Lecture 3

The neuroethology perspective in neuroscience.
Case of study: models of vocal production in birds.

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Neuroethological approach
Neuroethological approach

Neuroethology: interdisciplinary science that combines neuroscience and ethology (study of animal behavior in natural conditions).
Neuroethological approach

Available online at www.sciencedirect.com

Spikes alone do not behavior make: why neuroscience needs biomechanics
ED Tytell¹, P Holmes² and AH Cohen³

Current Opinion in Neurobiology 2011, 21:816–822
www.sciencedirect.com
Neuroethological approach

Case of study: birdsong production

The vocal organ and the brain are nonlinear devices.
Why songbirds?

• Well-established animal model to study:
  ➢ mechanisms of vocal learning
    (not common in mammals).
  ➢ complex motor control.

• Shared properties with humans:
  ➢ Similar learning stages.
  ➢ Similar sound production mechanisms.
The behavior: birdsong

Zebra Finch song

The song is like a fingerprint:
Every individual has its Own Song (BOS)

- Complex sounds
- Spectrally rich
- Highly repetitive

Spectrogram: visual representation of song

Frequency (Hz)

0

10^4

50ms
The behavior: zebra finch song

Complex and stereotyped song

b Spectrally rich notes

c Almost tonal notes
Avian vocal organ

Syringeal muscles + respiratory muscles

Credits: Rod Suthers
When physics and biology meet...

- Biology is used to complexity
- Physics is obsessed with simplicity
Dynamical system model for the syrinx

Sound is generated by modulations of the airflow passing through the syrinx.

The motion of the oscillating labia is represented as a surface wave propagating in the direction of the airflow.

Equation of motion:

\[ m \ddot{x} + \beta(\dot{x}) \dot{x} + \kappa(x) x + c x^2 \dot{x} + f = P_s a_{lab} \frac{\Delta x + 2 \tau \dot{x}}{x_0 + x + \tau \dot{x}} \]

- \( m \ddot{x} \): nonlinear dissipative force
- \( \beta(\dot{x}) \dot{x} \): nonlinear restitution force
- \( \kappa(x) x \): collision force
- \( c x^2 \dot{x} \): active gating
- \( f \): subsyringeal pressure

\[ k(x)x = k_1 x + k_3 x^3 \]
\[ \beta(x) \dot{x} = \beta_1 \dot{x} + \beta_3 \dot{x}^3 \]
Dynamical analysis of the model

Parameters $k_1$ and $P_s$ are related to physiological variables:

$k_1 \propto$ activity of vS syringeal muscle

$P_s \propto$ subsyringeal pressure

**Bifurcations:**

**H: Hopf:**
- almost tonal
- frequency defined by $k_1$

**S: SNILC:**
- spectrally rich
- fundamental frequency defined by pressure

Numbers indicate regions of the parameter space with qualitative similar outputs
Dynamical analysis of the model

Parameters $k_1$ y $P_s$ are related to physiological variables:

$k_1 \propto$ activity of vS syringeal muscle
$P_s \propto$ subsyringeal pressure

**Bifurcations:**

**H: Hopf:**
- almost tonal
- frequency defined by $k_1$

**S: SNILC:**
- spectrally rich
- fundamental frequency defined by pressure
Complete model

Normal form reduction

Normal form

\[
\frac{dx}{dt} = y \\
\frac{dy}{dt} = -\alpha(t)\gamma^2 - \beta(t)\gamma^2 x - \gamma^2 x^3 - \gamma x^2 y + \gamma^2 x^2 - \gamma xy
\]
Generating synthetic songs: source

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

\(x\): medial position of a labium
\(\alpha\): pressure of the air sac system, \(\beta\): tension of the syringeal labia

Dynamical analysis of the sound source
Generating synthetic zebra finch songs

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

- \(x\): medial position of a labium
- \(\alpha\): pressure of the air sac system
- \(\beta\): tension of the syringeal labia
- \(\gamma\): scale factor

Looks good! Sounds good! But is this relevant?
Synthetic copies of zebra finch song

Neural recordings to validate the model

Ask the bird!

Extracellular recordings

Bird’s Own Song (BOS)

Synthetic copy (SYN)

Neuronal soma

Detection radius
Neural recordings to validate the model

Neural selectivity in the song system

Neurons respond to the *auditory presentation* of the bird’s own song (BOS) with a *distinctive pattern*. No other auditory stimulus elicits any response.
Synthetic copies of zebra finch song

\[
\begin{align*}
\frac{dx}{dt} &= y \\
\frac{dy}{dt} &= -\alpha(t) \gamma^2 - \beta(t) \gamma^2 x - \gamma^2 x^3 - \gamma x^2 y + \gamma^2 x^2 - \gamma x y
\end{align*}
\]

- $x$: medial position of a labium
- $\alpha$: pressure of the air sac system
- $\beta$: tension of the syringeal labia
- $\gamma$: scale factor

Zebra finch song

BOS

SYN
Testing the model

Neurons in HVC respond selectively to the Bird’s Own Song (BOS)

Guess what happens when testing the model in this way

Sound presentation during sleep
Neurons in HVC respond selectively to the Bird’s Own Song (BOS)

Testing the model

Sound presentation during sleep
What do we do now ???

NEVER GIVE UP

NEVER SURRENDER
The challenge is to remain simple!

This is not working
A more detailed modeling

✓ More detailed modeling of the vocal tract (before: 3 tubes).

Oropharyngeal cavity as a resonator

✓ Noise in the labial tension (controlled by syringeal muscles)

\[
P_i(t) = v(t)x(t) - rP_i(t-T)
\]

Filter action

\[
\begin{align*}
\frac{dx}{dt} &= y \\
\frac{dy}{dt} &= -\alpha(t)\gamma^2 - \beta(t)\gamma^2x - \gamma^2x^3 - \gamma x^2y + \gamma^2x^2 - \gamma x y
\end{align*}
\]

Same source

Amador et al, Nature 2013
A more detailed modeling

Amador et al., Nature 2013
A more detailed modeling

**Before**

- No noise in Vs activity
- No oropharyngeal cavity

**After**

- ✓ Noise in Vs activity
- ✓ Oropharyngeal cavity
Synthetic copies of zebra finch song

Neural selectivity in the song system

Extracellular recordings in HVC (sensorimotor nucleus)

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

Amador et al. (2013) Nature
The synthetic song elicits the same neural response than the bird’s own song

Amador et al, Nature 2013
• A **minimal model** is able to generate **complex behavior** that is coded by neurons in the same way as natural behavior.

• We can now use the mathematical model as a **tool** to **study motor control, auditory perception** and **neural coding** in songbirds.
Studying relevance of static parameters

Decreasing presence of the cavity

Dissipation

Noise

Amador et al. (2013) Nature
Studying relevance of static parameters

Decreasing presence of the cavity

Dissipation

Spikes/bin Trial number

0.5 s

Amador et al. (2013) Nature
Hierarchy of static parameter relevance

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

Grouped data:
- 4 birds
- 30 selective HVC neurons

The noise has a specific value that maximizes the neural responses.

Amador et al. (2013) Nature
Gracias por su atención!

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