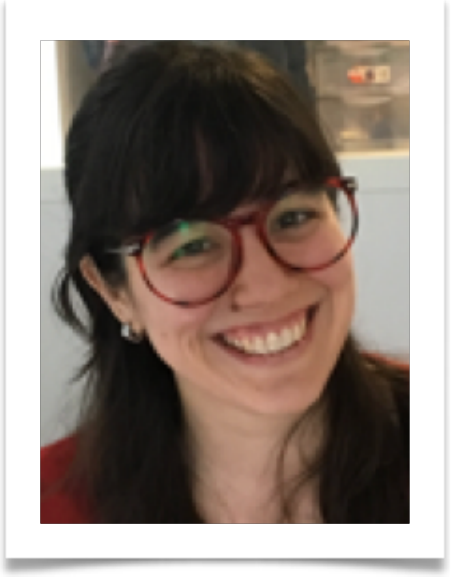
Counting flies: A neurobiological foundation of the sensitivity to numbers

Bassem Hassan

ICM Paris Brain Institute

Do flies “count”?

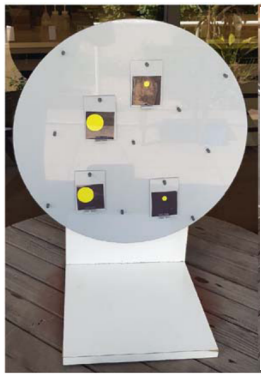


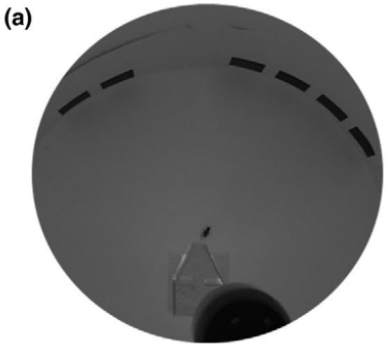
Mercedes Bengochea

How can we test numerical discrimination ability in flies?

Numerical abilities in invertebrates

Spontaneous preference





Howard et al., 2020
Gatto and Carlesso, 2019

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Numerical abilities in invertebrates

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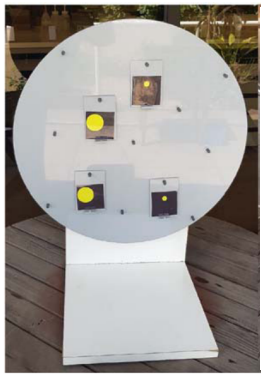

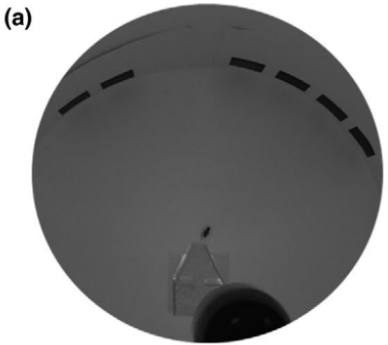

Howard et al., 2020
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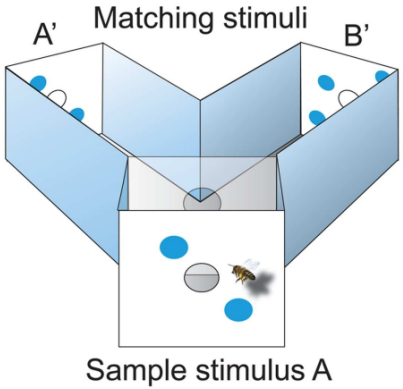
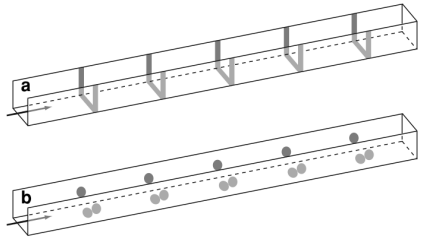
Associative Learning

Delayed-match-to-sample task



Landmark counting



Gross et al., 2009
Dacke and Srinivasan., 2008
Chittka and Geiger, 1995

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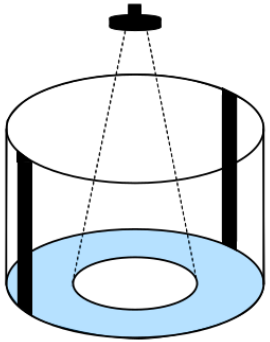

Buridan Paradigm

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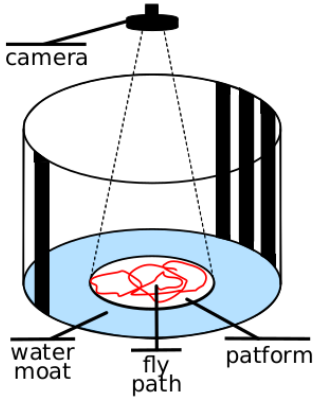
How can we test numerical discrimination ability in flies?

Spontaneous preference



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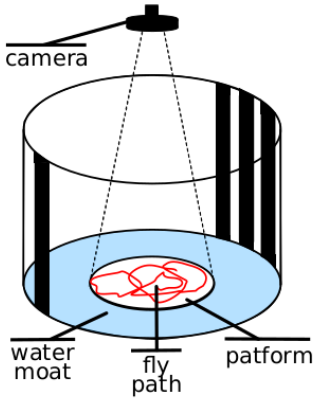
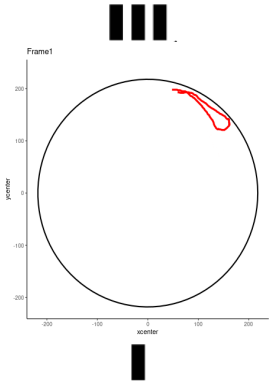
How can we test numerical discrimination ability in flies?

Spontaneous preference



15min



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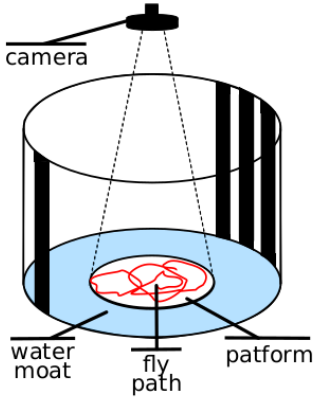

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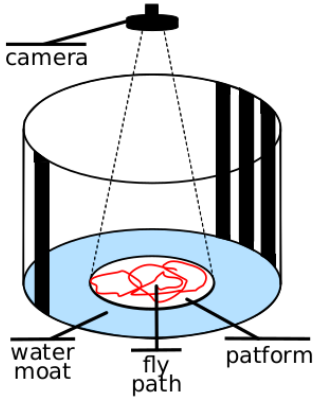

$$PI = \frac{total\ time\ (larger\ set\ area) - total\ time\ (smaller\ set\ area)}{total\ time\ (larger\ set\ area) + total\ time\ (smaller\ set\ area)}$$

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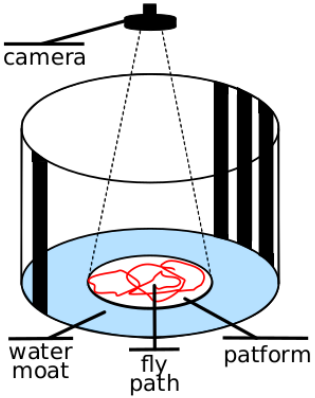

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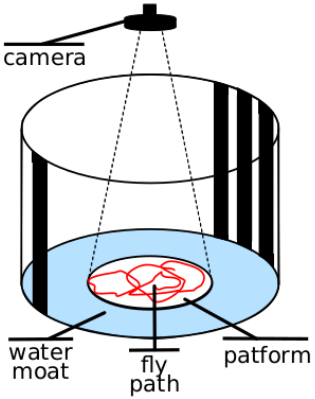

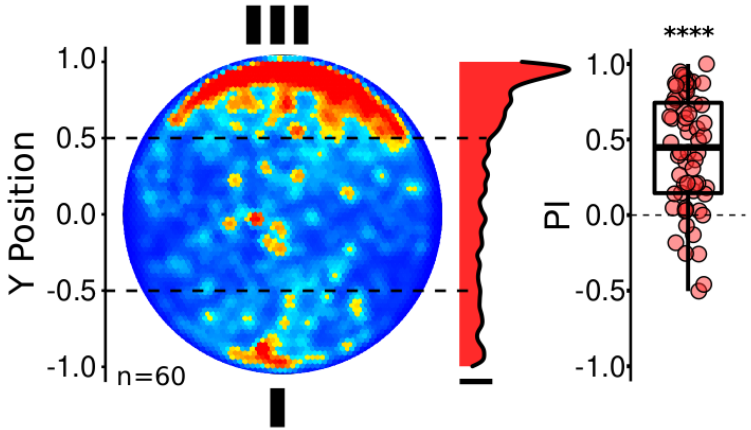

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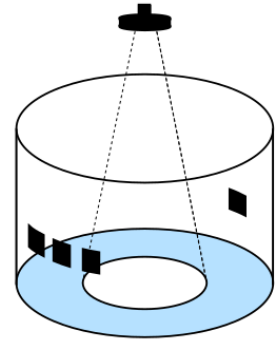
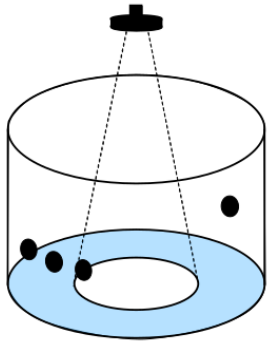
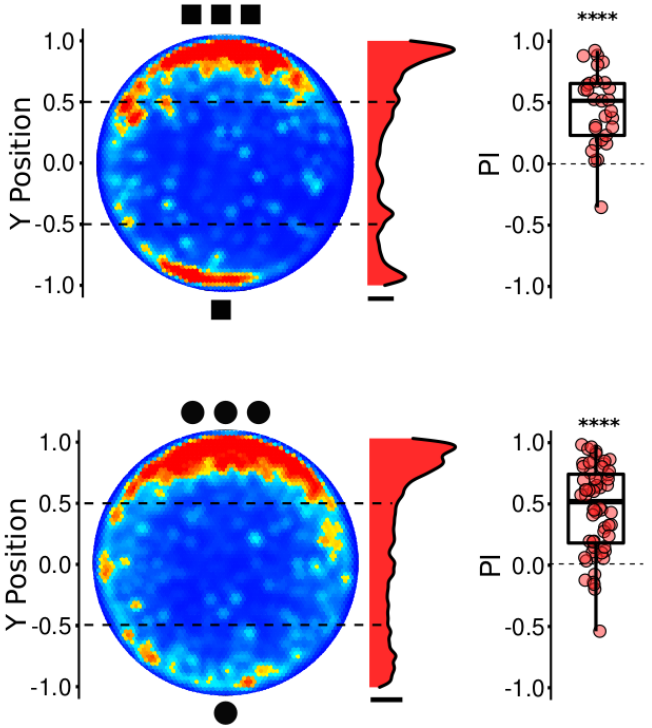
Numerical preference is independent of the shape







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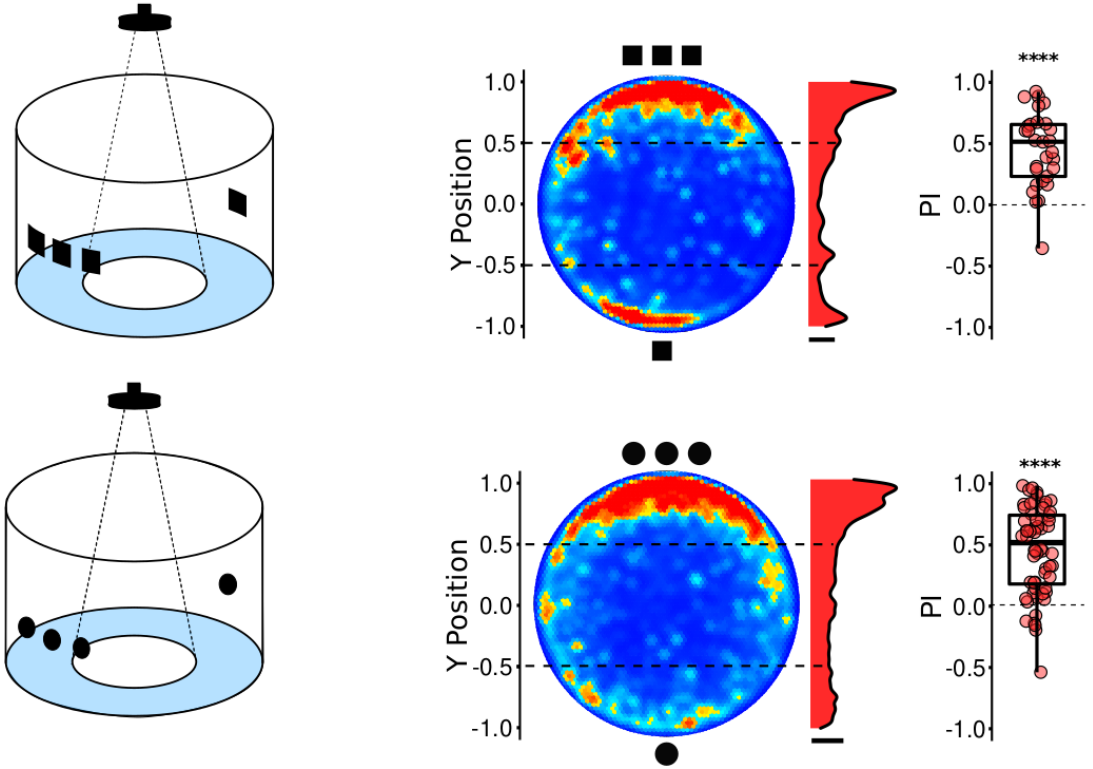

Total dark area? Overall area occupied?

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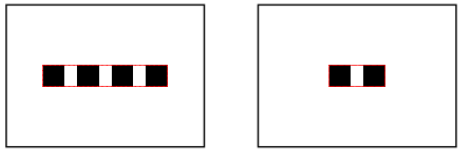
Numerical preference prevails when non-numerical continuous variables are controlled

4 vs 2

= size
= distance

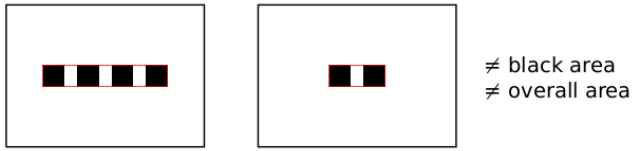


≠ black area
≠ overall area

Numerical preference prevails when non-numerical continuous variables are controlled

4 vs 2

= size
= distance



≠ black area
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4 vs 2

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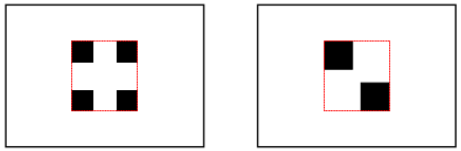

≠ size
≠ distance

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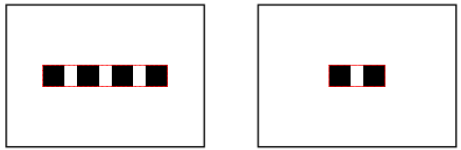
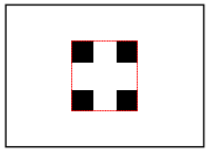


≠ black area
≠ overall area

Square size	Black Area	Overall Area	Density
=	≠	≠	=

4 vs 2

= black area
= overall area



≠ size
≠ distance

Square size	Black Area	Overall Area	Density
≠	=	=	≠

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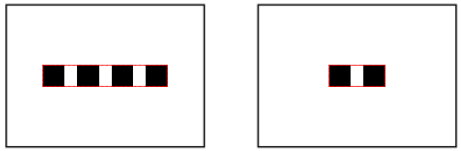

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4 vs 2

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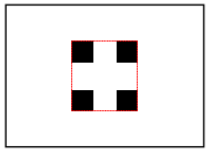

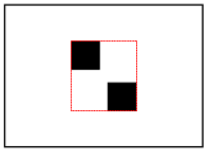

≠ size
≠ distance

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=	≠	≠	=

Square size	Black Area	Overall Area	Density
=	≠	=	≠

Square size	Black Area	Overall Area	Density
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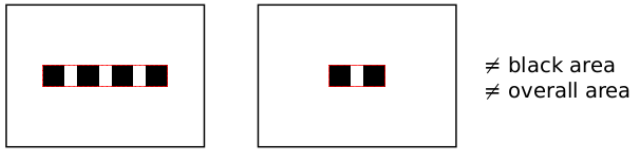

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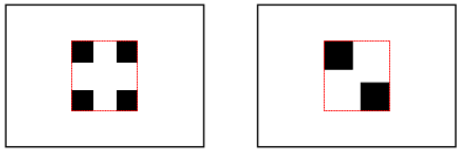

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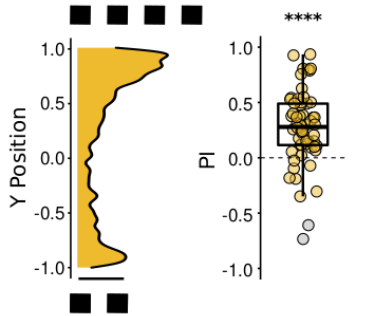

Square size	Black Area	Overall Area	Density
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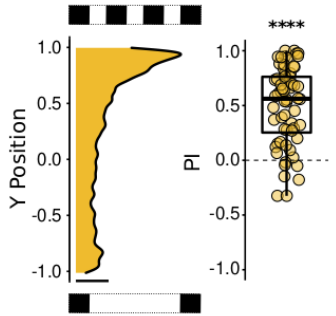

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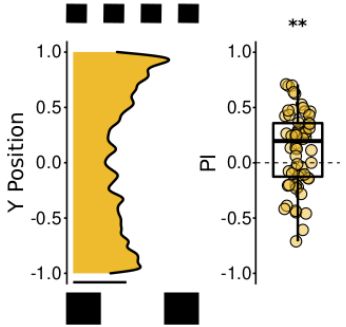

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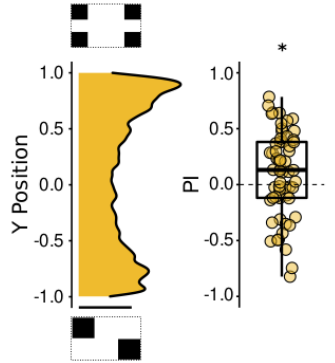

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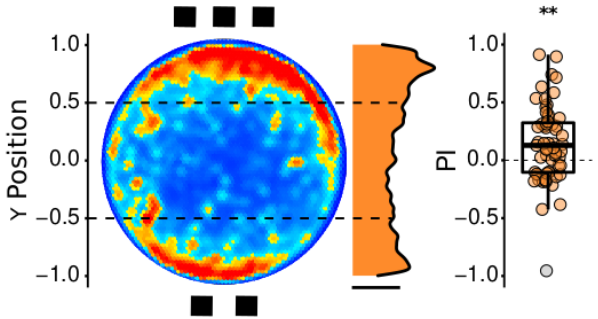
Numerical preference prevails when non-numerical continuous variables are controlled



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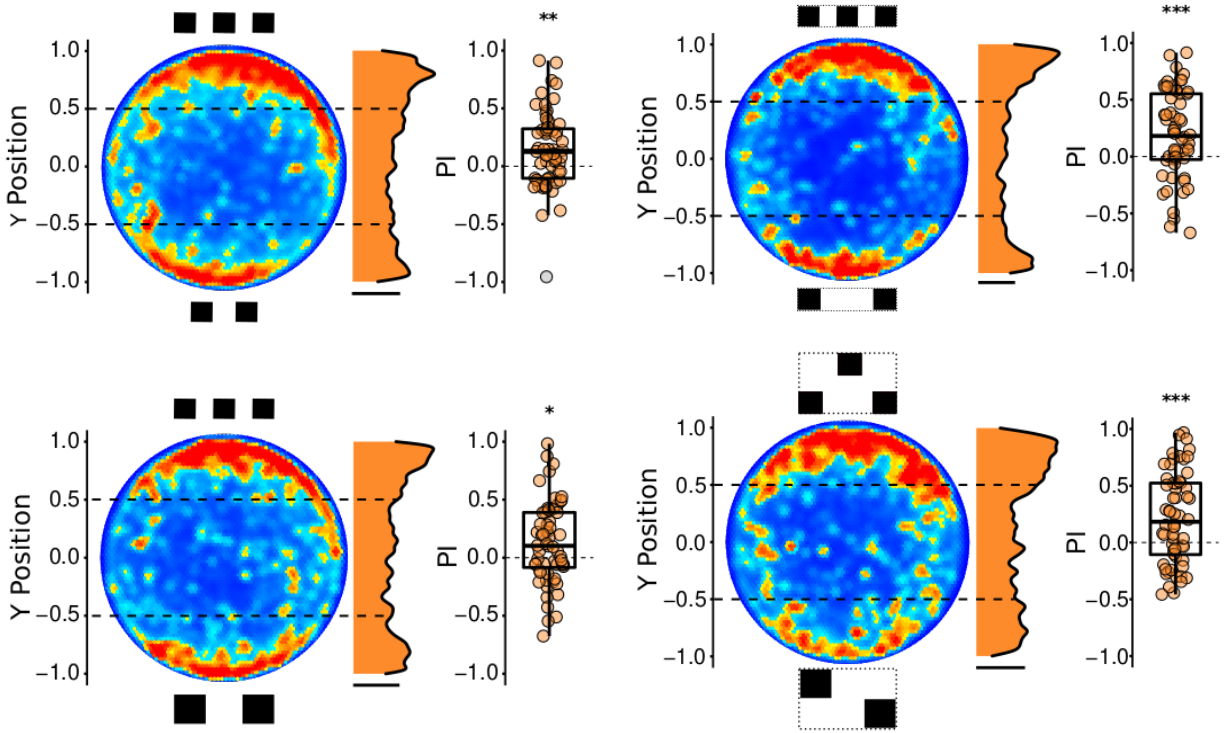

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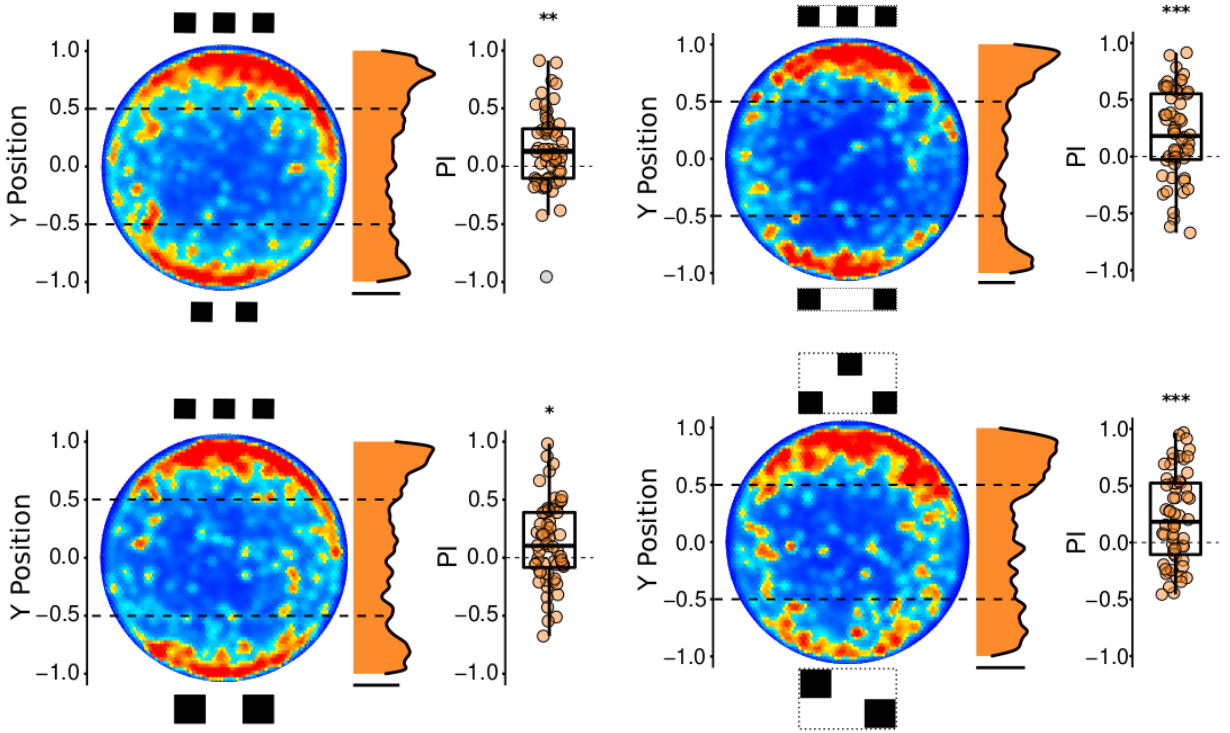

How do flies process numerosity?

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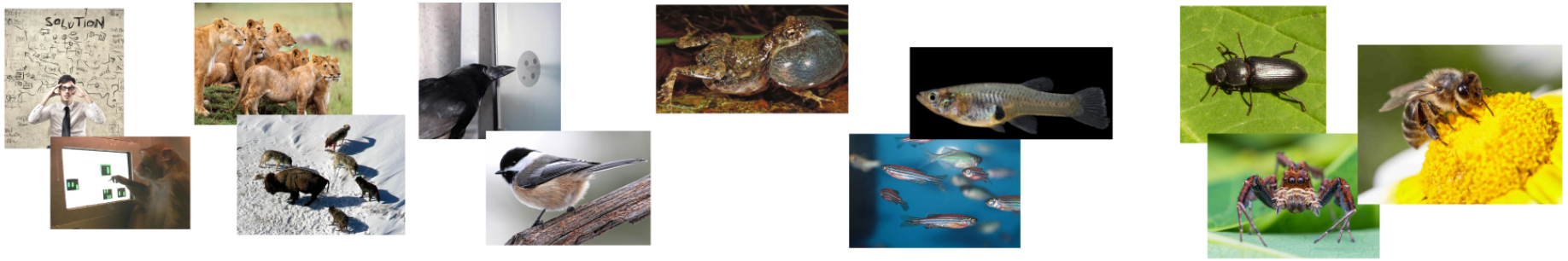
Numerical abilities: Two representation systems

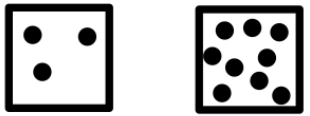


Numerical abilities: Two representation systems

Symbolic system

3 9

Non-symbolic system



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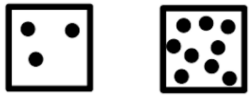
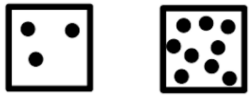
Non-symbolic system



Small numbers - Object Tracking System

Large numbers - Approximate Number System

Non-symbolic system



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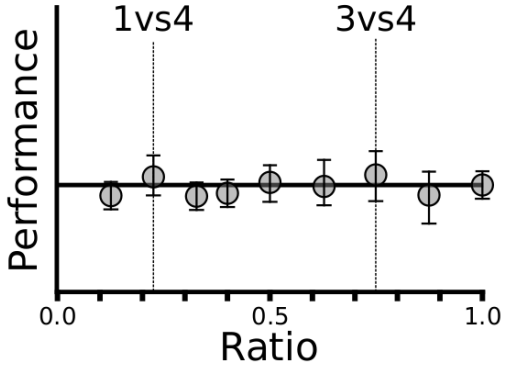

- Count
- Exact.
- **Limit arround 4**
- Track absolute values

Large numbers - Approximate Number System

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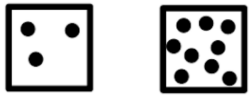
Non-symbolic system



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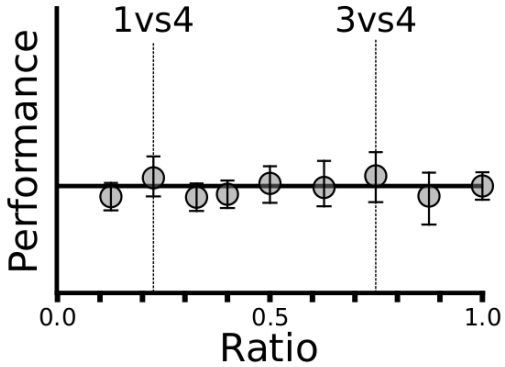

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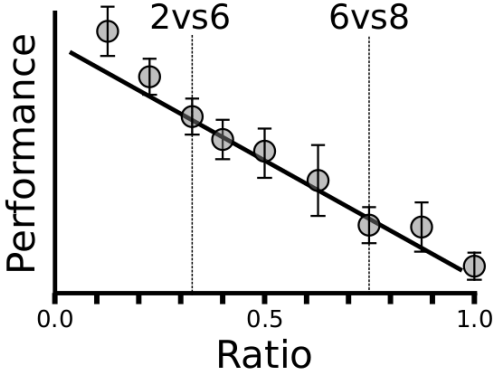

- No counting
- Approximation based on magnitude.
- No particular upper bound limit
- Rapid recognition

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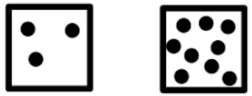
Non-symbolic system



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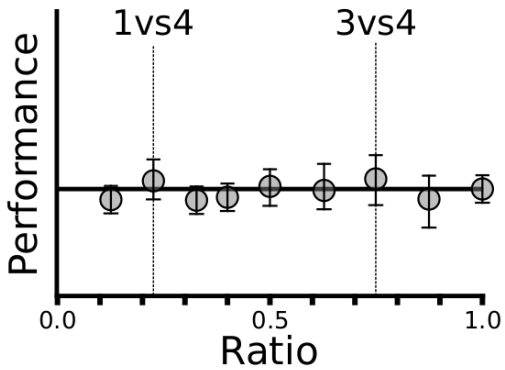

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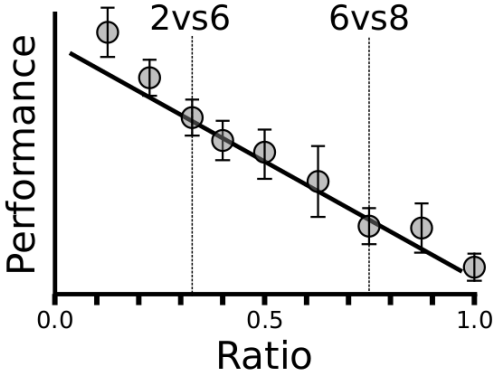

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Which of these systems do flies use?

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Flies use the ANS to discriminate between numerosities

Do flies have a limit at number four?

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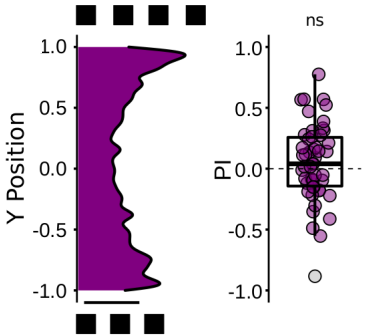
Flies use the ANS to discriminate between numerosities

Do flies have a limit at number four?



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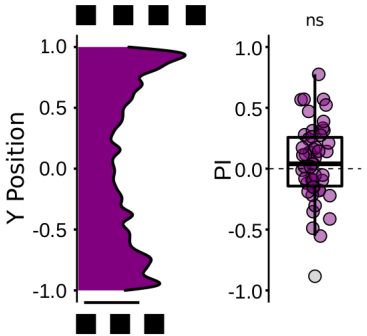

similarity in total dark area of the two numerical sets?

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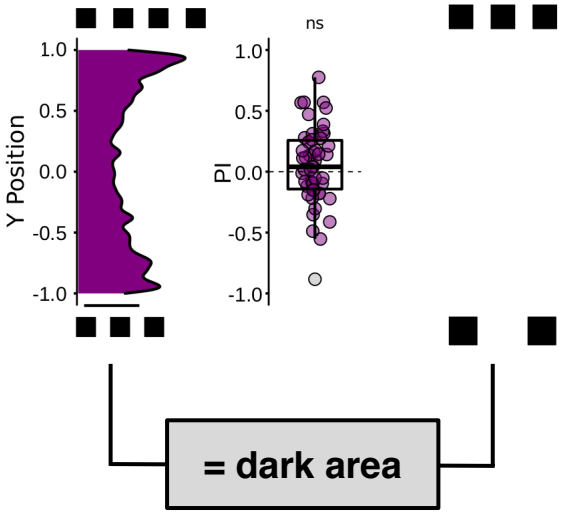
Flies use the ANS to discriminate between numerosities

Do flies have a limit at number four?



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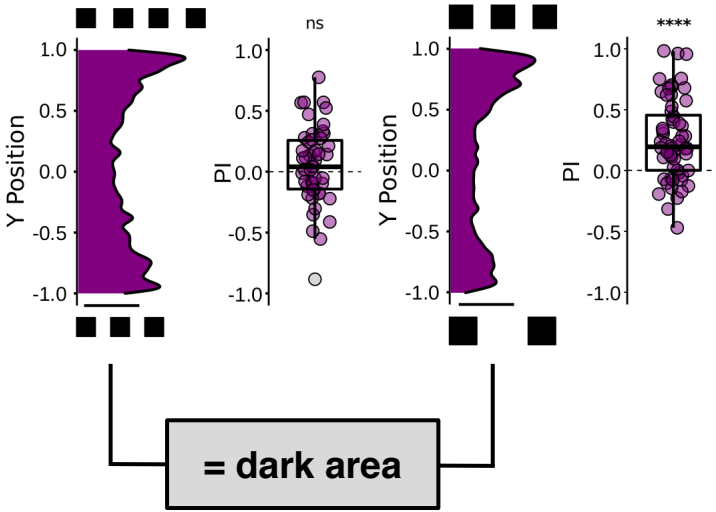

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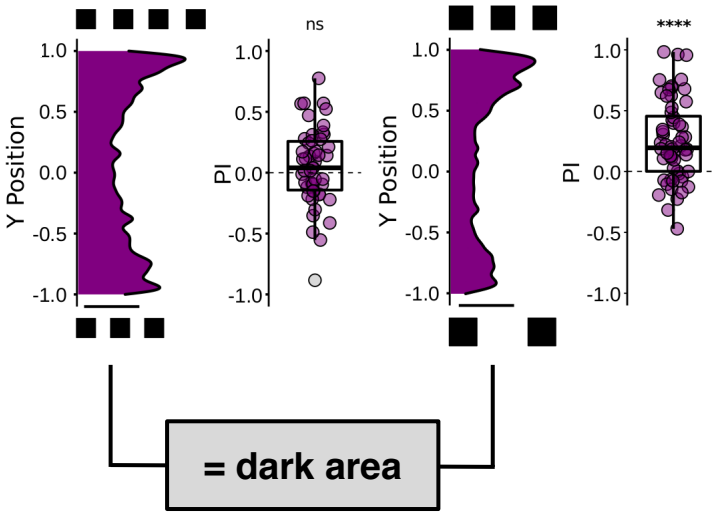

1) High proportional difference (ratio 0.75)

1) Upper limit at number 4

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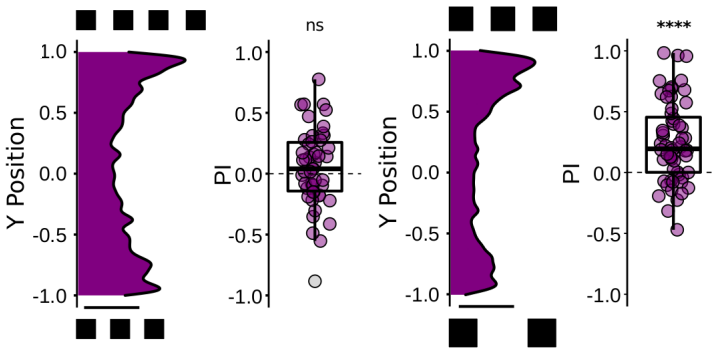
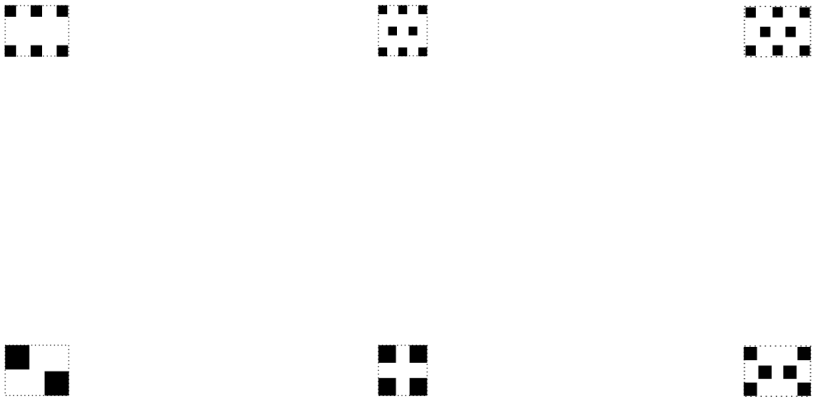


Are flies able to discriminate numbers higher than four?



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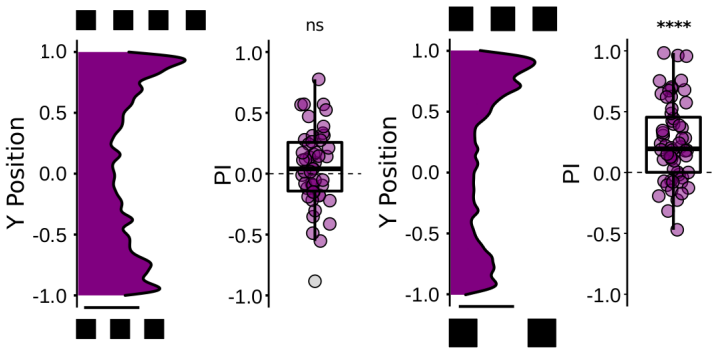
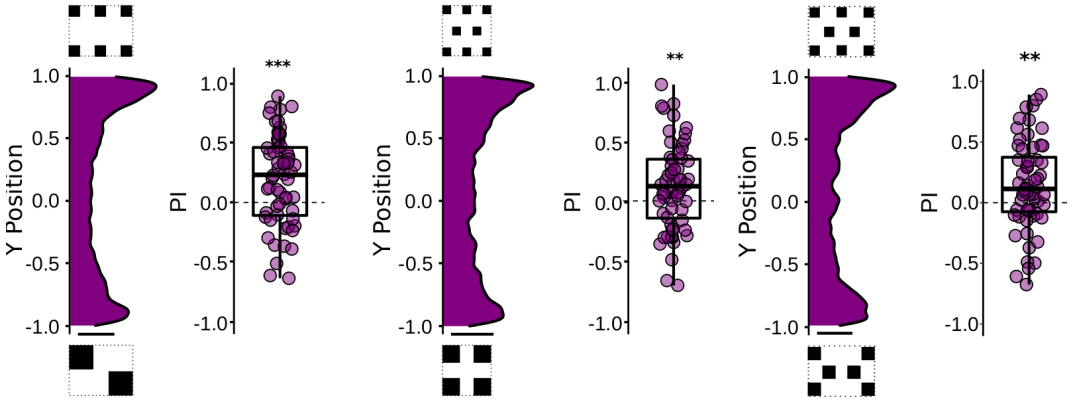
Flies use the ANS to discriminate between numerosities

Do flies have a limit at number four?



Are flies able to discriminate numbers higher than four?



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Flies use the ANS to discriminate between numerosities

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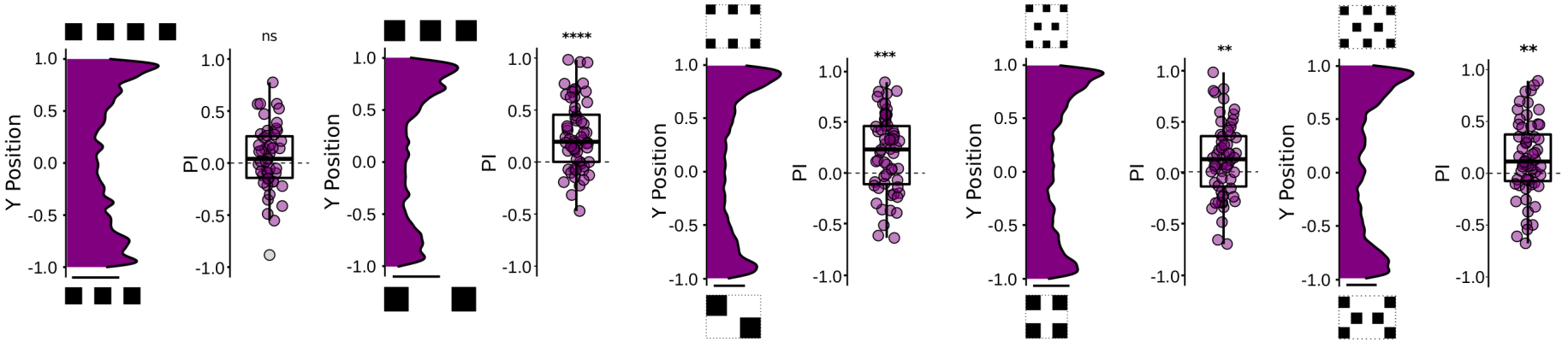

Which parameter of the visual set best explain the performance of the flies?

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Flies use the ANS to discriminate between numerosities

Global stepwise regression model

- Numerical ratio
- Total dark area
- Total perimeter
- Overall area
- Absolute numerical distance

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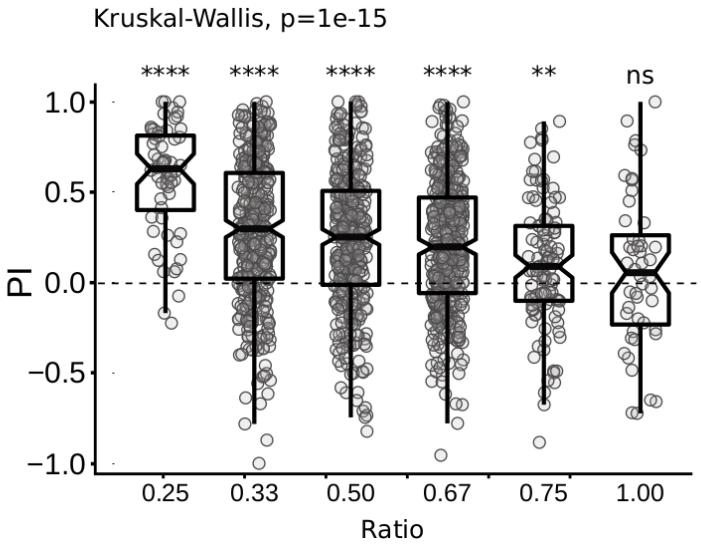

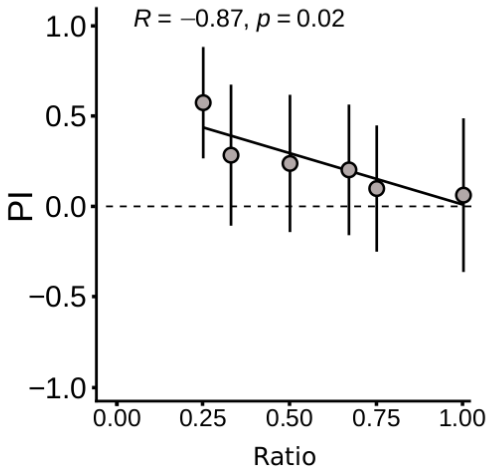

n=1361

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Flies use the ANS to discriminate between numerosities

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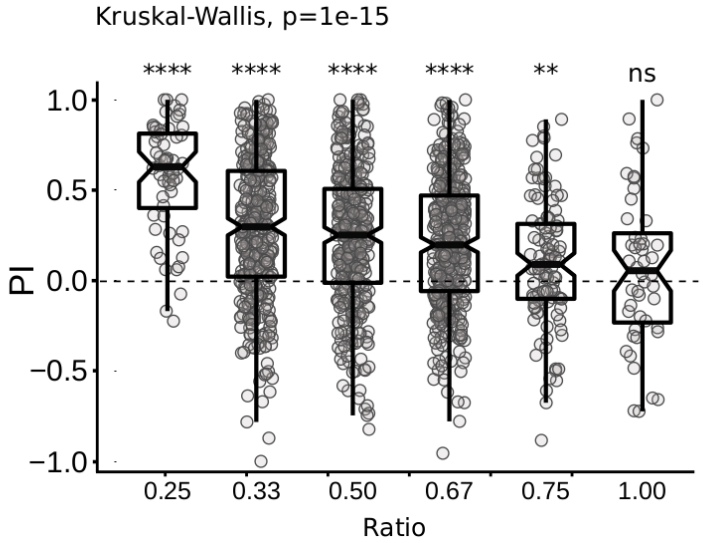

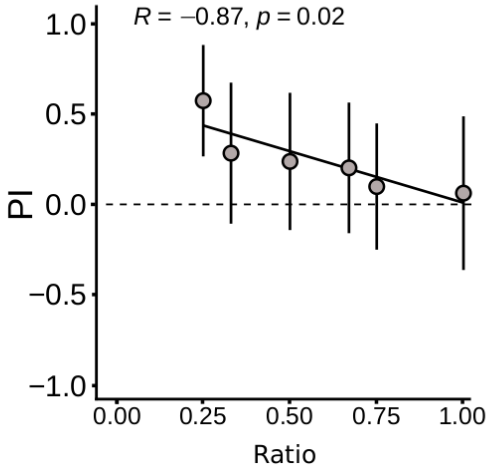

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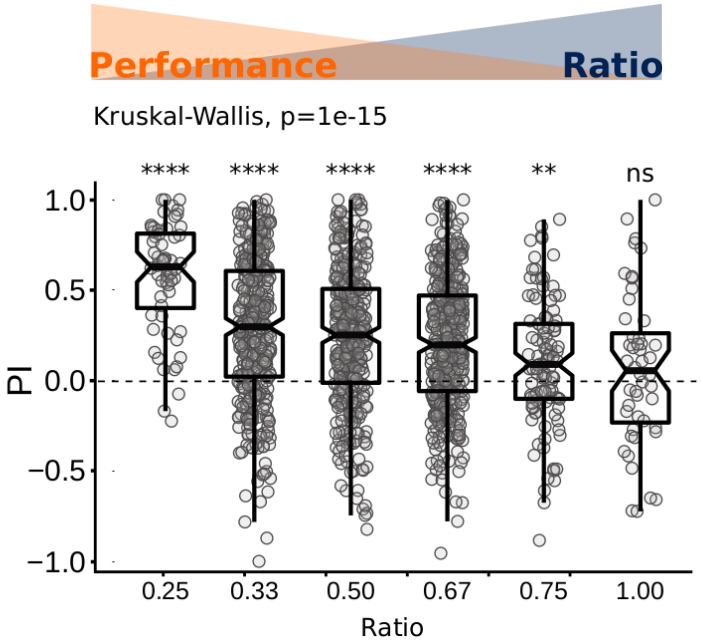

How do flies make their numerical choice?

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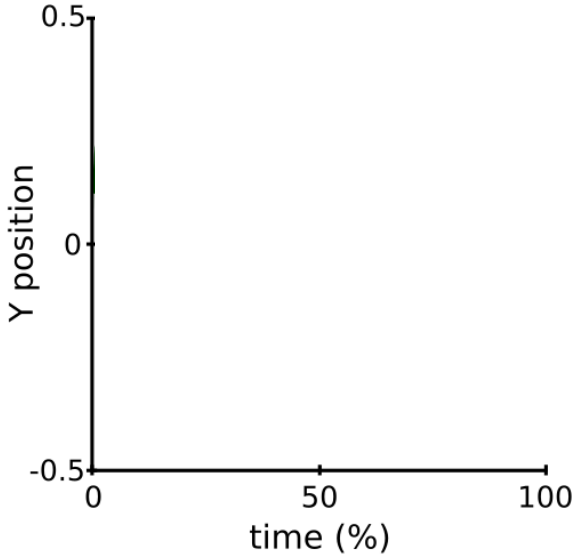
Flies display three main dynamical behavioral patterns which are stable over time



Jacobo Sitt

Malkinson et al. biorvix, 2021

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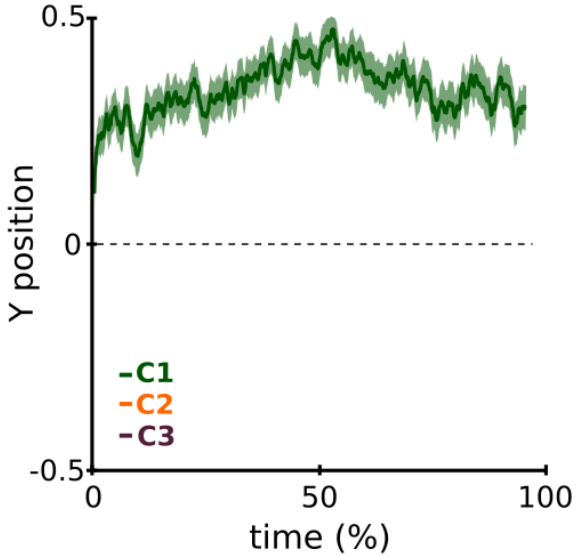
Flies display three main dynamical behavioral patterns which are stable over time



Jacobo Sitt

Malkinson et al. biorvix, 2021

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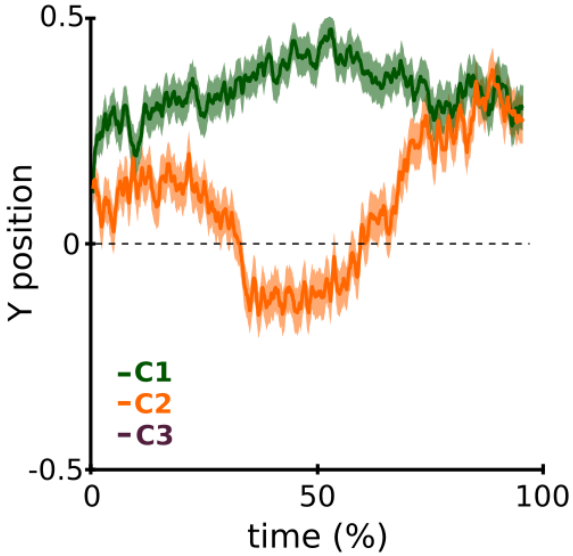

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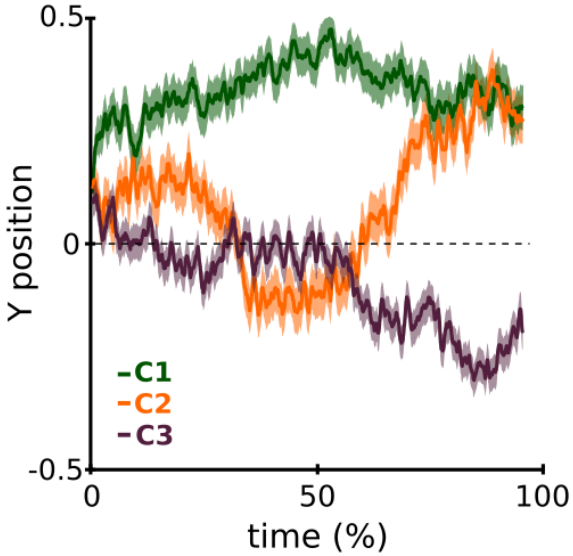

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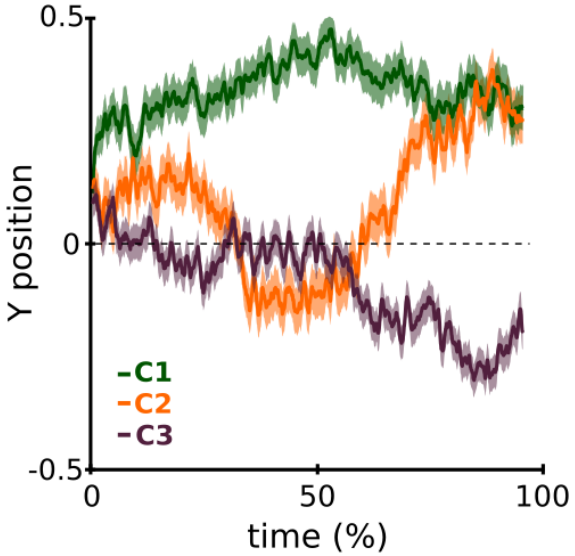

Are these patterns stable?

Do flies have ‘numerical personality’?

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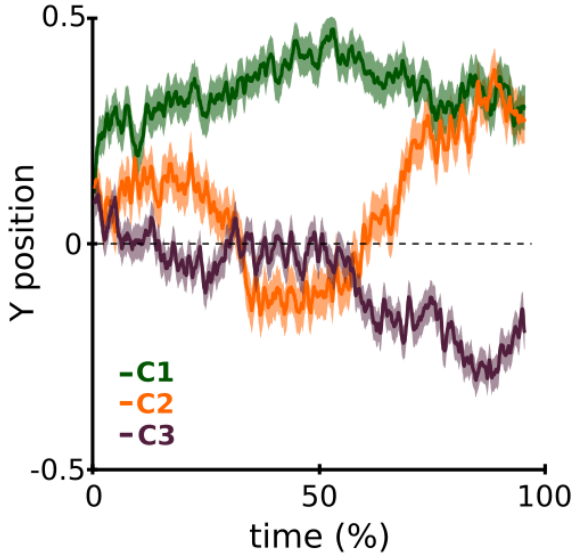
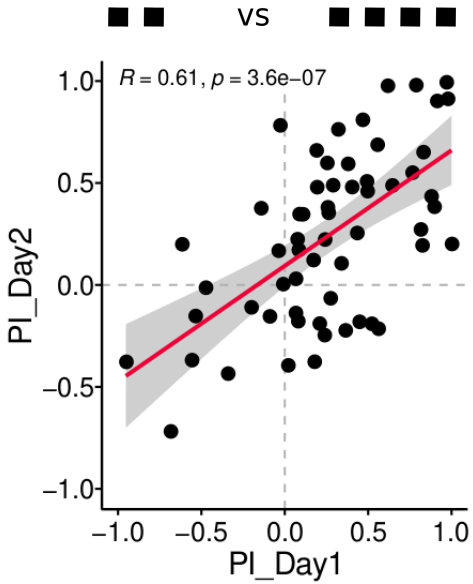
Flies display three main dynamical behavioral patterns which are stable over time





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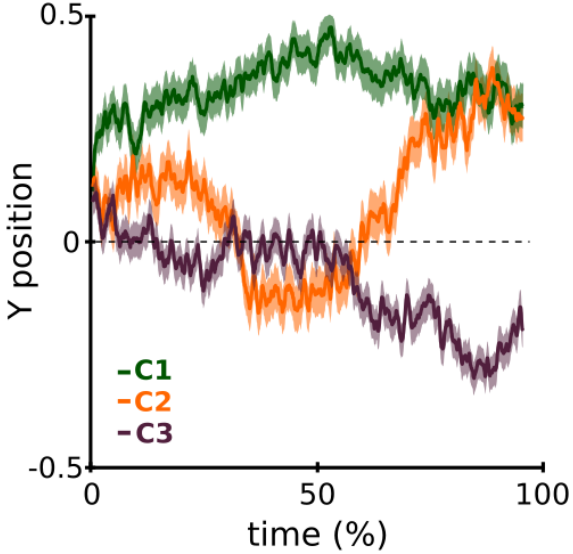

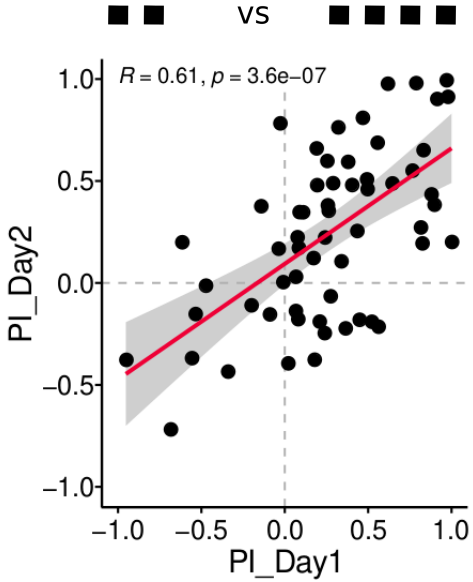

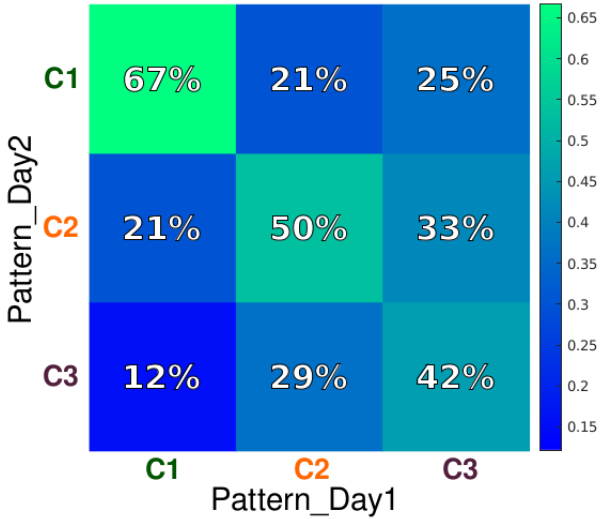

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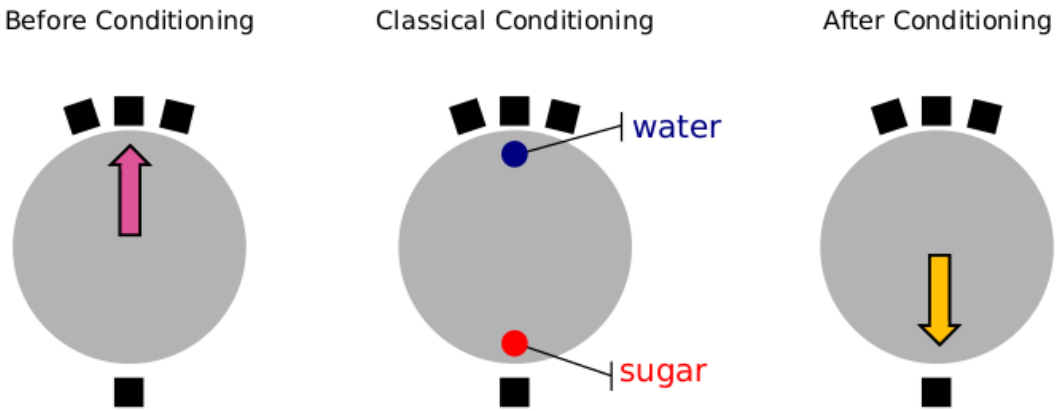
Is it possible to modify number preference through learning?



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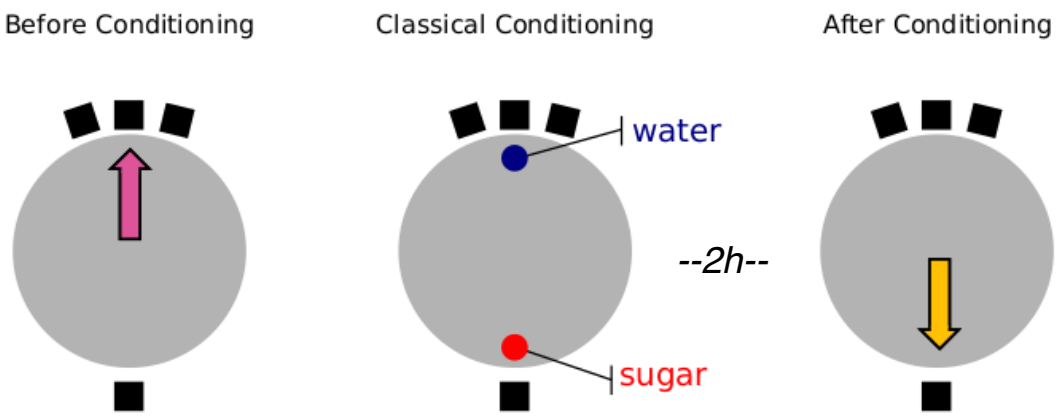
Is it possible to modify number preference through learning?

Training Session **Testing Session**



1 trial - 3 min 5 min

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Spontaneous numerical preference can be modified by classical conditioning

■ ■ ■ (CS-)

■ (CS+)

Ratio: 0.33

■ ■ ■ (CS-)

■ ■ (CS+)

Ratio: 0.67

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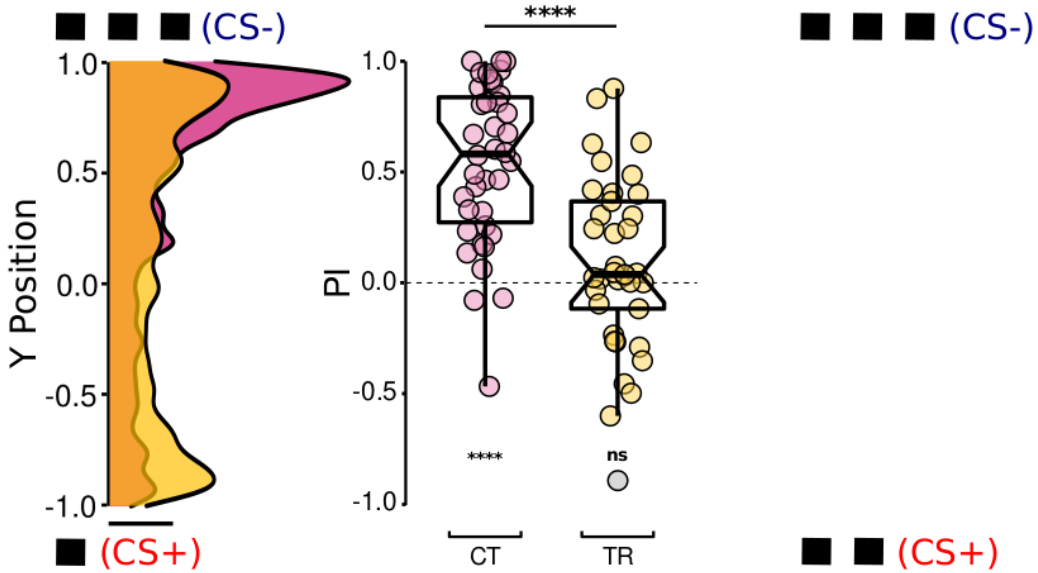
Spontaneous numerical preference can be modified by classical conditioning

CT Group

TR Group



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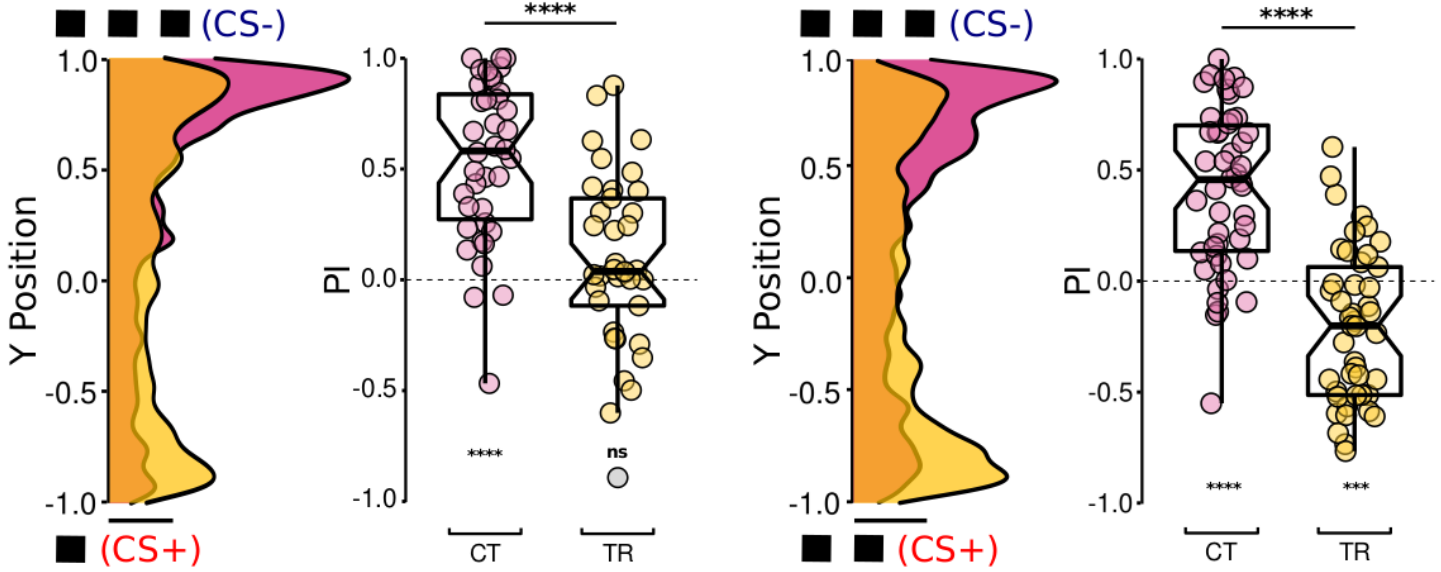

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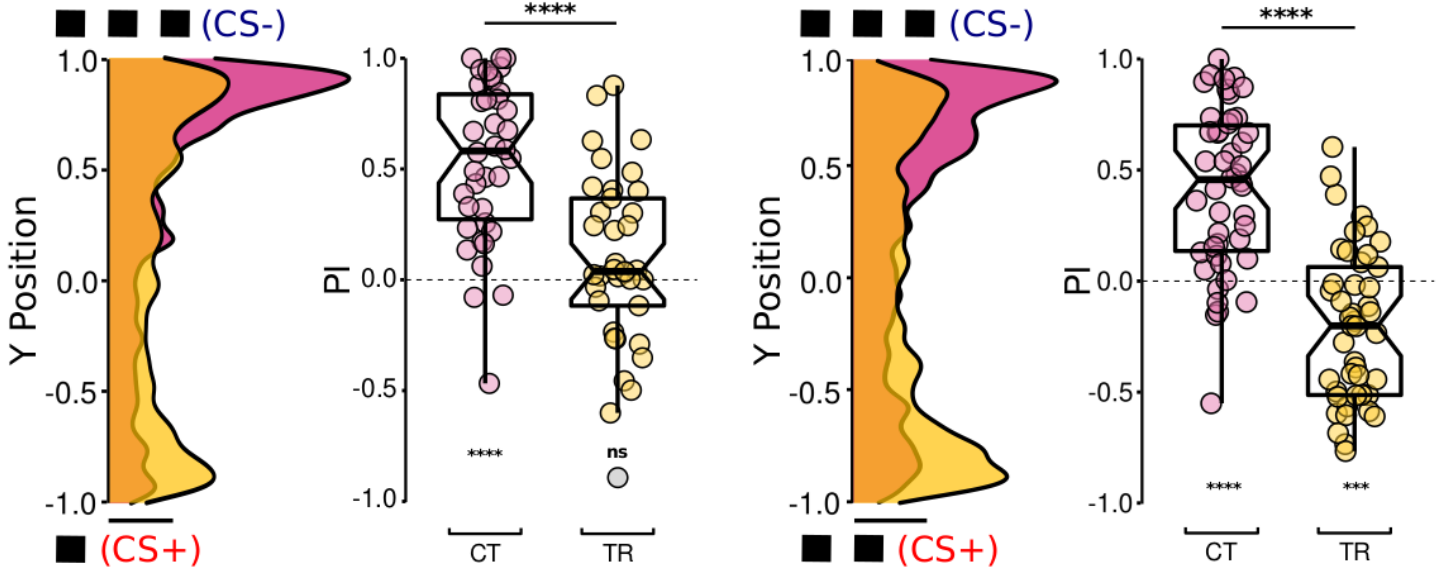

Ratio: 0.33

Ratio: 0.67

Did flies learn to respond to numerosity, or to other variables of the visual displays?

Paris Brain Institute ICM

Spontaneous numerical preference can be modified by classical conditioning

■ ■ ■ ■ (CS-)

■ ■ ■ ■ (CS+)

CT Group

TR Group

■ ■ ■ (CS+)

Ratio: 0.75

■ ■ ■ (CS-)

Ratio: 0.75

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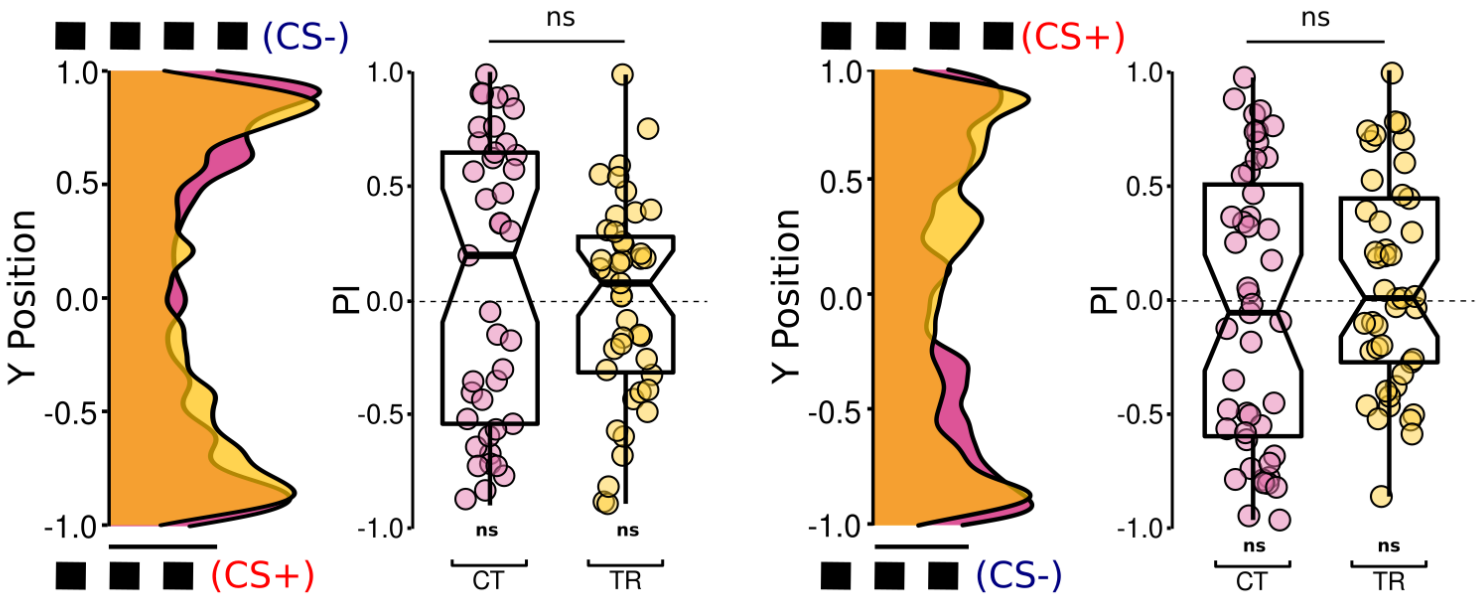

Ratio: 0.75

Ratio: 0.75

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Which brain regions or neurons are required for numerical processing?

Which brain regions or neurons are required for numerical processing?

Numerical skills

High-order brain areas

Primary sensory systems

Bortot et al.,2020
Giurfa, 2019
Butterworth et al., 2017

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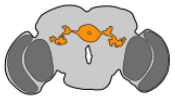
Which brain regions or neurons are required for numerical processing?

High-order brain areas

Mushroom bodies
Optic lobes
Central brain



Central complex
Optic lobes
Central brain

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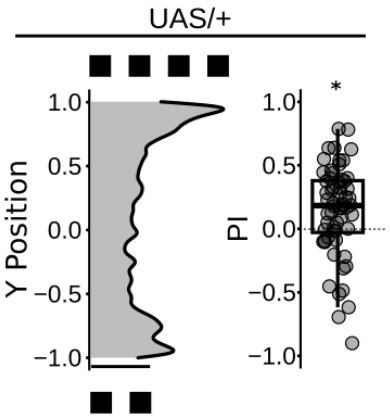
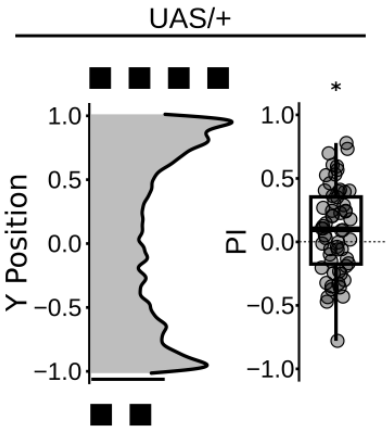


Central complex
Optic lobes
Central brain



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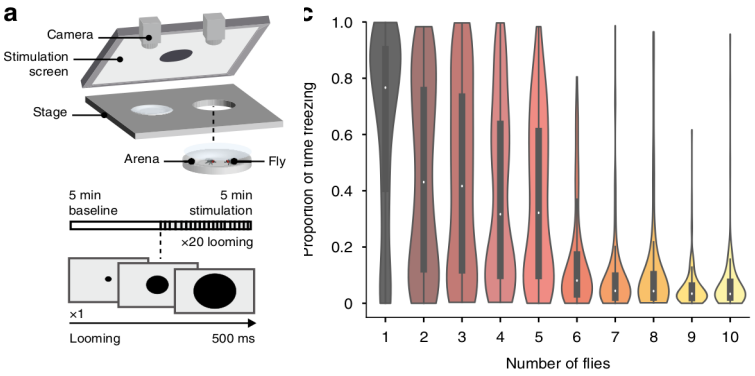
ARTICLE

https://doi.org/10.1038/s41467-020-17856-4 OPEN

Behavioral and neuronal underpinnings of safety in numbers in fruit flies

Clara H. Ferreira [1]✉ & Marta A. Moita [1]✉

2020



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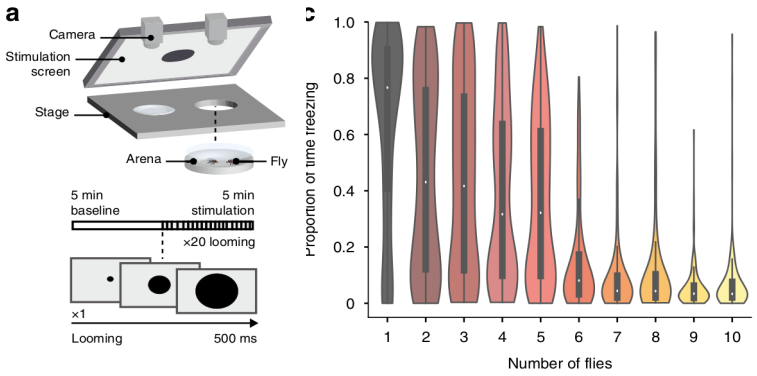

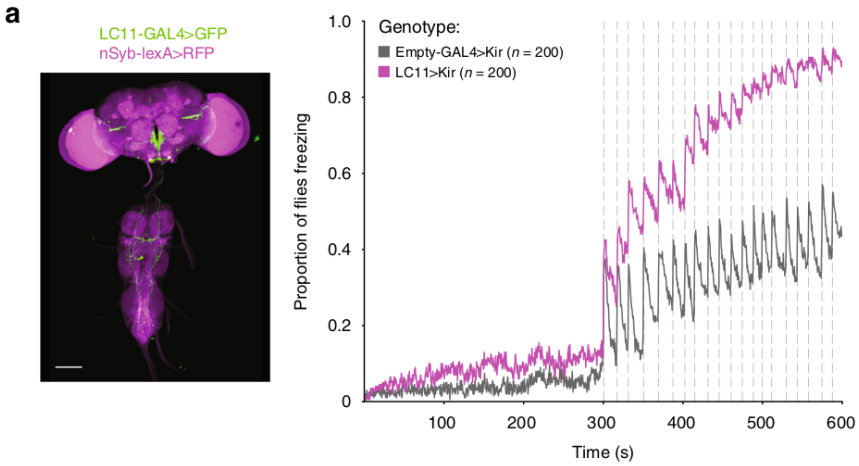

Group of 5 flies

ARTICLE

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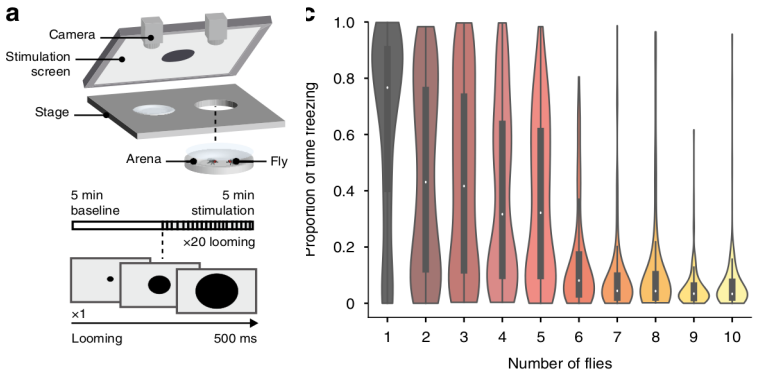
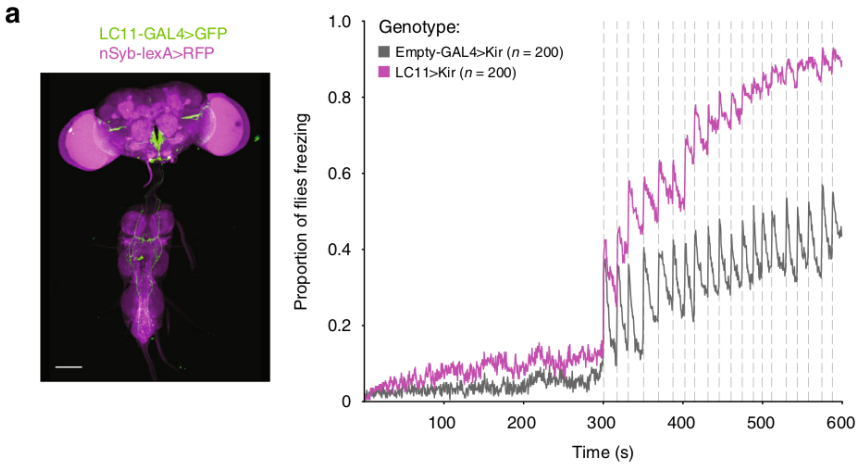
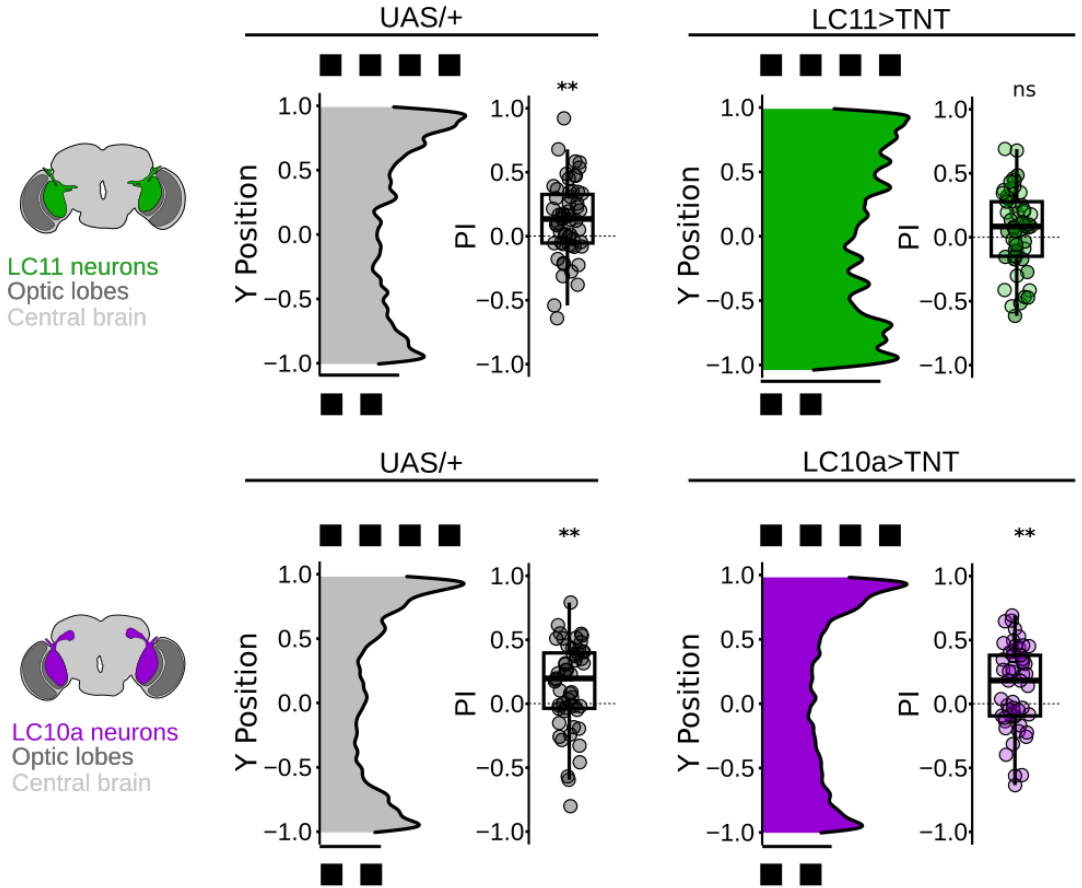




Group of 5 flies

Are these neurons detecting the group size?

Which brain regions or neurons are required for numerical processing?



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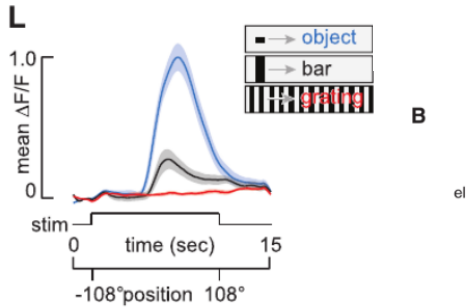
LC11 respond strongly to the motion of the small square (~10) but not to the longer bar

Current Biology

Object-Detecting Neurons in *Droso*

Keles and Frye_2017

Respond to small object



B

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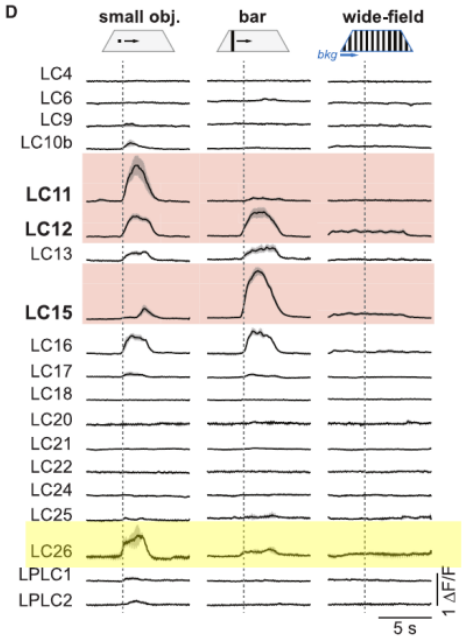
Article

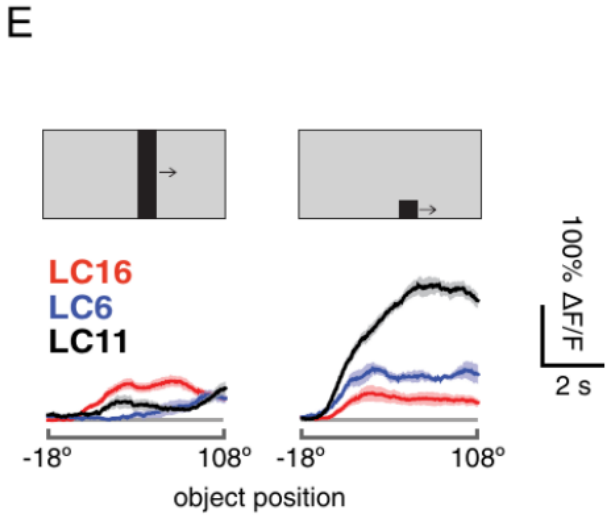
Non-canonical Receptive Field Properties and Neuromodulation of Feature-Detecting Neurons in Flies

Carola Städele,[1,2] Mehmet F. Keleş,[1,3] Jean-Michel Mongeau,[1,4] and Mark A. Frye[1,5,*]



Visual projection neurons in the *Drosophila* lobula link feature detection to distinct behavioral programs

Ming Wu[†‡], Aljoscha Nern[*†], W Ryan Williamson, Mai M Morimoto, Michael B Reiser, Gwyneth M Card, Gerald M Rubin[*]



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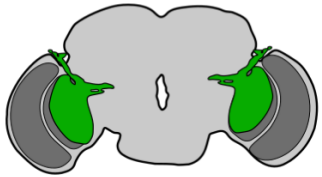

LC11 neurons
Optic lobes
Central brain

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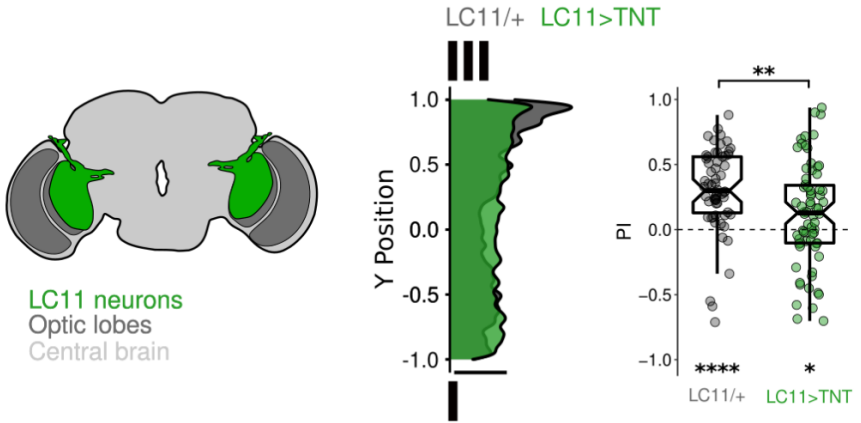

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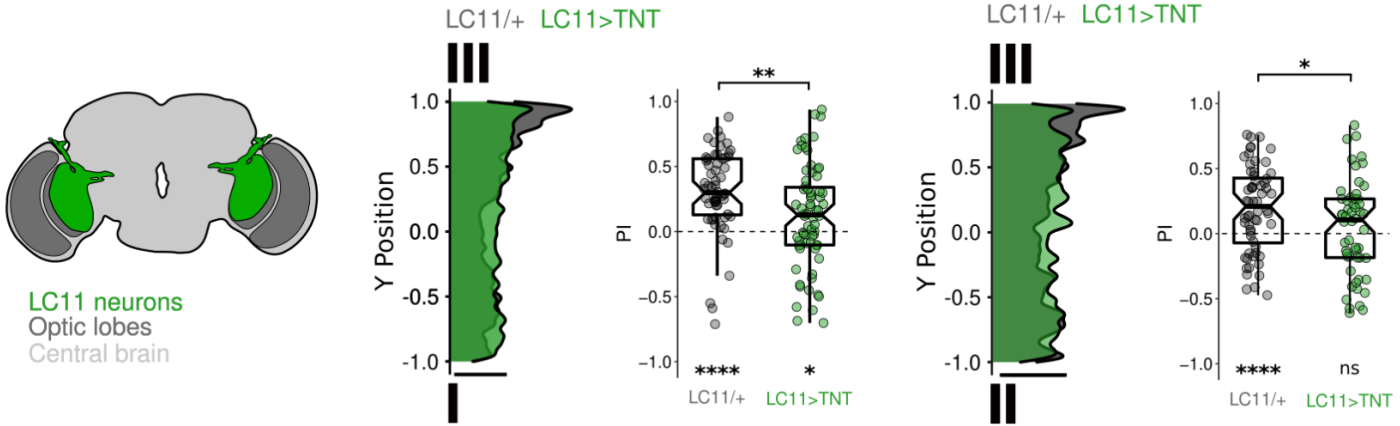

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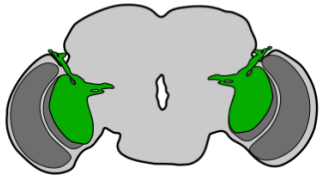

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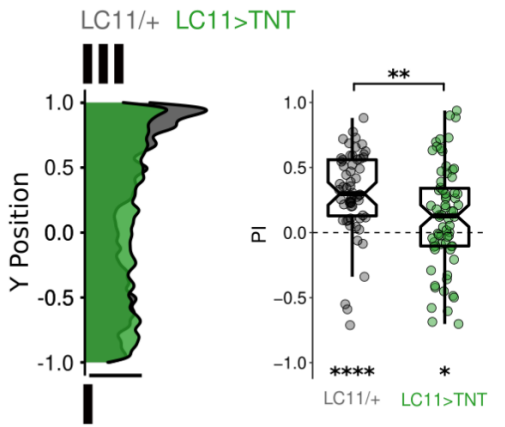
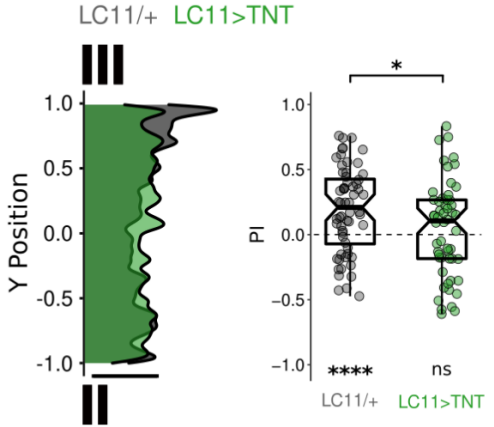
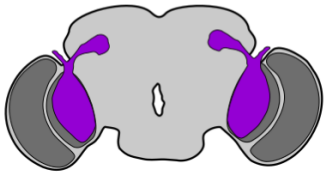
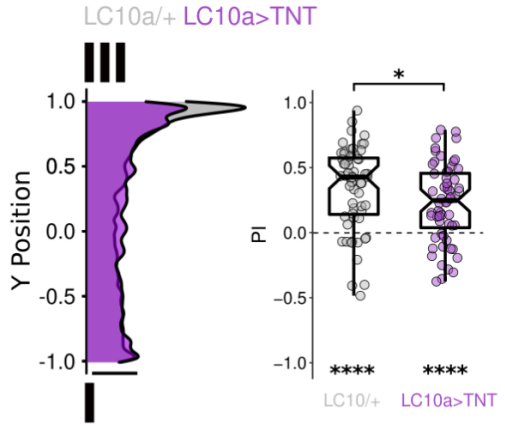
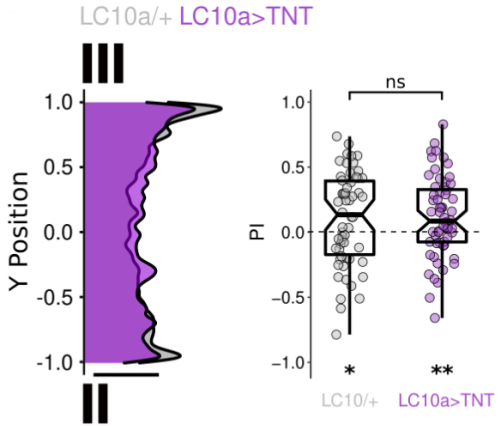






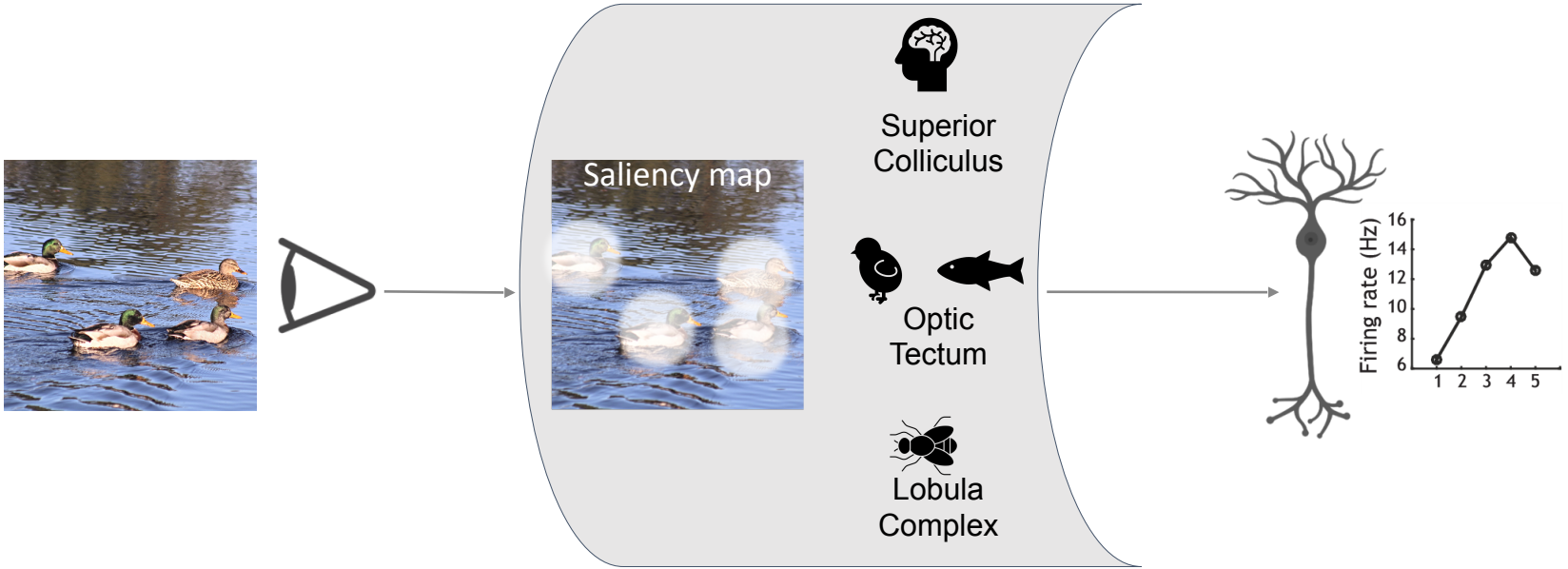
LC10a neurons
Optic lobes
Central brain





Where does Visual Number Sense Come From?

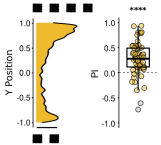
our hypothesis: a crucial role for conserved brain structures



Number is derived from a **saliency map,** that extracts positions of salient objects in visual scenes

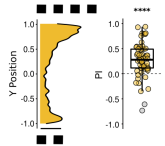
The saliency map emerges in **conserved brain regions** prior to information transfer to number neurons

Take-home message



Flies spontaneously present a preference for larger numerosities in a two-choice discrimination test independently of low-visual cues.

Take-home message



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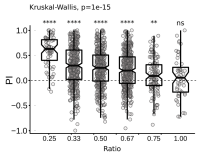
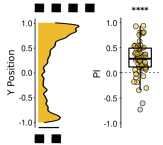


Numerical discrimination accuracy is ratio-dependent.

Take-home message



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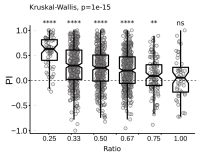

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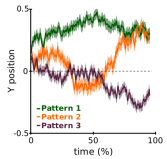
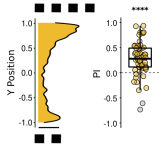


Flies display three main behavioral patterns that are stable over time.

Take-home message



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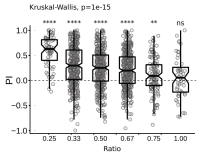

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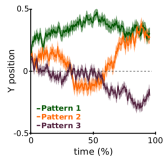

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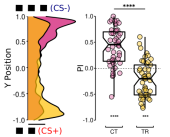

Flies learn to associate the lower numerosity to a positive stimulus.

Laurent Cohen

Jacobo Sitt

Thomas Preat

Veronique Izard

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