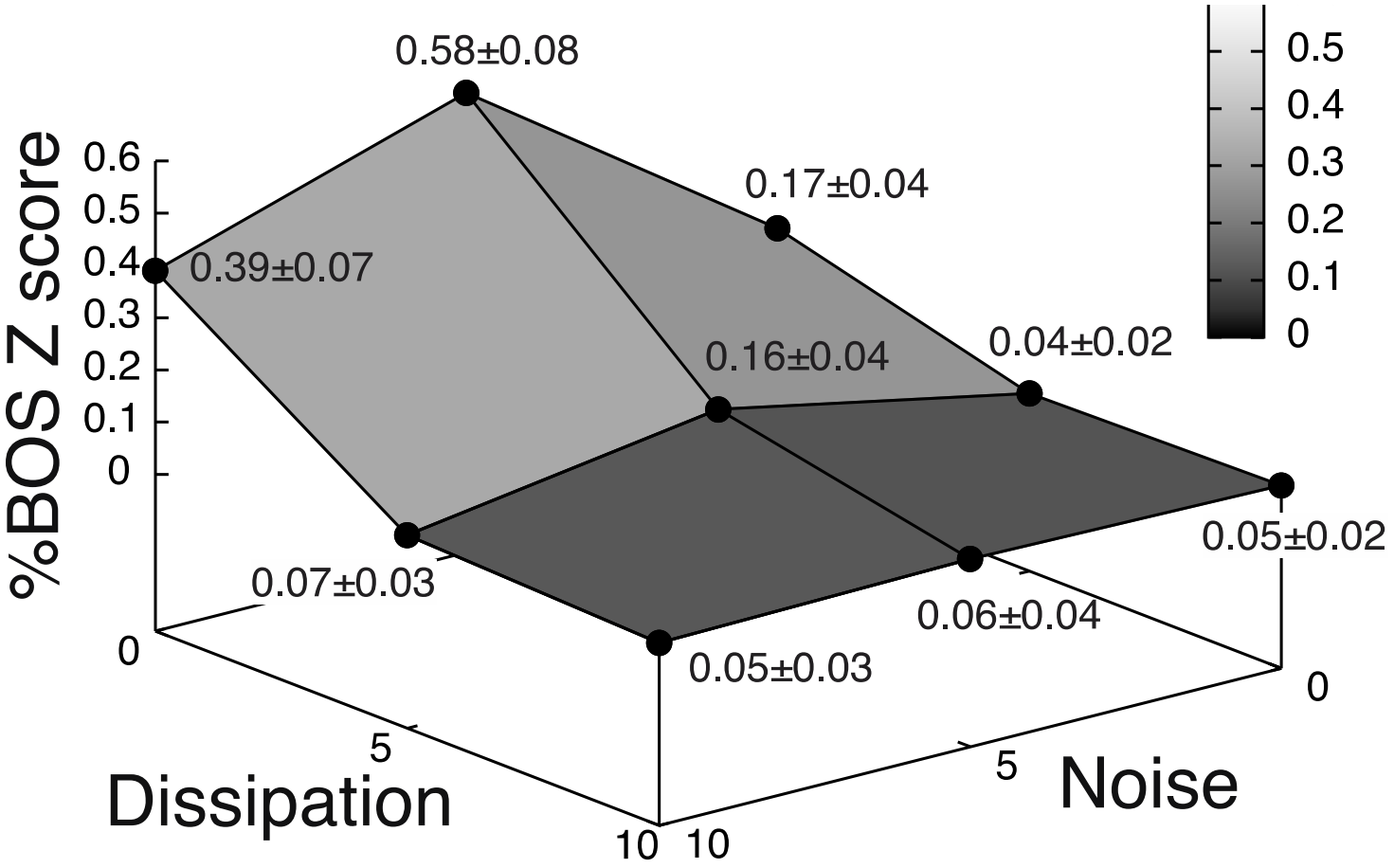


Tuning surface

Grouped data: 5 birds

The resonant cavity is very relevant (can be controlled by the birds while singing)

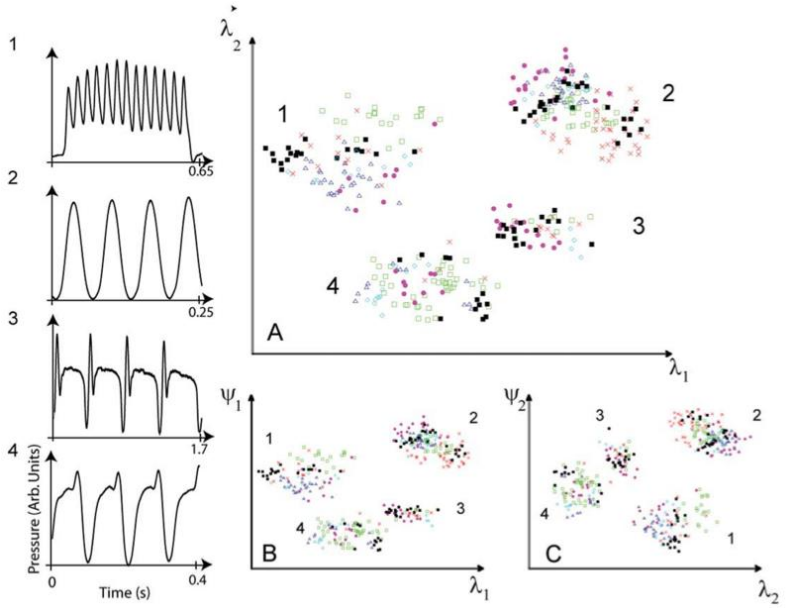
The noise has a particular value that maximize the responses



Nature 2013, Amador et al.

How complex, those instructions? The canary, candidate for simpler gestures…

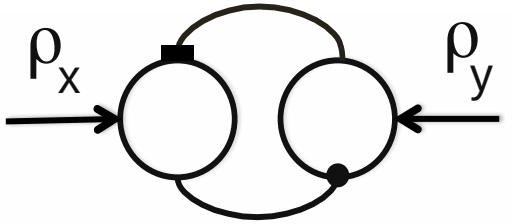
a

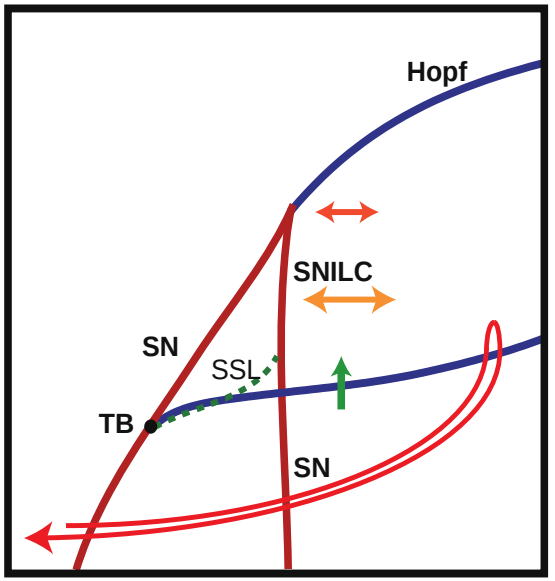


And they are the solutions of a
low dimensional dynamical system

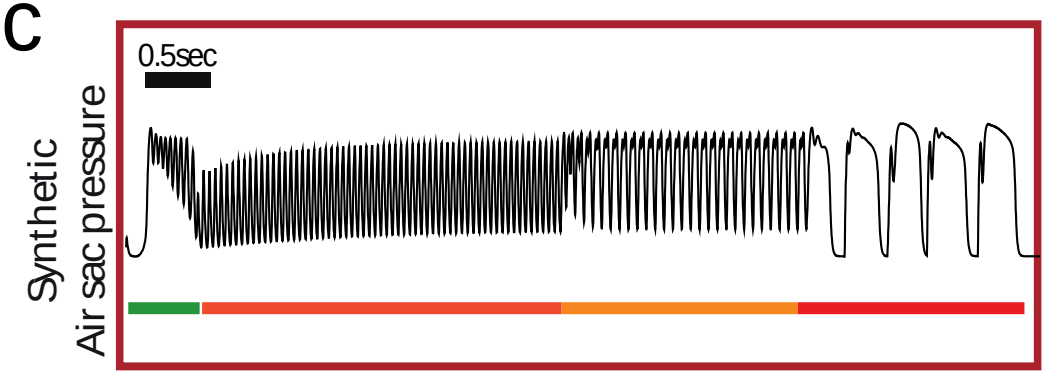
a

b





c



Can we design such a dynamical system compatible with the known anatomy?

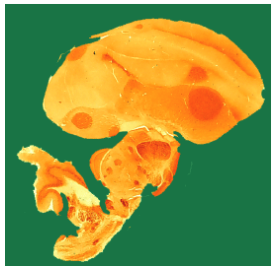
Is it possible to build **a model**?

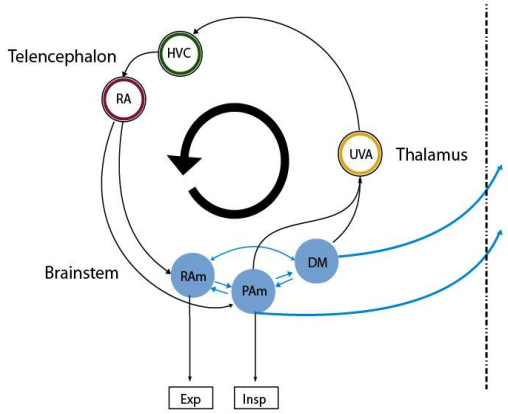
1. whose variables are **the activities** of different areas of the song system,

2. With an **expiratory related** area whose activity fits the **recorded pressure** patterns,

Conceptual model

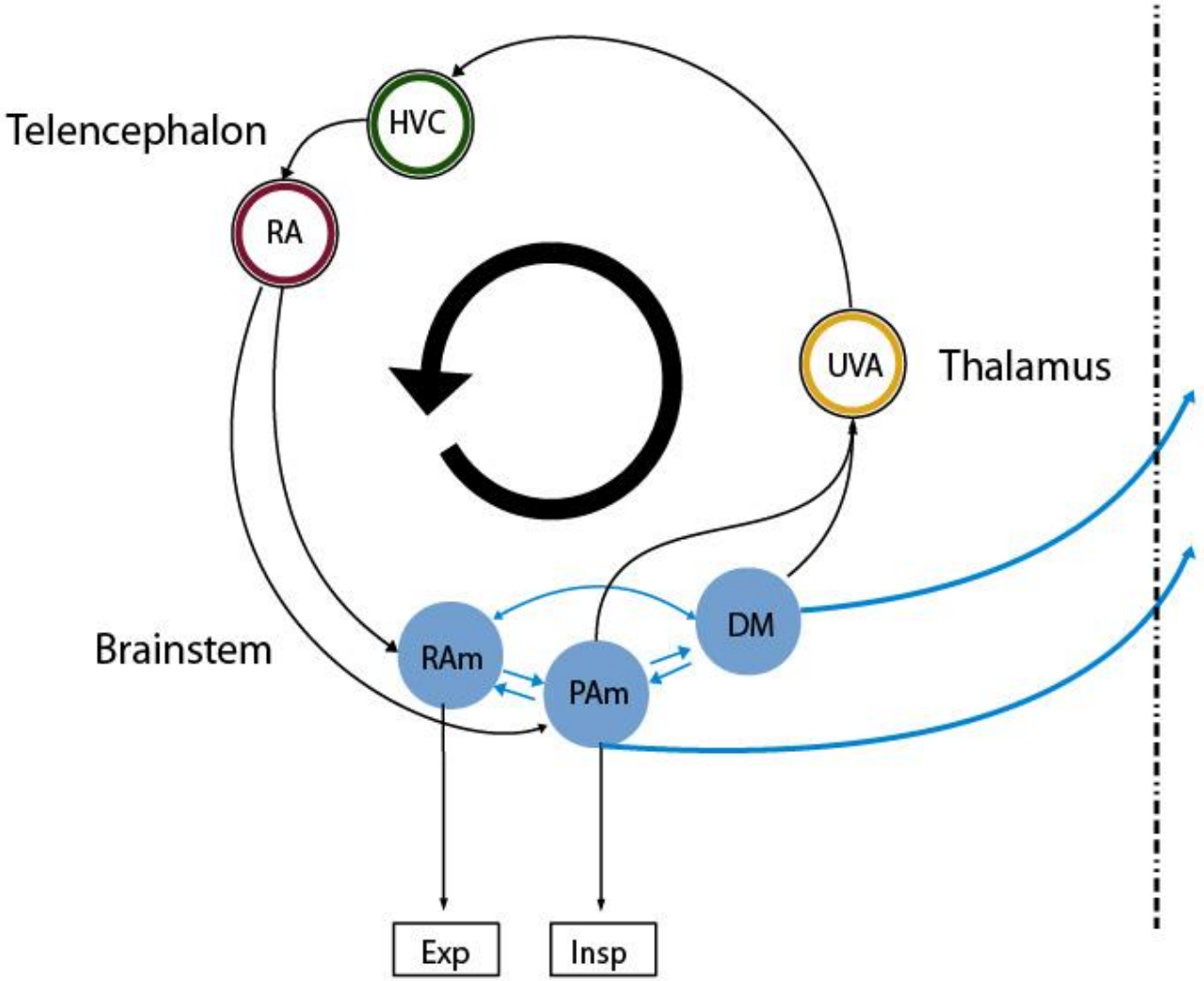
Mathematical model





$$\frac{dx_i}{dt} = -x_i + S\left(\rho_i + \sum_j a_{ij}x_j\right),$$

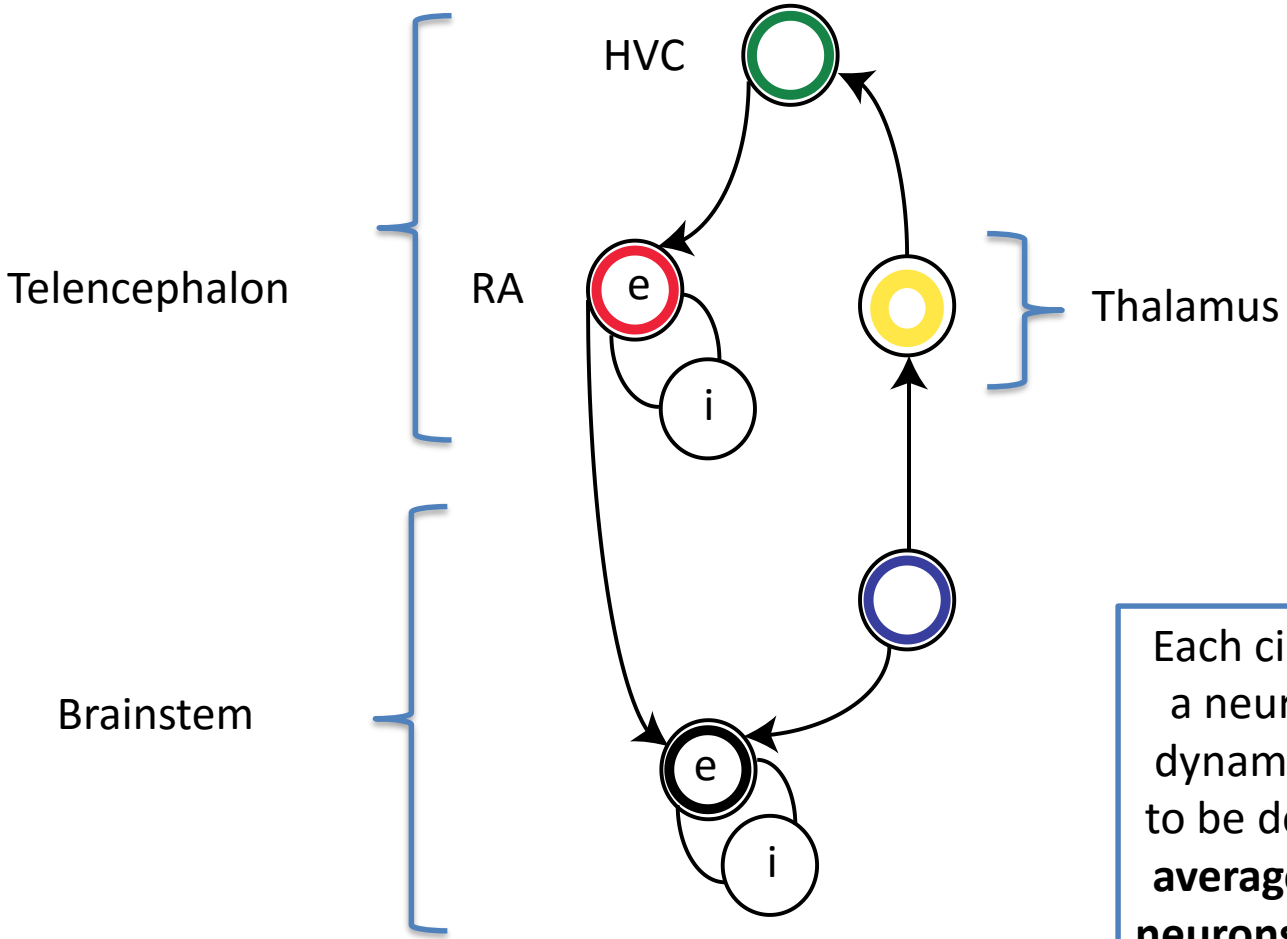
$$S(x) = \frac{1}{1+e^{-x}}$$



To achieve these goals we'll need an integrative or circular architecture

Adapted from Marc Schmidt's

This architecture is capable of generating the observables, with the known neural nuclei

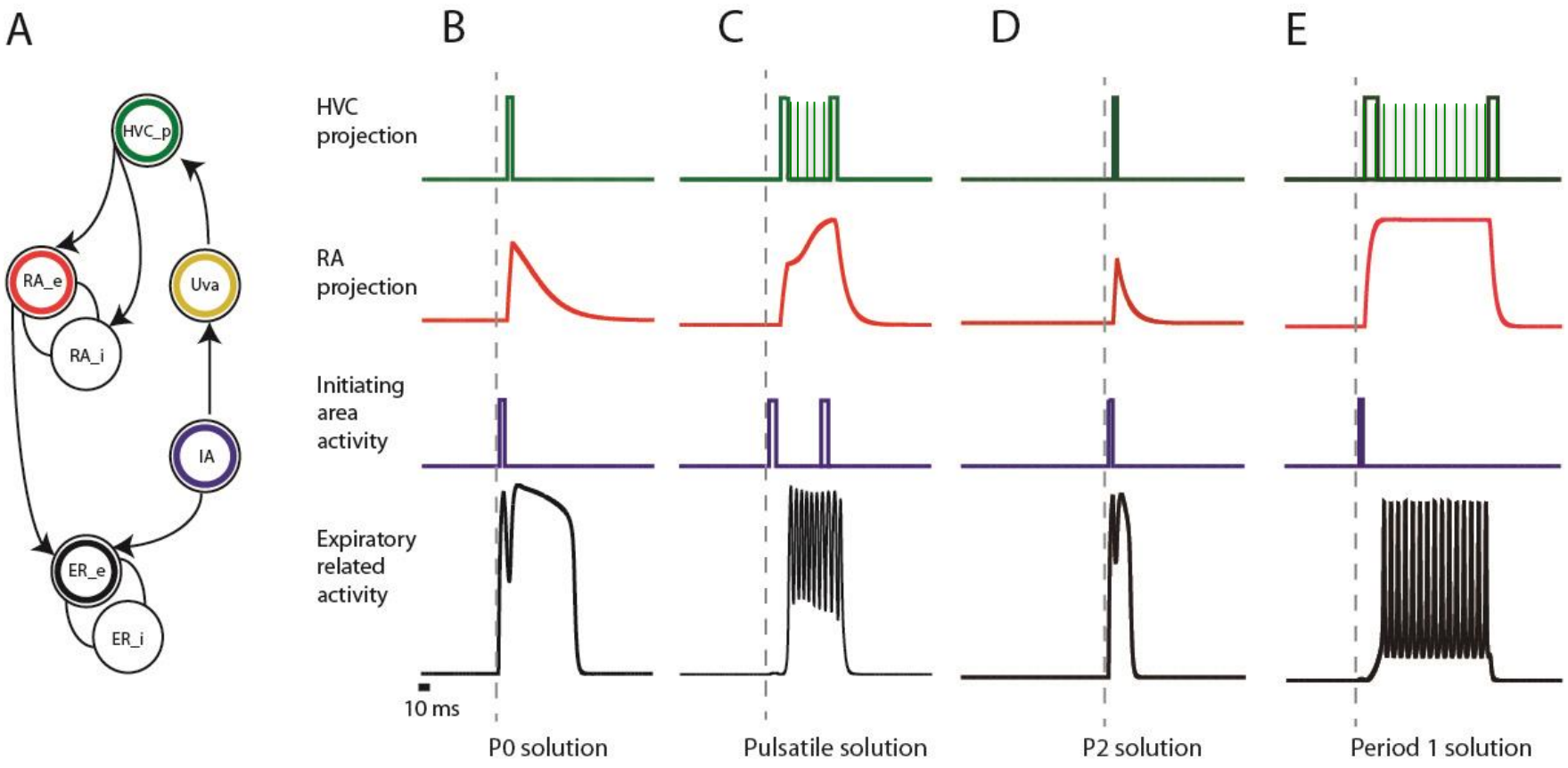


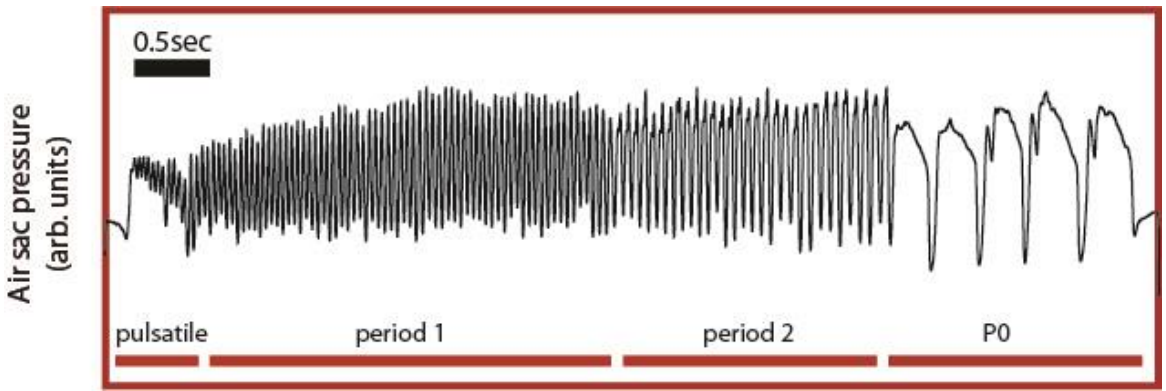
$$\frac{dx_i}{dt} = -x_i + S\left(\rho_i + \sum_j a_{ij}x_j\right),$$

$$S(x) = \frac{1}{1+e^{-x}}$$

Each circle represents a neural nucleus, its dynamics is assumed to be described by **the average activity of Its neurons**, and for those, we propose a simple **additive model**

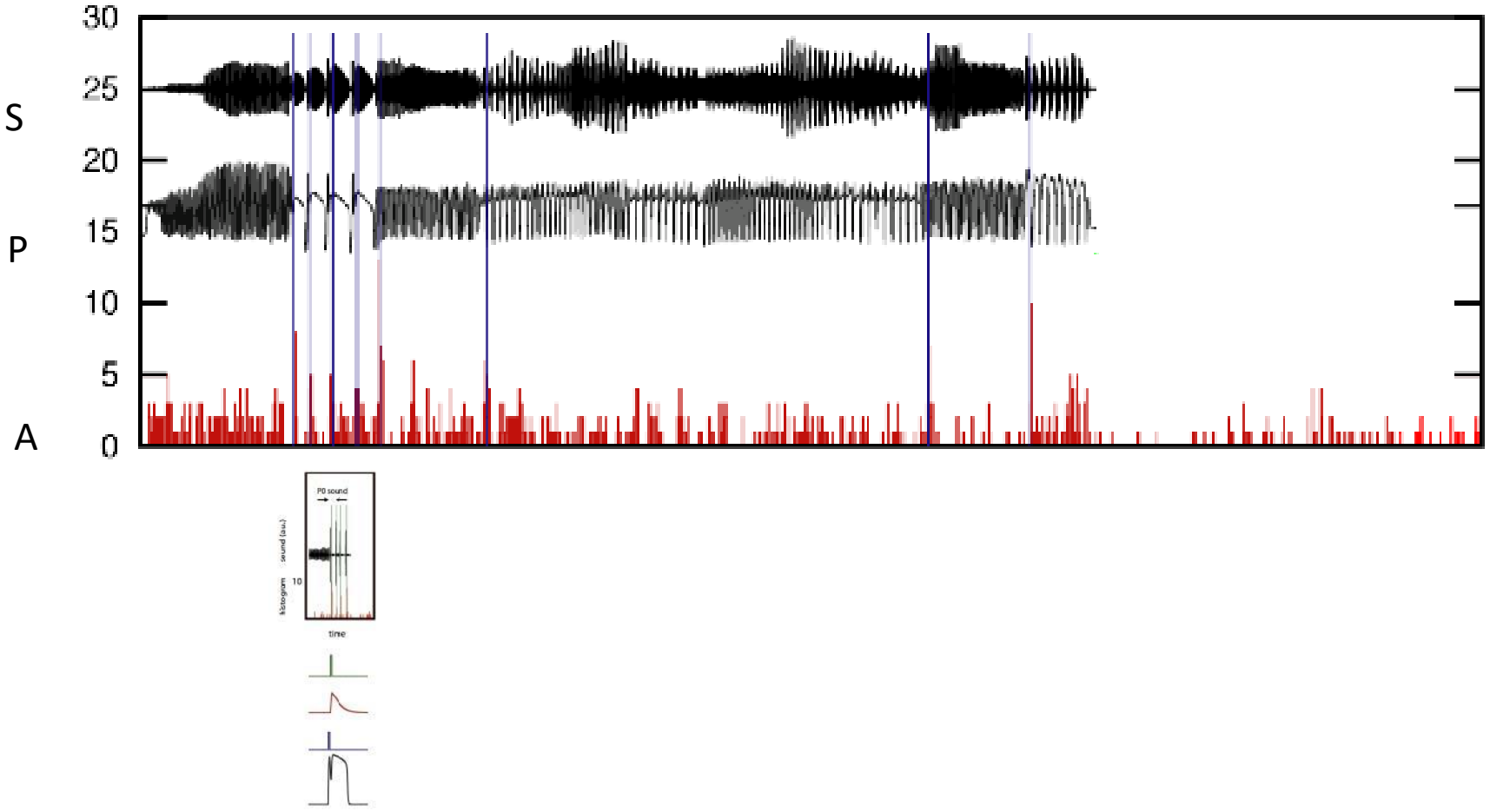
The circular model

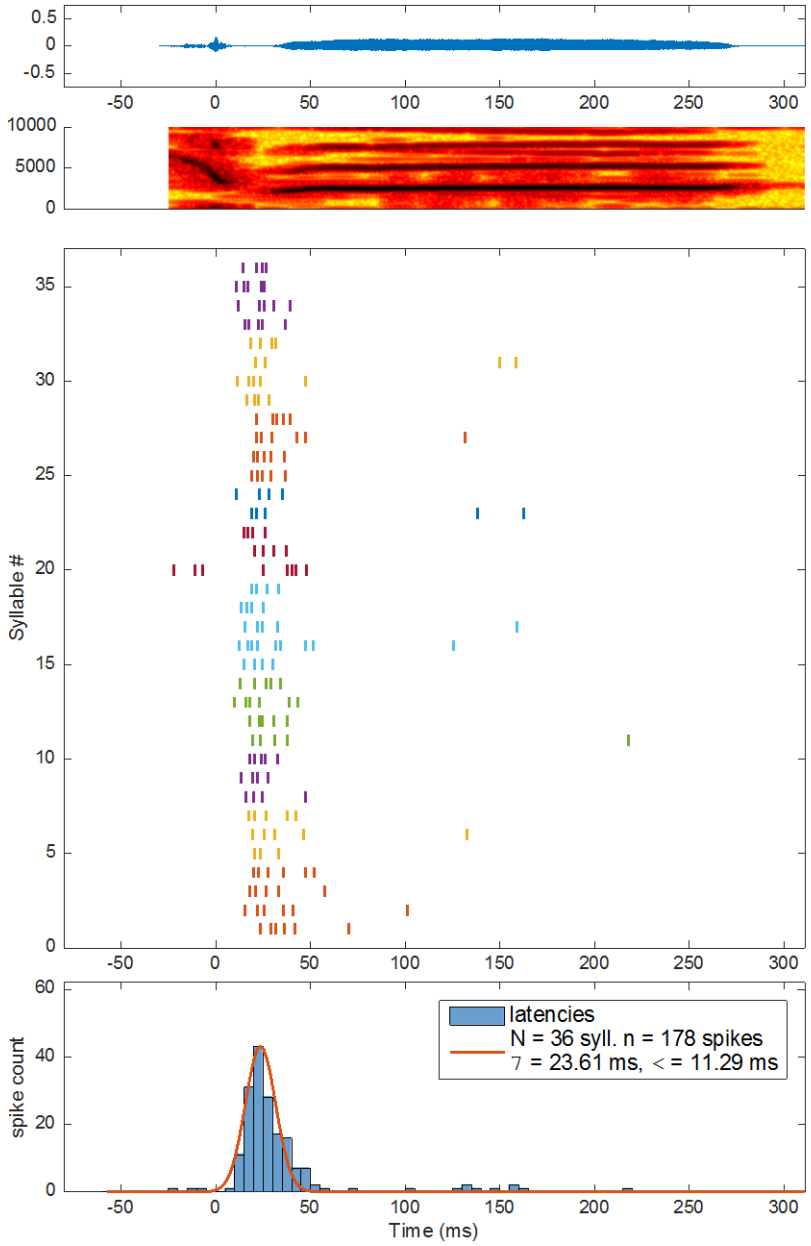




Preliminary data

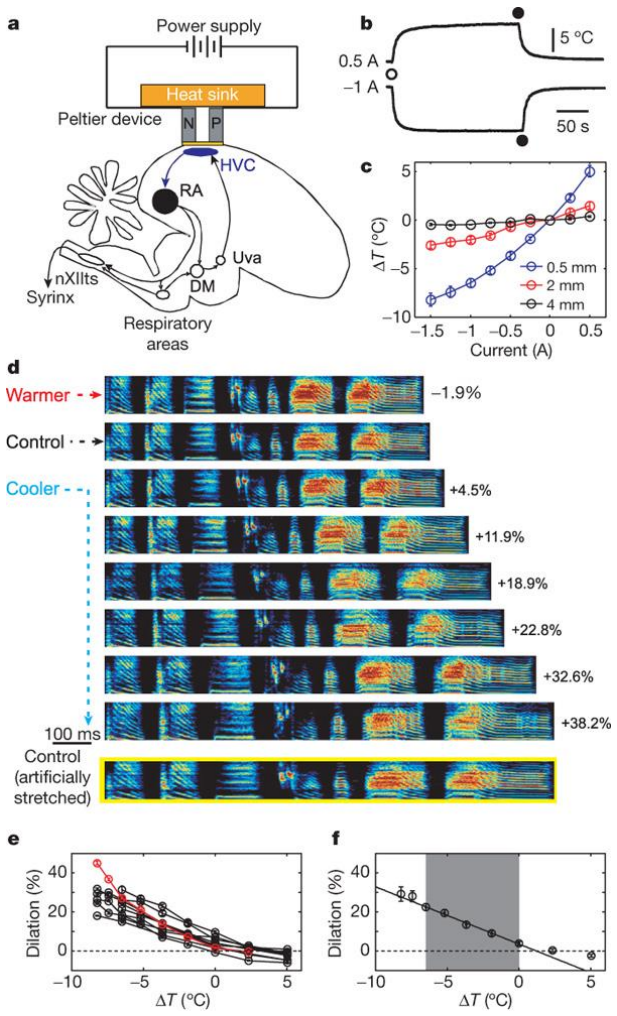
1. For P0 solutions, after the first pressure peak
2. At transitions





Ana Amador,
Santiago Boari
Cecilia Herbert

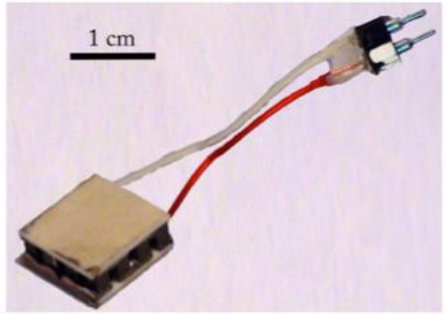
A continuous representation of time at the telencephalon, organizing the system as a top down structure:
"Cool" experiments

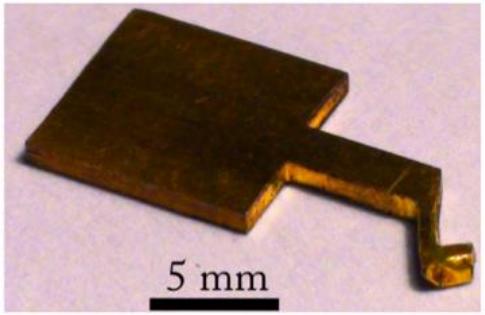


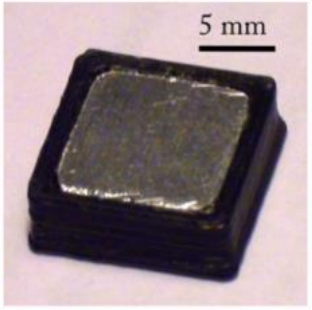
Long & Fee

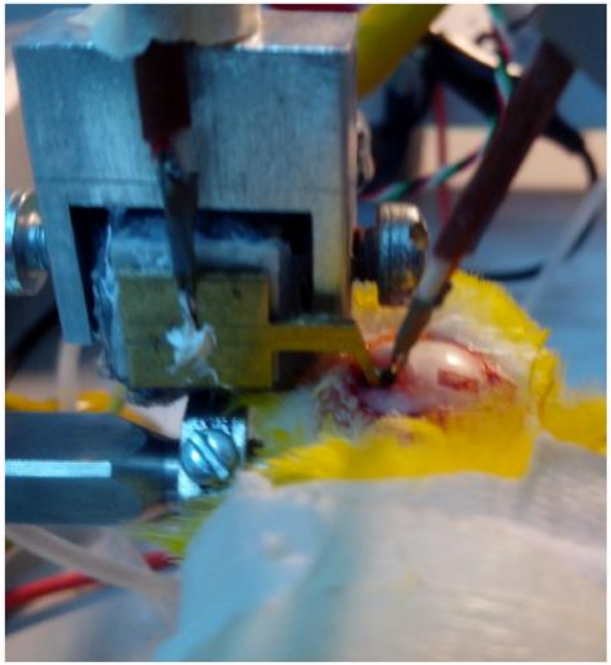
Consistent with one Time scale…

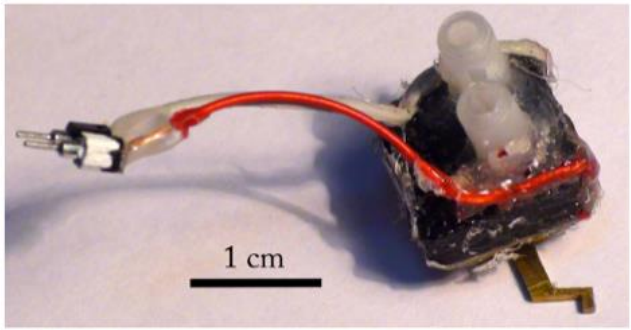
How do we introduce the cooling into the model?

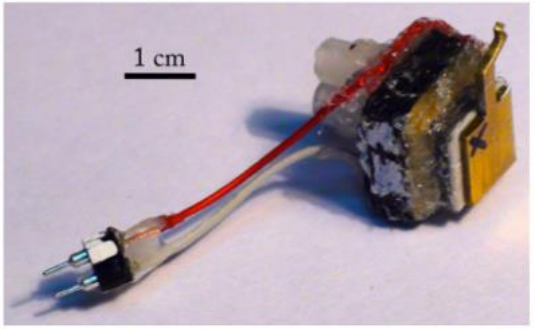


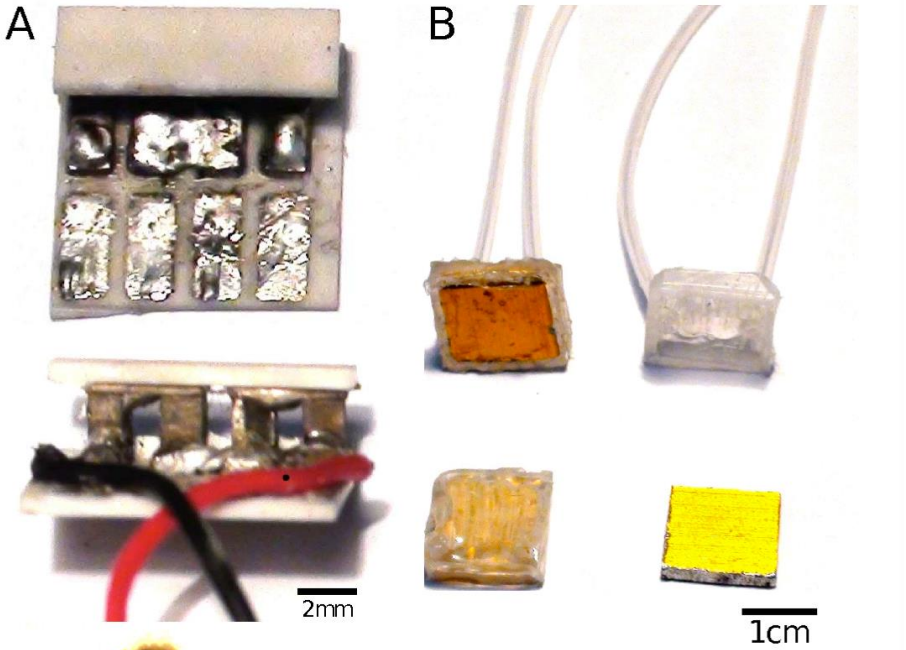


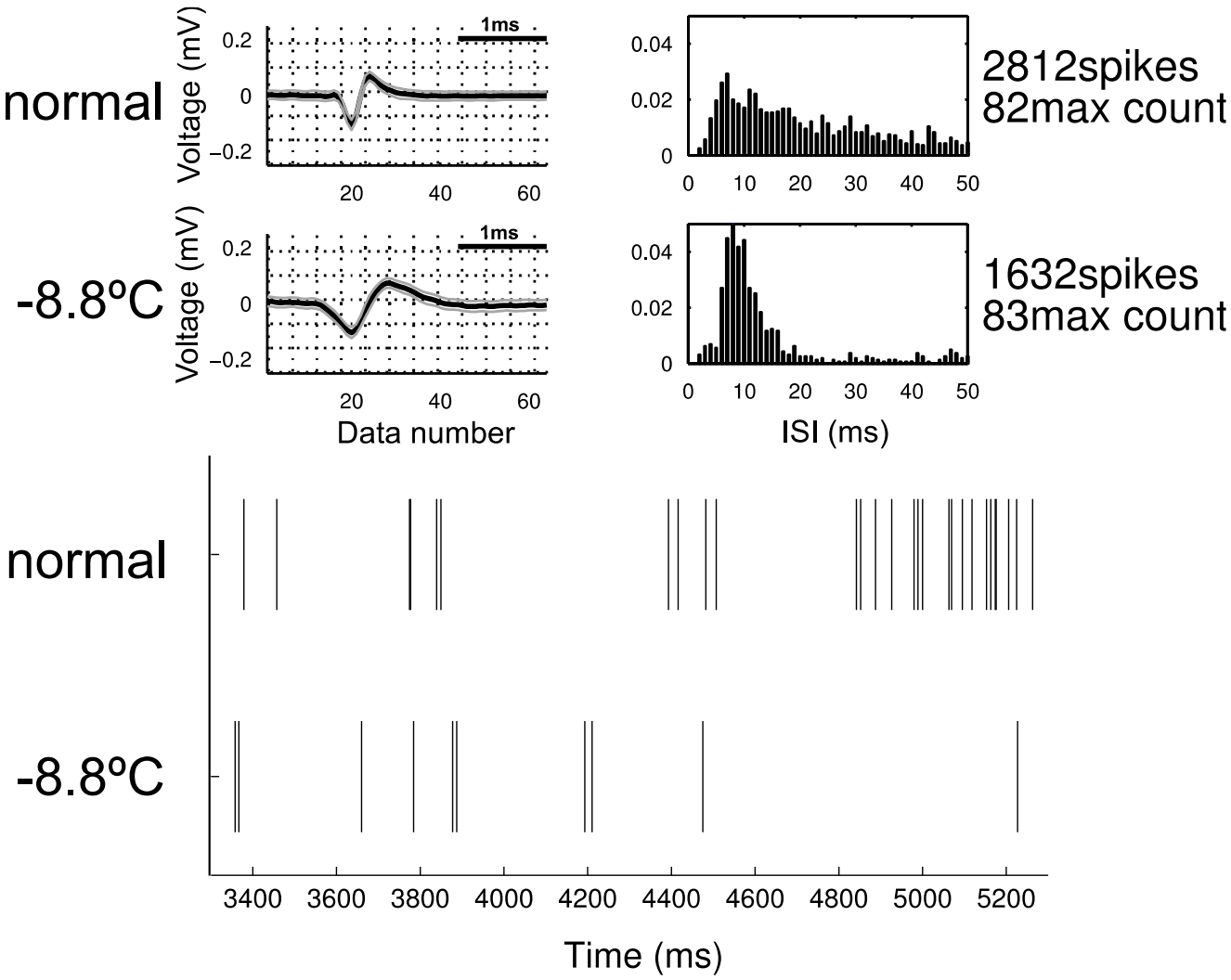




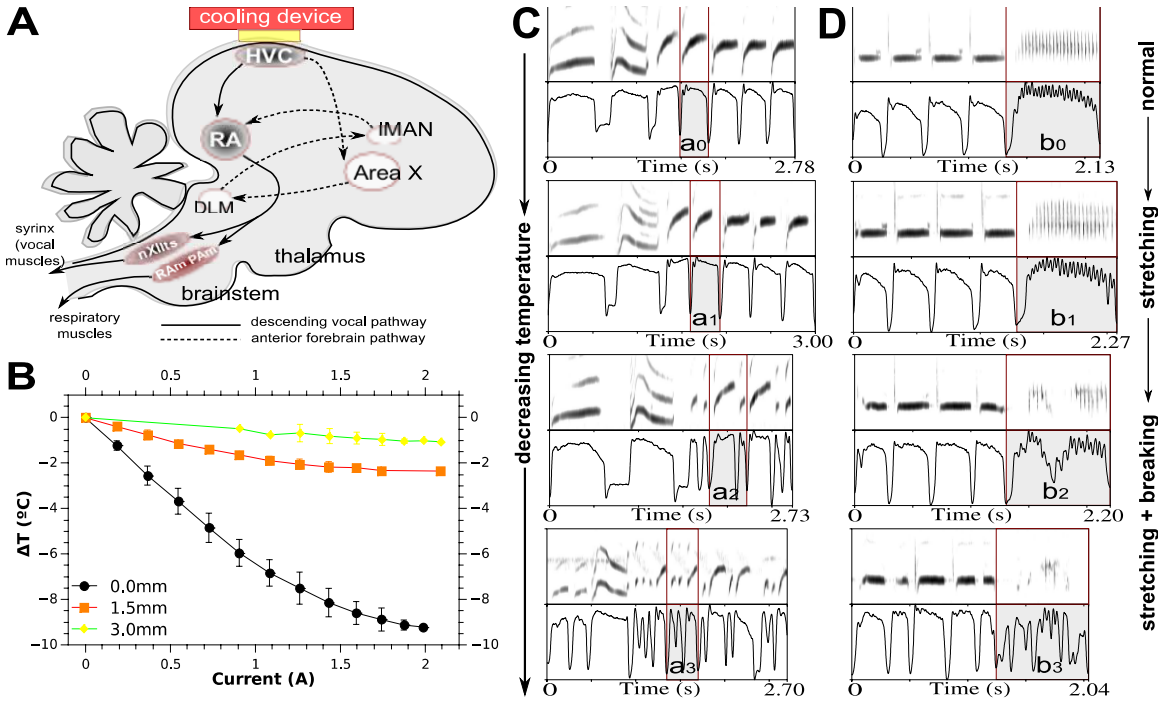


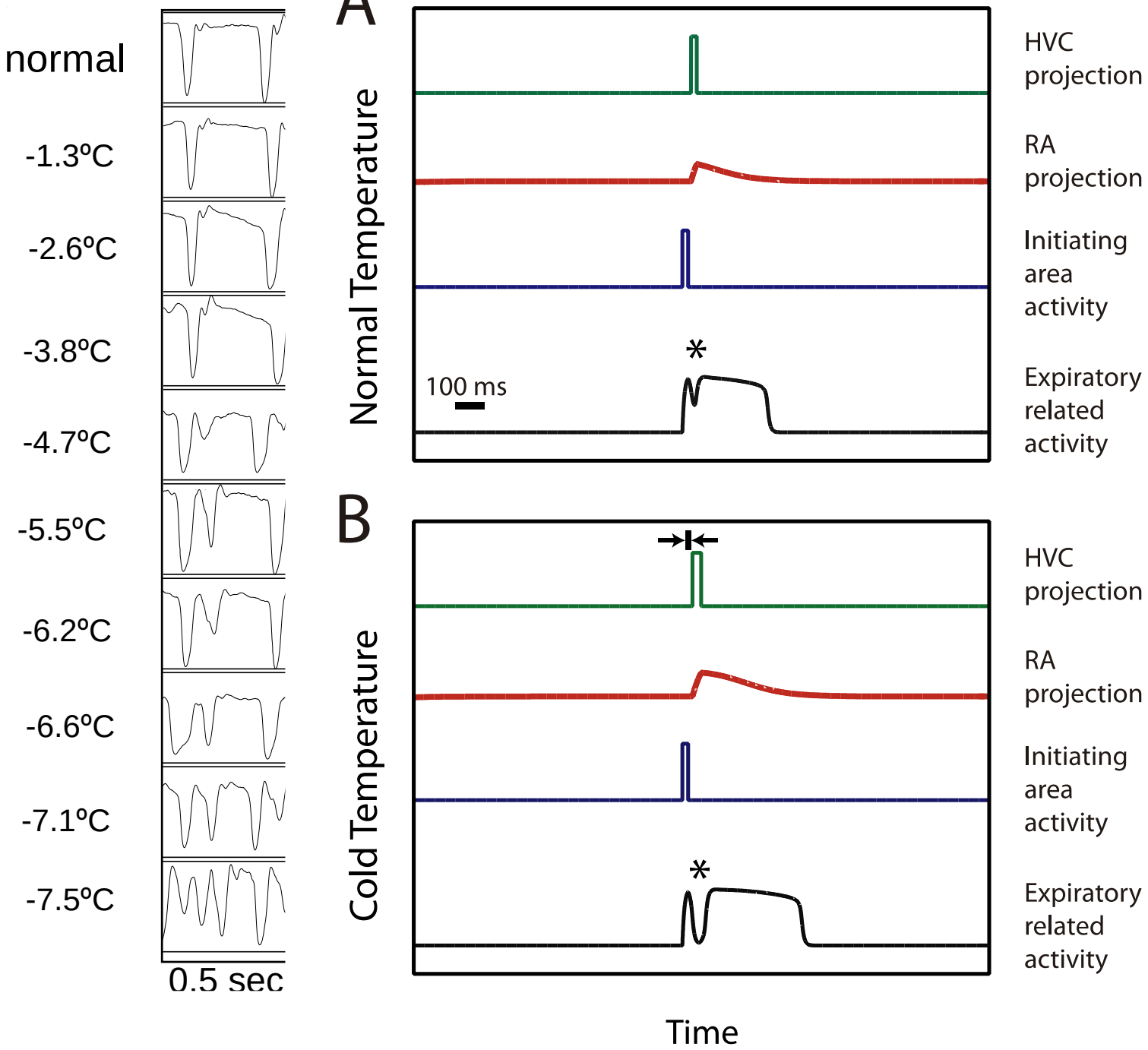



A
B
2mm
1cm
C
D


normal
-8.8ºC
Voltage (mV)
1ms
0.2
0
−0.2
20
40
60
Data number
0.04
0.02
0
0
10
20
30
40
50
ISI (ms)
2812spikes
82max count
1632spikes
83max count
normal
-8.8ºC
3400
3600
3800
4000
4200
4400
4600
4800
5000
5200
Time (ms)

The experimental data




normal
-1.3ºC
-2.6ºC
-3.8ºC
-4.7ºC
-5.5ºC
-6.2ºC
-6.6ºC
-7.1ºC
-7.5ºC
0.5 sec
A
Normal Temperature
100 ms
HVC projection
RA projection
Initiating area activity
Expiratory related activity
B
Cold Temperature
HVC projection
RA projection
Initiating area activity
Expiratory related activity
Time

Conclusions

1. A nonlinear**, low dimensional model** of the syrinx can transduce relatively simple sinstructions into realistic sounds.
2. There seems to be a hierarchy of **progressive simplicity**: those relatively simple instructions are not arbitrary: they are also the solutions of **low dimensional** ODEs.
3. Zebra finches use complex and diverse acoustic units. To build a model for the physiological instructions we chose to work with canaries.
4. Our model requires expiratory related areas receiving a direct input and a processed one, integrated in a circular architecture.
5. Why would bursts occur at GTEs? Auditory-motor integration?

Conclusions

- Physics and Biology. The paradigms are not necessarily incompatible. Hierarchies of importance can be established and progressive modeling is possible.

- Evidence of low dimensional dynamics at the level of the periphery

- Evidence of low dimensional dynamics at the level of the CNS?