

INTEGRATIVE MODEL OF DYNAMIC FACILITATION IN INSECT VISION

Patrick Shoemaker

Computational Science Research Center

San Diego State University

San Diego CA



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Dr. P. Bradshaw, PM

INTRODUCTION

➤ WHAT IS THE SYSTEM UNDER CONSIDERATION?

- Visual processing stream that detects small moving objects:
Small Target Motion Detector (STMD) neurons

➤ WHAT DOES 'DYNAMIC FACILITATION' MEAN?

- An increase in responsivity to small moving objects w/ prior exposure to continuous object motion

➤ WHAT MODEL ANIMALS?



Dragonflies, Hoverflies
& (putatively) Fruit Flies



➤ WHAT IS THE MODEL TO BE INTEGRATED WITH?

- A 'Framework' for STMD processing: model elements developed over last 2 decades

INTRODUCTION

➤ **OBJECTIVES:** To better understand

- How dynamic response facilitation in insect small target motion detection neurons (STMDs) is implemented;
- Computational implications with respect to small target detection & tracking;
- Relationship to other elements in same visual processing stream

➤ **GOALS:**

- To elaborate a biologically-based model for response facilitation;
- To integrate this model into a larger model framework for small target motion detection
- To test & refine the model via neurophysiological & neuropharmacological experiments;
- To identify (possible) broader applicability of the findings to neural computation, beyond model organisms

GENERAL PROGRESS

- **YEAR 1: Primary activities = organization, preparation, data mining**
 - Defined modeling approach (facilitation mediated by wave propagation);
 - Expanded focus to *Drosophila*
 - Added collaborators: Wiederman (U Adelaide), Frye (UCLA)
- **Initiated work with Frye lab (UCLA) re: *Drosophila***
 - Examining classes of lobula columnar cells as putative STMDs
- **Administrative / Hiring (Sep 2024):**
 - **MS Student: Teresa Christie**
 - Biology degree from Boston University;
 - 9.5 years as a US Naval officer;
 - **Undergrad research assistant (paid program): Isabelle Bernal**
 - Collaborative project w/ UCLA (connectome mining)

SMALL TARGET MOTION DETECTOR NEURONS

- Neurons in 3rd optic ganglion (lobula) & central brain
(In dragonfly & hoverfly)
- **Sensitive to & selective for** small moving objects
- Two types:
 - **Small-field** and **wide-field** cells (meaning field-of-regard)
 - Small-field cells distributed across visual field
 - *Retinotopically* mapped
 - Wide-field may integrate small-field outputs
- Possible analogs to sf-STMDs found in fruit fly*
 - ID: LC11 (Lobula Columnar Cell 11) (possibly also LC18)
 - Studied with calcium imaging
- Interest piqued by *Drosophila* connectome!

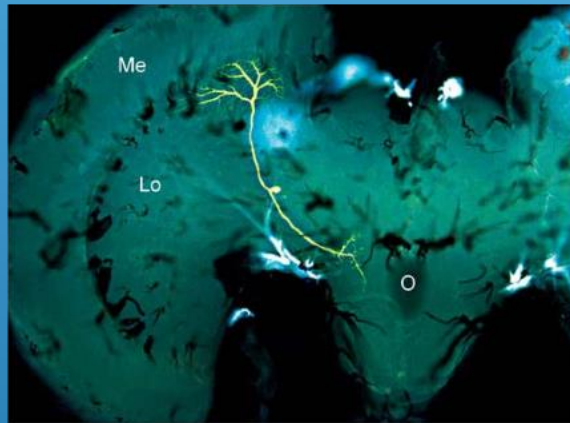
*Keleş, Frye, *Curr Biol* 27, 2017;
Klapoetke et al., *Neuron* 110, 2022

STMD NEURONS:

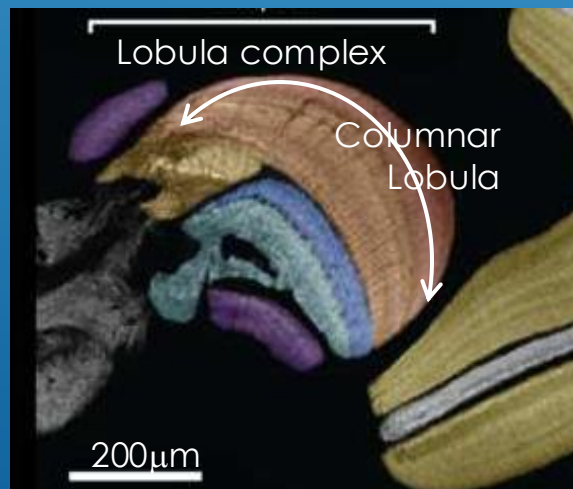
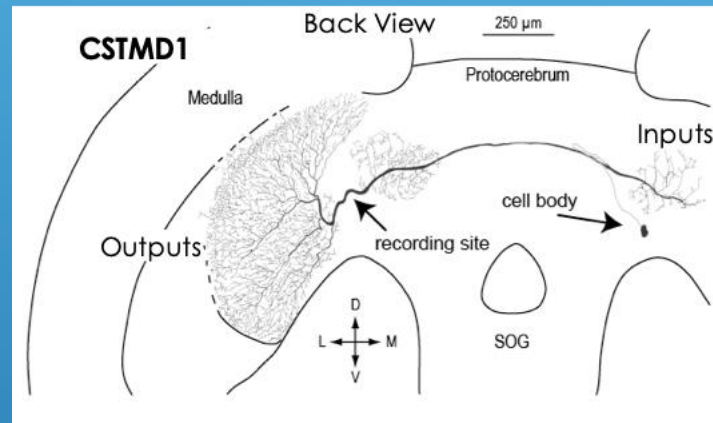
- Various STMDs recorded from lobula, deeper brain in dragonfly & hoverfly

----- DRAGONFLY →

Dye-fill, STMD that projects from lobula to central brain



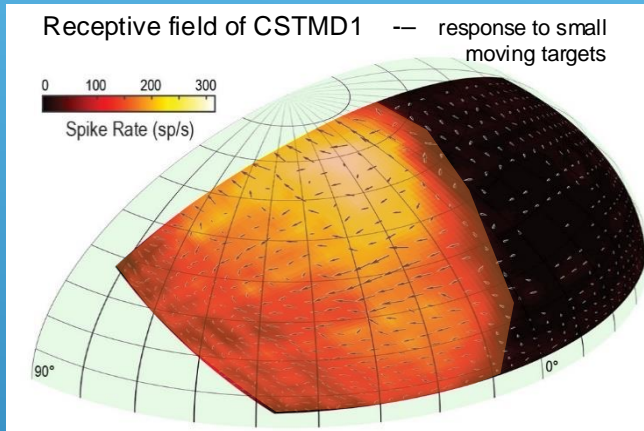
CSTMD1: identified wf cell, lab 'workhorse'; projects to contralateral brain & entire lobula



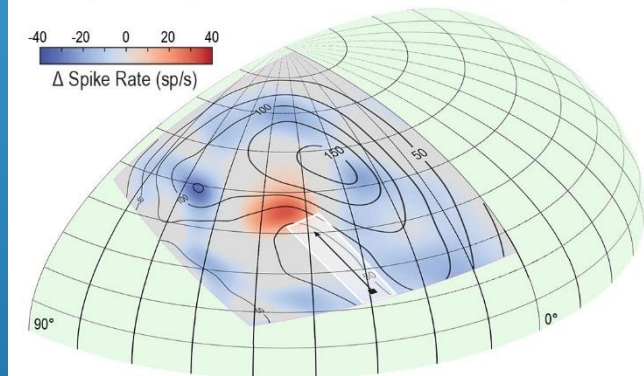
Small-field STMDs arborize in columnar, retinotopic part of lobula, in dipterans as well as dragonflies

Image: Fabian, el Jundi, Wiederman, O'Carroll

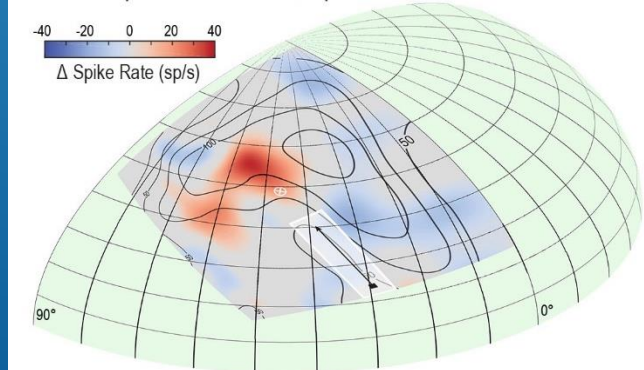
RESPONSE FACILITATION IN WIDE-FIELD STMDs:



b. Change in receptive field induced by primer (vertical)



c. Vertical primer with 300 ms pause



FACILITATION:

AN INCREASE IN *EXCITABILITY*
WITH EXPOSURE TO TARGET
MOVING ON A CONTINUOUS PATH

FACILITATION IS SPATIALLY LOCAL

It appears near / in front of a target that has
moved along a continuous path;

Remainder of the receptive field: *depressed*
responsiveness

It appears to *propagate* in retinotopic space
after stimulus ends! (=> predictive aspect)

Wiederman, Fabian, Dunbier, O'Carroll, eLIFE 6:e26478, 2017

FACILITATION IN wf-STMDs:

INITIAL APPROACH:

- MODEL W/ WAVE PROPAGATION IN A 2-D MEDIUM
- MEDIUM IS PRESUMED TO BE:
 - A retinotopically-organized network of cells, local to where facilitation takes place
 - Excited / activated by inputs to STMD neurons (e.g., some form of 'elementary STMD'*);
 - Able to supply neuromodulatory signals to STMDs

*Wiederman, Shoemaker, O'Carroll, *PLoS ONE* 3: e2784, 2008

Wiederman, Shoemaker, O'Carroll, *J Neurosci* 33, 2013

TASK: *Phenomenological* characterization of (putative) wave propagation (in dragonfly)

- Propagation speed
 - Speed dependence on stimulus velocity?
- Wave amplitude
 - Reinforcement by traveling stimulus
- Wave damping
 - Decay of facilitation after cessation of stimulus
- Directional Characteristics
- Wavefront shape & extent
 - Wake characteristic: moving point excitation in 2-D medium should generate a wave with a wake

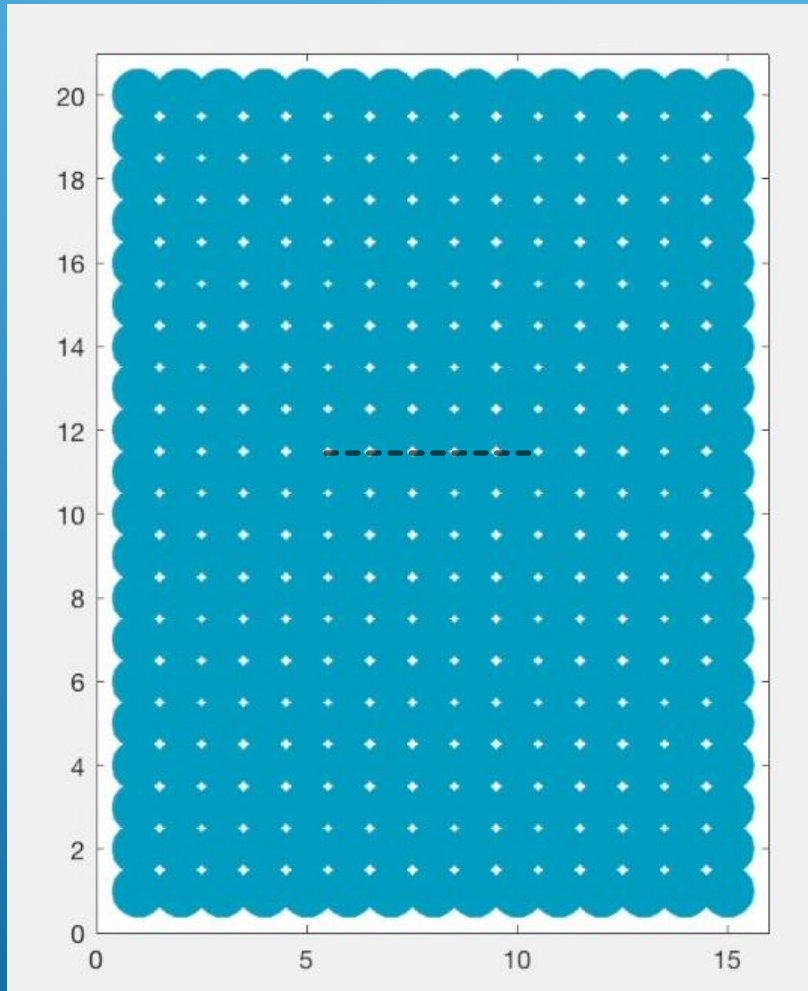
NBO = Nordström, Bolzon, O'Carroll, *Biol Lett* 7, 2011

DWSO = Dunbier, Wiederman, Shoemaker, O'Carroll, *Front Neur Ckts* 6, 2012

WFDO = Wiederman, Fabian, Dunbier, O'Carroll, *ELife* 6:e26478, 2017

FDOW = Fabian, Dunbier, O'Carroll, Wiederman, *J Exp Biol* 222, 2019

EXAMPLE 2-D WAVE PROPAGATION



- **‘Wave Plane’
driven by moving
point excitation**

**Stimulus traverses
half the network, then
vanishes**

Phenomenological characterization of (putative) wave propagation

- Propagation speed

- In the range of 30°/s to 40°/s (in visual space) (WFDO, FDOW)
 - Must be transformed to putative brain region by retinotopic mapping
- Does NOT appear to have appreciable dependence on *stimulus* speed, over 2–3X range (FDOW)

- Wave amplitude

- CONFLICTING RESULTS ON *BUILDUP OF FACILITATION*:

in most experiments, reinforcement by moving stimulus occurs over trajectories of tens of degrees (NBO, DWSO), although facilitation appeared complete in $<10^\circ$ in another result (FDOW)

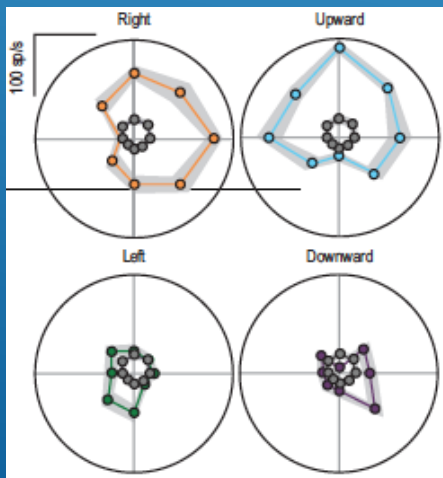
Phenomenological characterization of (putative) wave propagation

- Wave damping

- Post-stimulus: facilitation propagates w/ significant effect for 300ms (9°-12° spread); has largely died out after 500ms (WFDO, FDOW)

- Directional Characteristics

- Target motion away from midline and away from equator significantly more effective at inducing facilitation (dragonfly, upper-frontal 'acute zone', right eye) (WFDO)

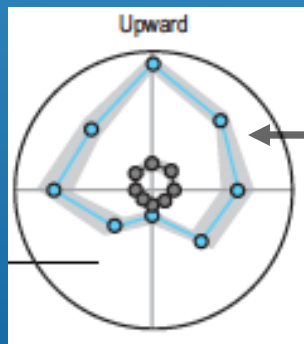


Polar plots: Response amplitude (radius) versus direction (angle) of probe stimulus, following priming stimulus in each of 4 cardinal directions

=> Anisotropic wave propagation?

Phenomenological characterization of (putative) wave propagation

- Wavefront shape & extent
 - **RECALL:** polar plots depict facilitation for probes in different directions than primer
 - ⇒ These are DE FACTO evidence for existence of a wake, in the context of the wave model
 - (However, approximate symmetry => complication for interpretation: anisotropic wave propagation)



(WFD0)



WAKE in 2-D retinotopic space

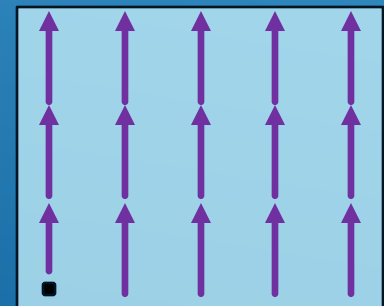
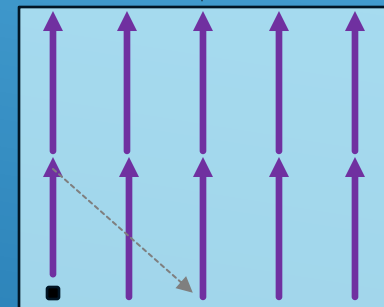
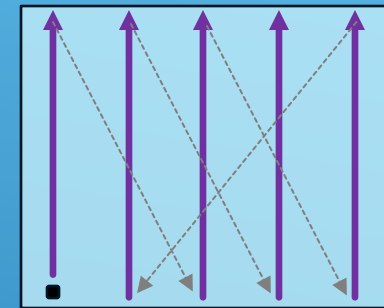
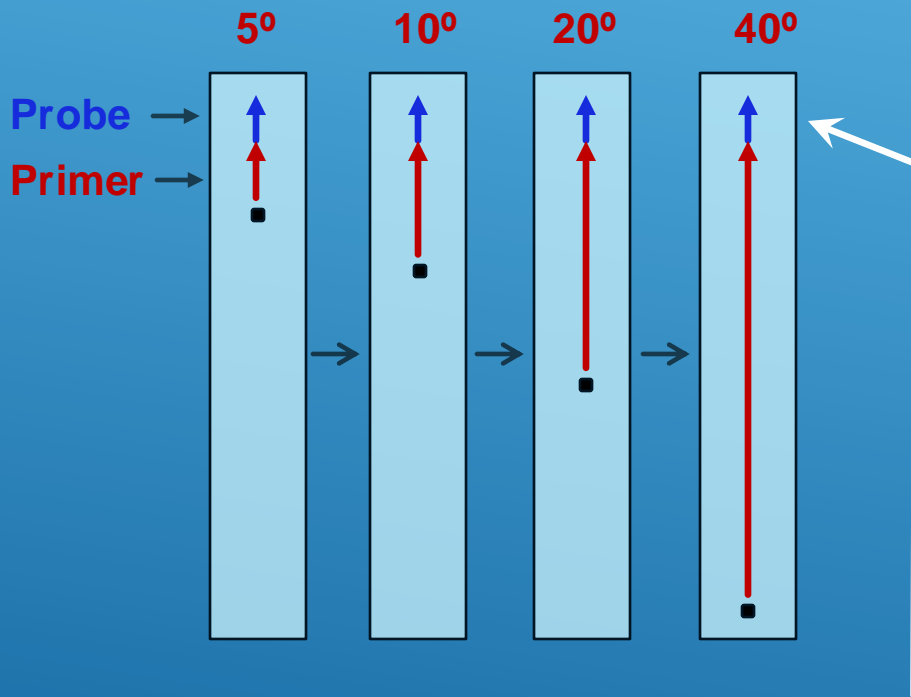
Facilitation for motion in different directions

TASK: Re-analyze 'outlier' data showing facilitation complete w/ short primers

Experiment of Fabian et al.:

vs.

Dunbier et al.:



Probes land in same location in visual field:

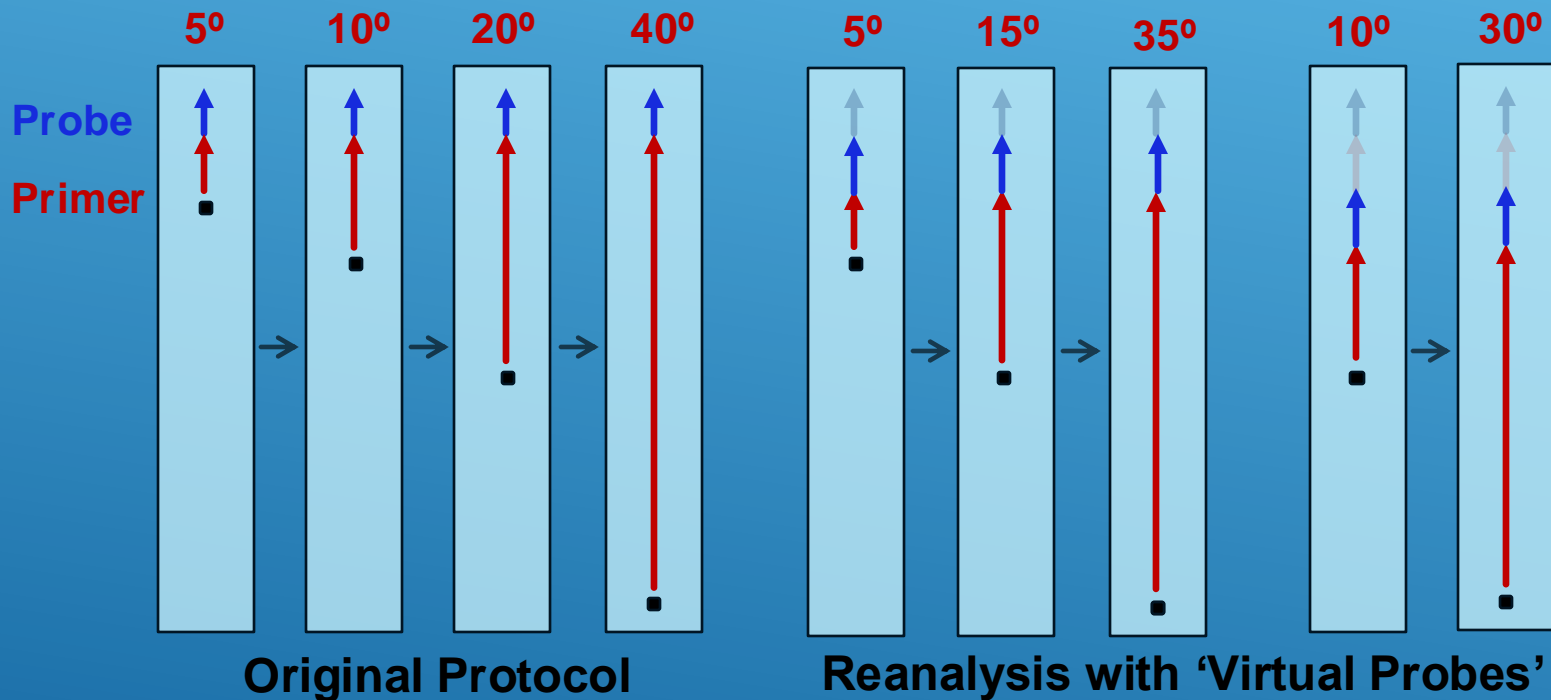
The “hot spot” = region of maximal excitability

Maybe facilitation masked by response saturation?

Re-analysis of *Fabian et al.* data:

Experiment of Fabian et al.:

Define 'virtual probes' within trajectories of longer primers

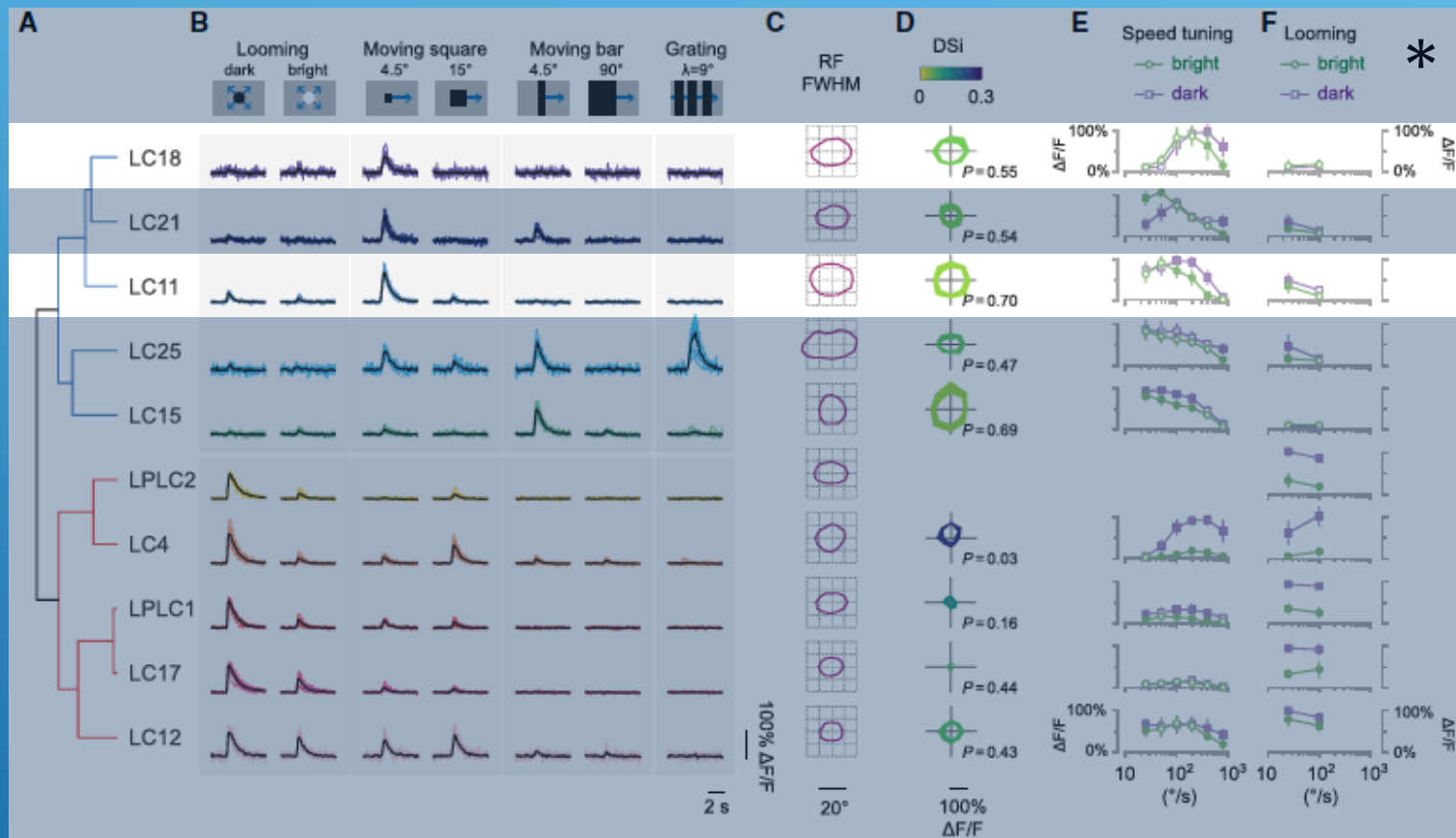


Analyze length dependence of facilitation for
'virtual probes' @ each location

TASK: Examine / evaluate putative sf-STMDs in *Drosophila* (new):

- **Unaware at proposal time of upcoming *Drosophila* connectomes covering (almost) *entire brain***
-
- ***IF Drosophila* possesses analogs to STMDs, great opportunity to expand understanding of overall processing**
 - **Possibility of deeper understanding => model framework**
 - **Have spent more time on this framework issue than anticipated!**
 - **Renewed relationship with Mark Frye @ UCLA**

Small target sensitivity / selectivity among *Drosophila* lobula columnar (LC) cells

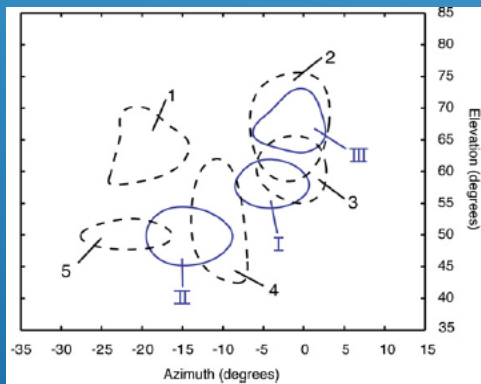


- LC11 and LC18
- Richness & # of inputs (+ other factors) => focus on LC11

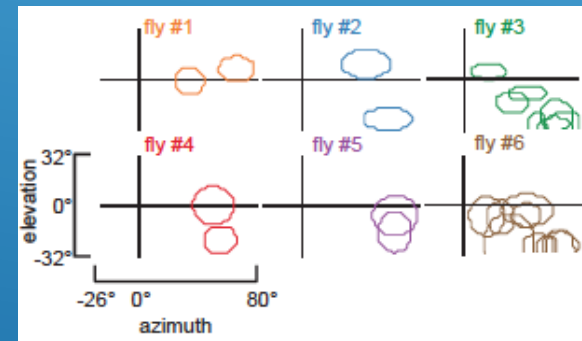
*Klapoetke et al., *Neuron* 110, 2022

Evidence for analogy between *Drosophila* LC11 & sf-STMDs in *Eristalis* (& odonates)

- Both responsive to small moving objects
- Both reject wide-field or larger object (e.g., bar) motion
- Cells arborize in columnar lobula
- Populations have retinotopically-distributed, overlapping, somewhat irregular receptive fields



Eristalis sf-STMD:
excitatory RF spans 5° – 15°
in visual field



Drosophila LC11: excitatory RF
spans 10° – 25° in visual field

AVAILABILITY OF CONNECTOME DATABASES COVERING (almost) ENTIRE *DROSOPHILA* BRAIN:

A Game-Changer



FlyWire



SUBTASK: Develop inventory of what drives LC11

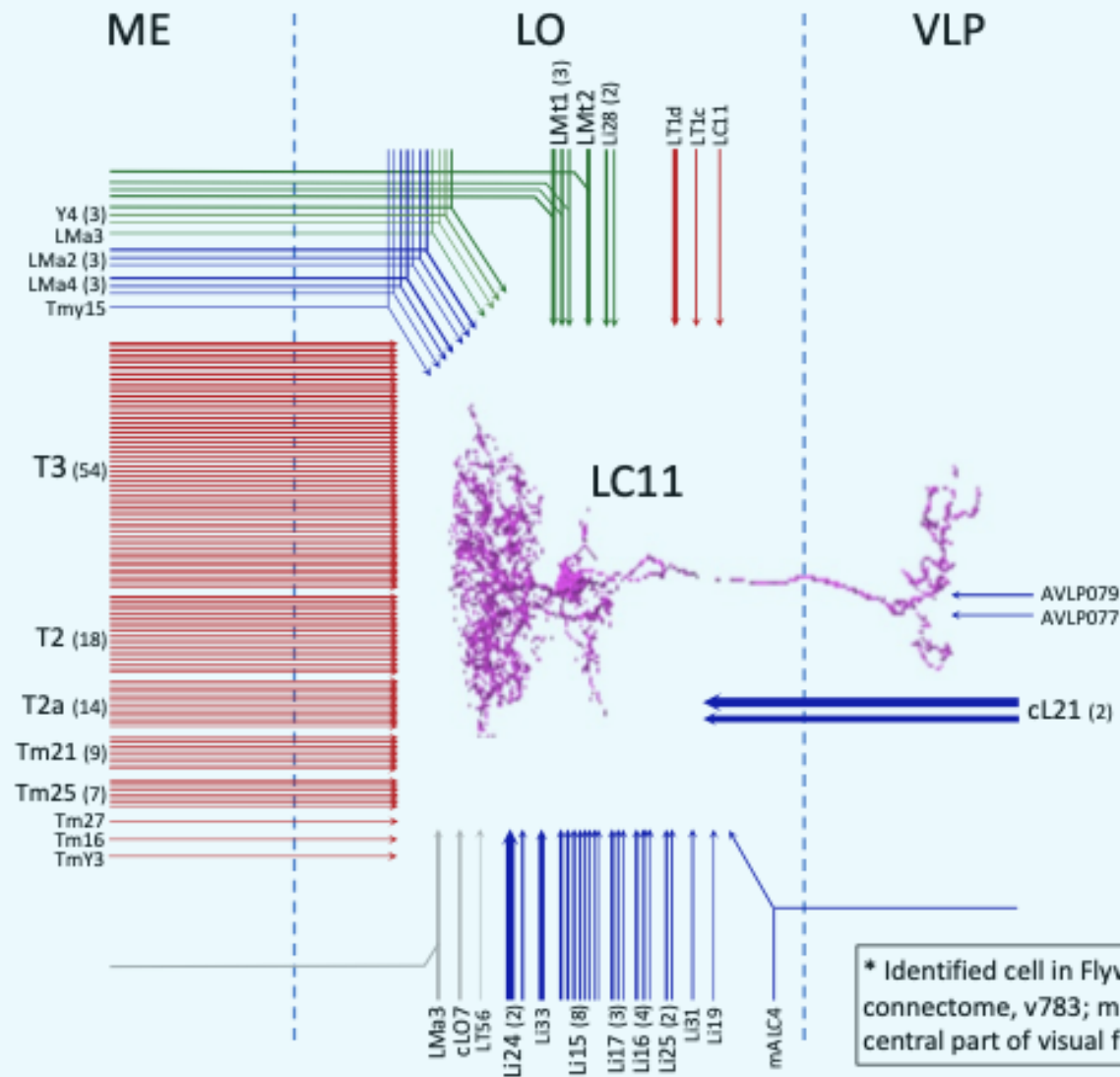
SOURCES OF SYNAPTIC INPUTS TO LC11 NEURON (LO.PVLP.11*)

- EACH LINE/ARROW REPRESENTS AN INPUT (PRESYNAPTIC) NEURON
- ORIGIN OF EACH LINE INDICATES PREDOMINANT SOURCE NEUROPILO FOR INPUT NEURONS
- TWO ORIGINS INDICATES SIGNIFICANT INPUTS FROM BOTH NEUROPILS
- LINE THICKNESS INDICATES NUMBER OF SYNAPSES ONTO LO.PVLP.11 (min. 5, to 39)
- ALL CELL TYPES LABELED

Neurotransmitter Types:

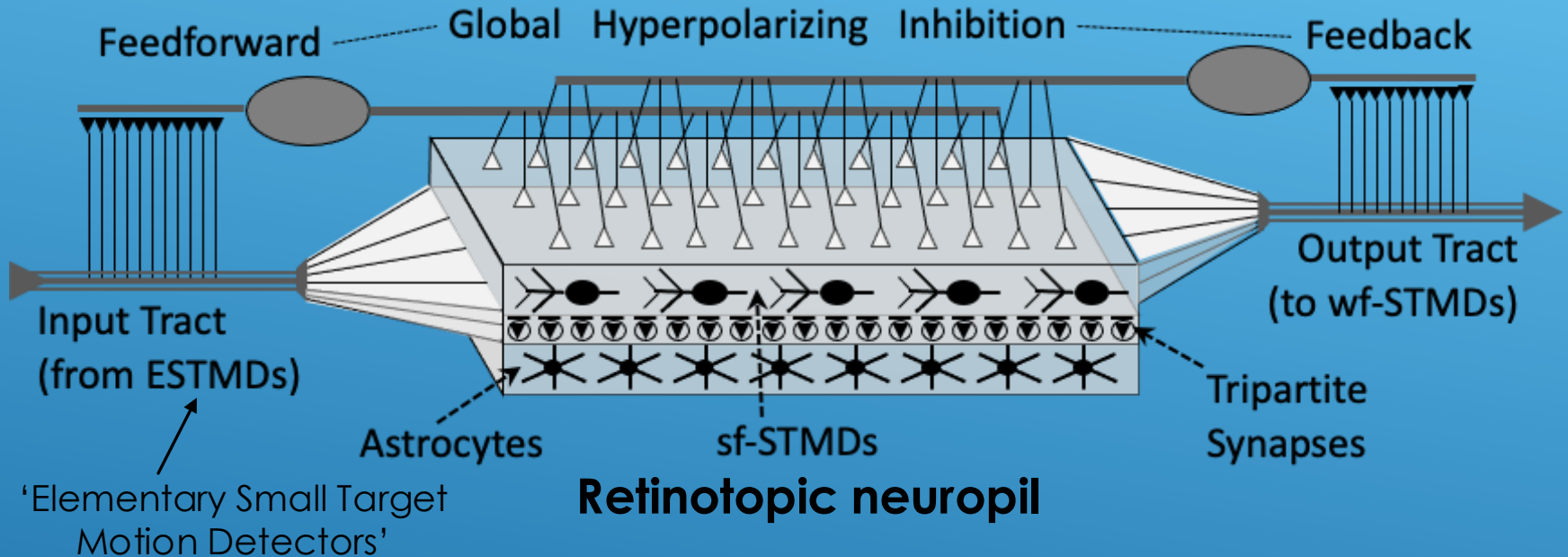
- ACH
- GABA
- GLUT
- Unknown

Unknowns likely either GLUT or GABA



A HYPOTHETICAL MODEL*

Assuming facilitation @ sf-STMDs



- Sparsely active, glutamatergic inputs (w/ some small-object selectivity)
- Interact with sf-STMDs and astrocyte network @ *tripartite* synapses
- Kick off *calcium waves* in astrocyte network
- Influences STMD response via tripartite synapses

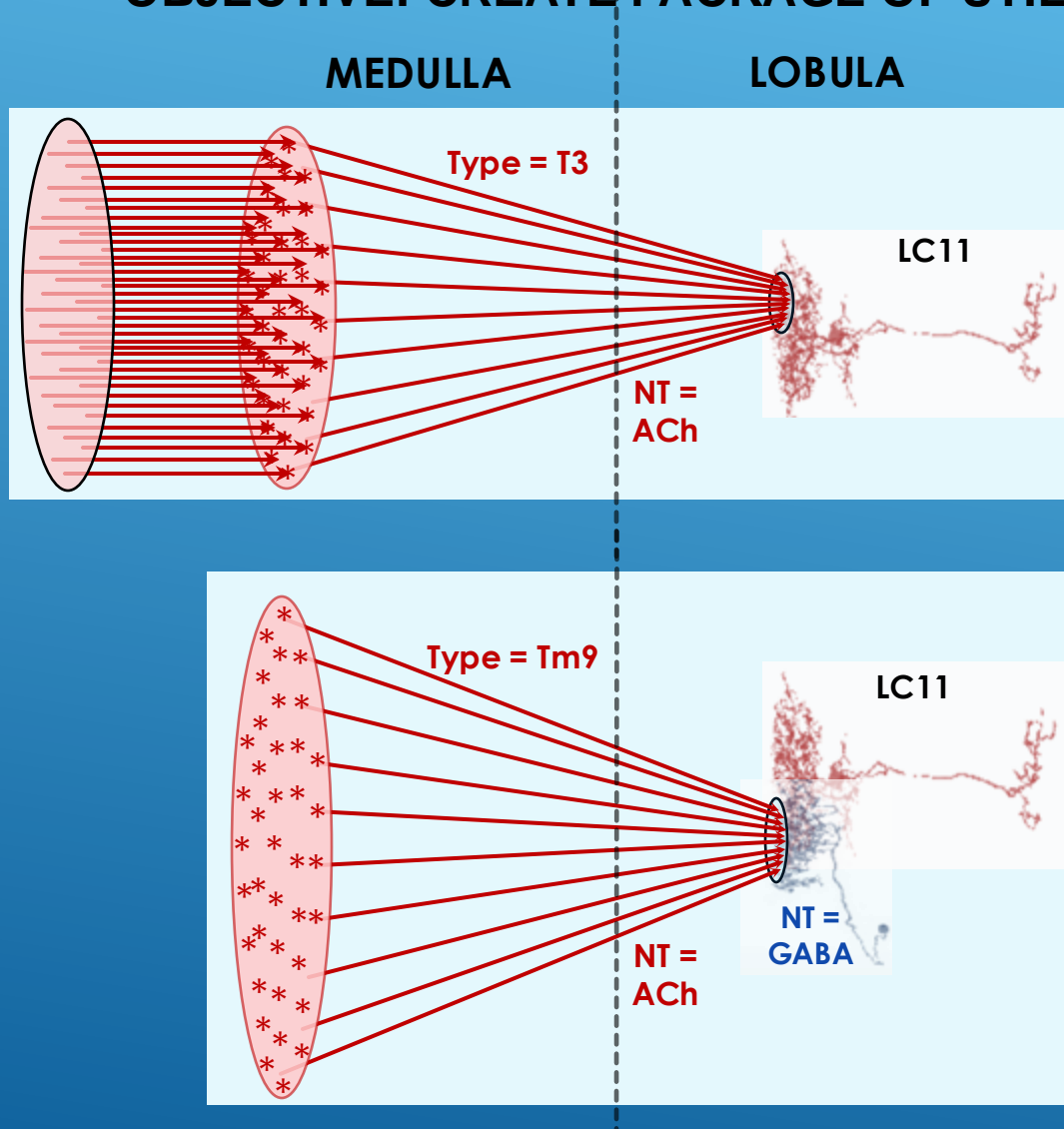
*Shoemaker, Modeling dynamic facilitation in insect small target detection system, *International Conference on Invertebrate Vision*, Kristianstad, Sweden, July-August 2023

CONNECTOME-MINING TASK:

Collaborative work, including SDSU undergrad & UCLA (Frye lab post-docs)

OBJECTIVE: CREATE PACKAGE OF UTILITIES

XING,
LAMINA
to
MEDULLA



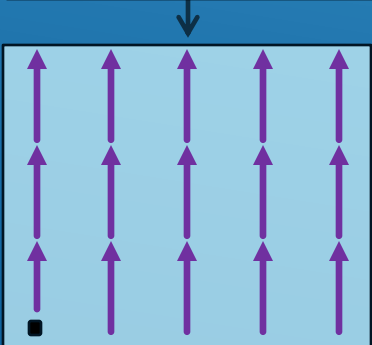
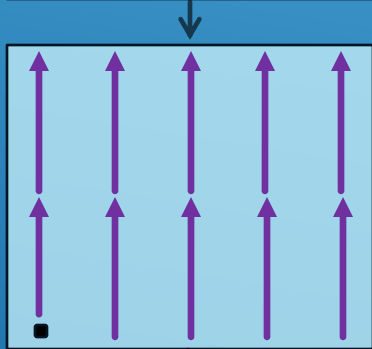
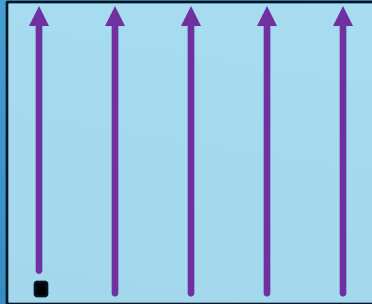
DESIRED CAPABILITY:

- Select cell to analyze
- Select an input neuron type
- Characterize:
 - Neurotransmitter
 - Number of cells
 - Interconnection strength
 - Coverage in retinotopic space
- Do the same for interneurons synapsing onto target

TASK: Experimental design to look for facilitation in LC11 / LC18:

Stimulus idea: replicate protocol of Dunbier et al.

BUT:



- Original experiment: e-phys recording from (single) wide-field STMD
- Proposed experiment: 2p calcium imaging from *population* of small-field cells
- Approach: image from *glomerulus* where all LC11 (or LC18) outputs are localized
- Instead of counting spikes, integrate $\Delta F/F$ over peri-stimulus interval

OTHER ACCOMPLISHMENTS

➤ Leveraging

- Proposal in conjunction with M. Frye in development
Connectivity and physiology of object-detecting neurons, *Drosophila*
- Secured funding for undergraduate research project

➤ Publications

- **In Review:** Modeling Traveling Calcium Waves in Cellular Structures
Shoemaker, Bekkouche: *Journal Computational Neuroscience*

➤ Presentations

- Computational Basis of Visual Motion Detection in Insects
Shoemaker; *CSRC Research Colloquium*, Mar 2024

TO BE DONE, NEXT PERIOD:

- **Experiments: Looking for facilitation in *D.m.***
 - Pilot Experiments on LC11 imminent (< 1 month)
 - Additional cells (LC18), added protocols
- **Computational Modeling**
 - T. Christie & Shoemaker: wave-based model
- **Experiments in *Eristalis***
 - Secure 2nd student
 - To spend a recording season in O'Carroll lab
- **Hypothesis testing, refinement**
 - Design experiments (*Drosophila* & *Eristalis*; numerical)
 - Carry out 1st round, test / refine



MECHANISMS FOR SPATIOTEMPORAL VISUAL FEATURE DETECTION IN INSECTS FY24



**THANKS TO AFOSR AND DR. PAT BRADSHAW FOR
THE SUPPORT!**

