Sensory guidance of locomotion in leeches and flatworms

KitP qBio Summer School
UCSB
6 August 2018

Bill Kristan
Neurophysics of sensory navigation

How animals sense and move in a stimulus gradient

Two recurring strategies:

1. Spatial difference: two (or more) receptors at one time.

2. Temporal difference: two (or more) measurements by the same receptor(s) at different times.
   - continuous or discontinuous gradient.
   - during movements either along or across the body axis.

Three projects, each looking at different gradients in different worms:

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Leeches come in a variety of shapes and sizes.
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*Helobdella austinensis*

*Hirudo verbana*
*Dugesia japonica* (flatworm)

Dylan Le
Eva-Maria Schoetz-Collins
The flatworms are actually quite small:

- Helobdella austinensis
- Hirudo verbana
- Dugesia japonica
- Flatworm
- Small leech
- Big leech
Flatworms move away from light

Move forward ("glide"): beat cilia on ventral surface
Turn by contracting longitudinal muscles in body wall
Flatworm negative phototaxis

Initial distribution of ~100 flatworms

1 minute after turning on a light
Flatworm neuroanatomy

- Eyes
- CNS Regeneration
- Neoblasts and ovo+ cells
- Optic cup cells and photoreceptor neurons
- Axonal projections and ovo+ cells
- Regeneration after surgery and morphallaxis
Responses of individual planaria:

Provisional conclusion: planaria use an intensity comparison between the two eyes to avoid bright light.

Akihiro Yamaguchi will test this idea in the next 3 weeks.

Small leech moves to smooth surfaces, food
Small leeches on sandpaper of differing roughness

Kim, Le, Ma, Heath-Heckman, Whitehorn, Kristan, Weisblat (2018)
Number of steps on a uniform substrate (small leech)

<table>
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<tr>
<th>Time (min)</th>
<th>80 Grit</th>
<th>150 Grit</th>
<th>320 Grit</th>
<th>400 Grit</th>
<th>600 Grit</th>
<th>1500 Grit</th>
<th>Control</th>
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<tbody>
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<td>0</td>
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Kim, Le, Ma, Heath-Heckman, Whitehorn, Kristan, Weisblat (2018)
Small leeches choose smoother surfaces

Kim, Le, Ma, Heath-Heckman, Whitehorn, Kristan, Weisblat (2018)
Small leeches make L/R scanning movements before stepping:

...and make more head-lifts on coarser surfaces.

Jiayin Hong will tell you more about this at the end of the course.

Kim, Le, Ma, Heath-Heckman, Whitehorn, Kristan, Weisblat (2018)
Large leech moves into water waves, moving shadows
Qualitative description of scan behavior in the big leech
Heading changes after scanning behavior in the big leech

http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0086120
Scanning behavior becomes localized to a given stimulus (big leech)

In a tank above the leech tank

In the dark

http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0086120
S cell responses to mechanical and visual wave stimuli (big leech)

Mechanical stimulation

Visual stimulation

10 s mechanical wave stimulus

10 s visual wave stimulus

1 Hz

10 spikes s⁻¹

8 Hz

10 s mechanical wave stimulus

10 s visual wave stimulus

Andrew M. Lehmkuhl et al. J Exp Biol 2018;221:jeb171728
Dependence of S cell responses on wave direction (big leech)

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Dependence of S cell responses on wave direction (big leech)

Next steps: Jess Kanwal
Optical activity in motor neurons during swimming

Data of Adam Taylor
Some neurons are active during both crawling & swimming

- Neurons in phase with swim: 90
- Neurons in phase with crawl: 188
- Total neurons recorded: 350

How swimming and crawling interact

Swimming and crawling seem to be different dynamic states of the same neuronal network.
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Theodosius Dobzhansky, "Nothing in Biology Makes Sense Except in the Light of Evolution" (1973)

Kristan dictum (2018): Nothing in neuroscience make sense except in the light of behavior …..and even then, not always!
Behavioral choice group

KRISTAN LAB
* Kevin Briggman
  Tim Cacciatore
  Teresa Esch
  Paxon Frady
  Kathy French
* Quentin Gaudry
* Chris Palmer
  Brian Shaw
  Adam Taylor
  Krista Todd
  Daniel Wagenaar

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  Roger Tsien
  Tito Gonzalez
  Evan Miller
  Gary Cottrell
  Henry Abarbanel

Karen Mesce-U Minn
Eric Horvitz-Microsoft Research
Peter Brodfuehrer-Bryn Mawr
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National Institute of Neurological Diseases and Stroke

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Microsoft Research
Richard Geckler
Some hard-won wisdom:

• If you can think of a possible mechanism, it will be found somewhere …along with several others you never imagined.

• There are few clear dichotomies in biological systems… reality will always be “both”, “in between”, or “other”.

• “Model system” is a slippery concept, depending on the definition*:
  1. A substitute for the real system (e.g., human)
  2. The best system for approaching a given problem

• There is no such thing as a “simple system”!

• New tools (e.g., molecular, imaging, computational) are extremely effective —be prepared to use them all!

SUMMARY AND SPECULATIONS

Decision-making can use a number of mechanisms:

• inhibition of sensory input (feeding inhibits everything else) ....sledge hammer
• inhibition of command neurons (feeding inhibits withdrawal in Pleurobranchaea)
• alternative states of shared decision-makers (swimming/crawling) ....velvet glove

Decisions may be made in stages:

• take some action ("do something")
• broad decisions ("get out of here")
• more specific decisions ("swim" or "crawl")

Some neurons have multiple functions (cell 208 is a decision-maker and a swim CPG neuron).

Pure speculation: most neurons in complex brains are multifunctional, because new behaviors arise in evolution by using neurons that already have a function.

A consequence of multifunctional neurons: quick transitions between behaviors:
Why a leech?

August Krogh (1874-1949)

Danish comparative physiologist

“For such a large number of problems there will be some animal of choice, or a few such animals, on which it can be most conveniently studied.”

“Krogh’s Principle”

Ted Bullock (1915-2005)

“Use the best animal to answer any particular question”
Why a leech?

Walter Heiligenberg
(1938-94)
“Use the champion animal”

Ted Bullock
(1915-2005)
“Use the best animal to answer any particular question”
Why a leech?

1. Can study a neuronal circuit from sensory input to motor output.
   Can drive each circuit into the ground.
   Totally.

2. Its behaviors are distinct and robust.

3. Its neurons are readily recordable, with both electrodes and voltage-sensitive dyes.

4. Its neurons are identifiable from animal to animal.

5. It has just the right number of neurons:
   • circuits are similar to those in more complicated animals.
   • because there is little or no redundancy, can test for necessity and sufficiency at the cellular level; i.e., a single neuron affects behavior.
Leeches make decisions to crawl......
…or to swim