What's catching your eye?

Bioinspired and neuromorphic algorithms to model visual attention

Giulia D’Angelo
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Bioinspired and neuromorphic algorithms to model visual attention

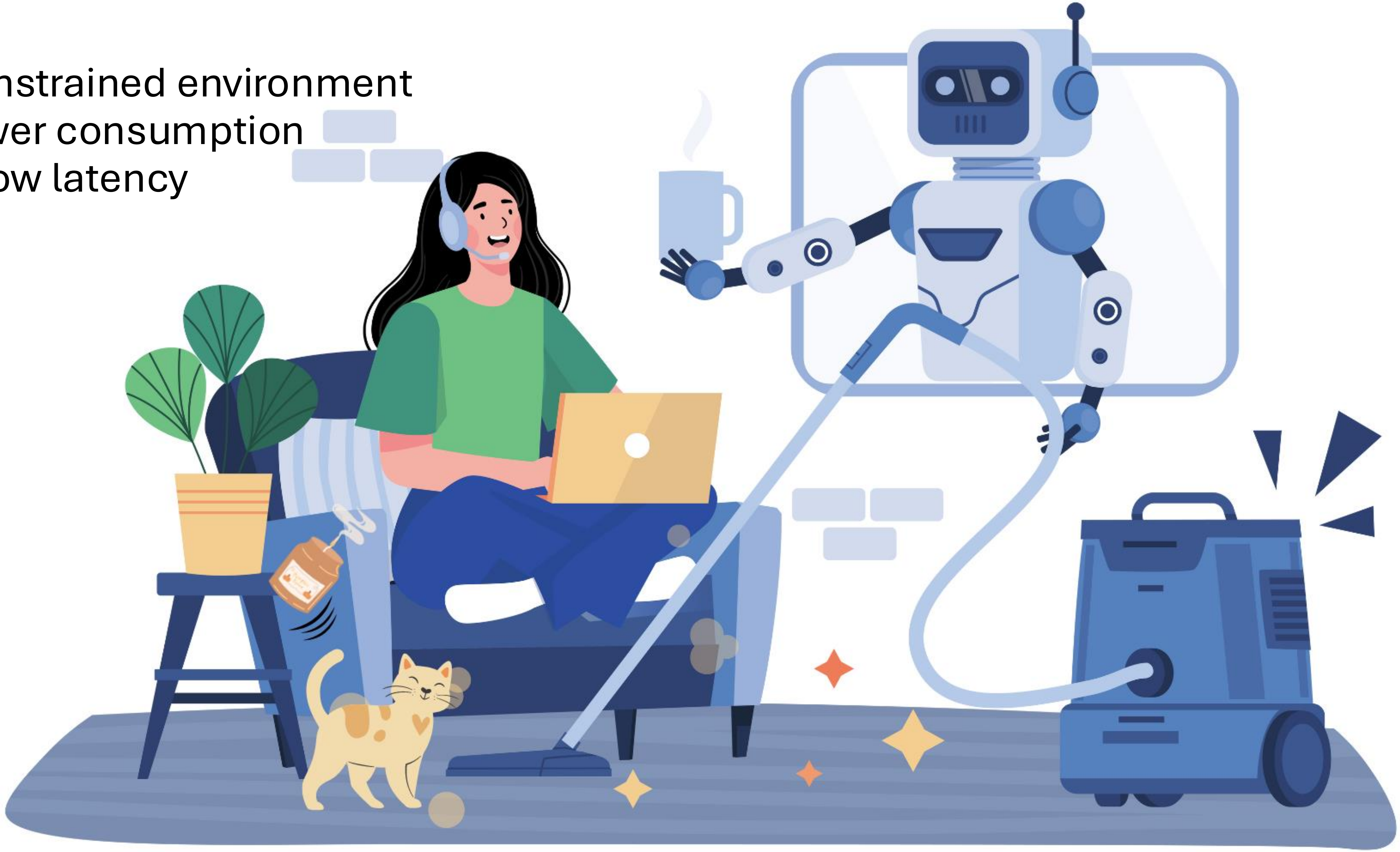
Vision is an exploratory behaviour that relies heavily on the dynamic relationship between actions and sensory feedback. For any agent—whether animal or robotic—processing visual sensory input efficiently is crucial for understanding and interacting with its environment. The key challenge lies in selectively filtering relevant information from the constant stream of complex sensory data. This process, known as selective attention, is also driven by the intricate interplay between bottom-up and top-down mechanisms, which together organize and interpret visual scenes.

I will explore how biologically plausible models for visual attention can enhance robotic interaction with the environment trying to understand the role of neuromorphic hardware in facilitating active vision and its limitations.

Giulia D’Angelo
MSCA Postdoctoral Fellow at The Czech Technical University (CTU), Prague

Giulia D'Angelo is currently an MSCA Postdoctoral Fellow at the Czech Technical University in Prague, focusing on neuromorphic algorithms for active vision. She obtained a Bachelor's degree in Biomedical Engineering at The University of Genoa and a Master's degree in Neuroengineering, during which she developed a neuromorphic system for the egocentric representation of peripersonal visual space at King's College London. She earned her PhD in neuromorphic algorithms at the University of Manchester, in collaboration with the Event-Driven Perception for Robotics Laboratory at the Italian Institute of Technology, where she proposed a biologically plausible model for event-driven, saliency-based visual attention.
She was recently awarded the Marie Skłodowska-Curie Fellowship, through which she explores sensorimotor contingency theories for neuromorphic active vision algorithms.

Unconstrained environment
Low power consumption
Low latency

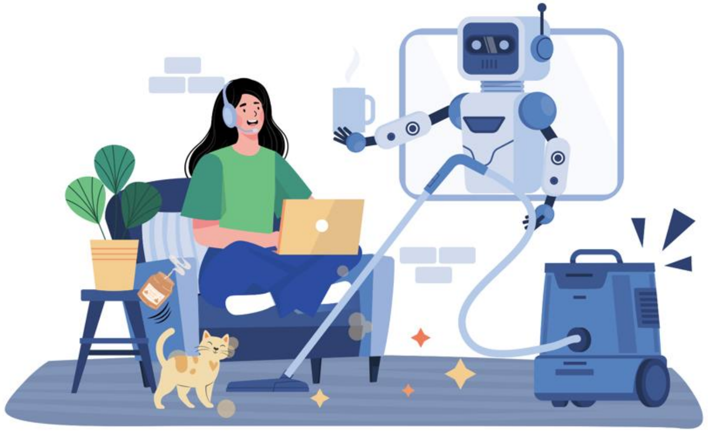


Unconstrained environment
Low power consumption
Low latency

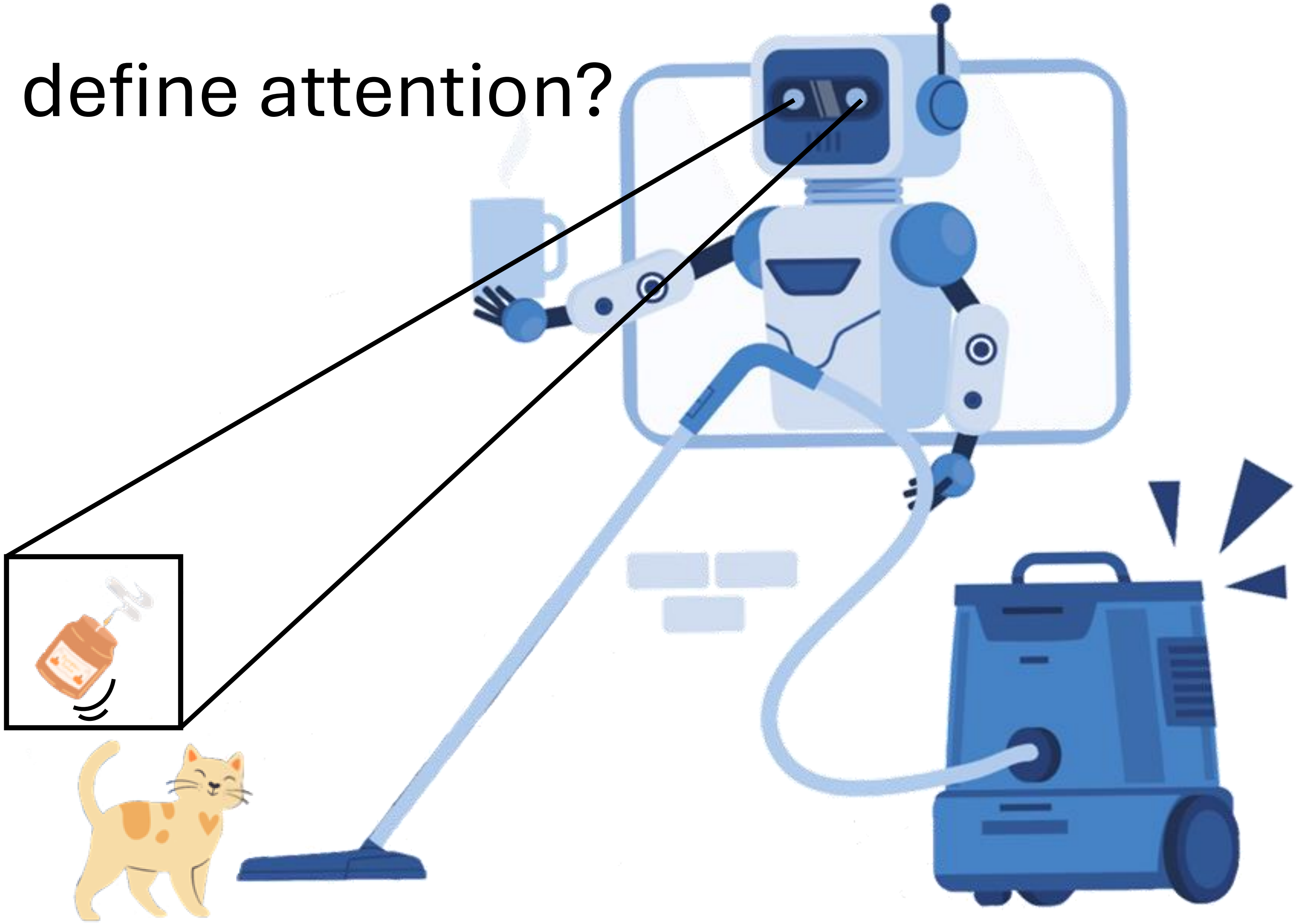
Someone has already done it!

"It consumes a paltry 20 watts, much less than a typical incandescent lightbulb"

Furber, Steve. "To build a brain." *IEEE spectrum* 49.8 (2012): 44-49.



How do we define attention?



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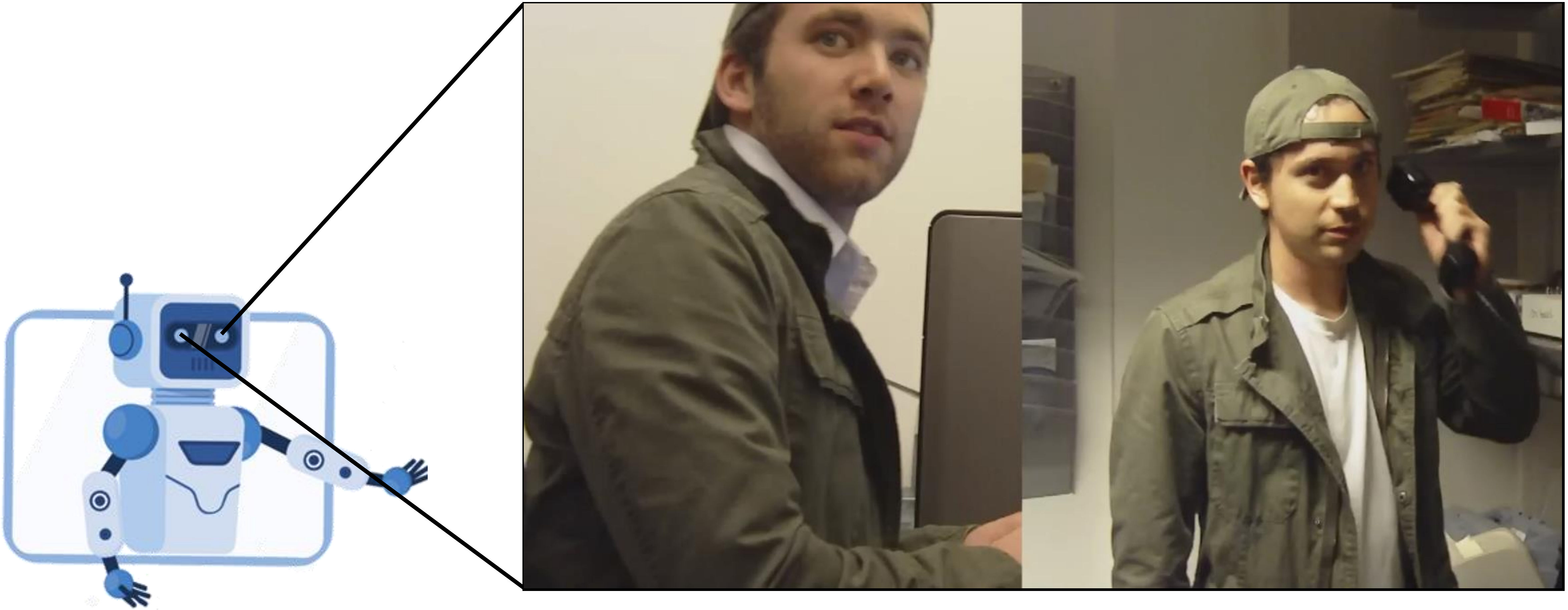
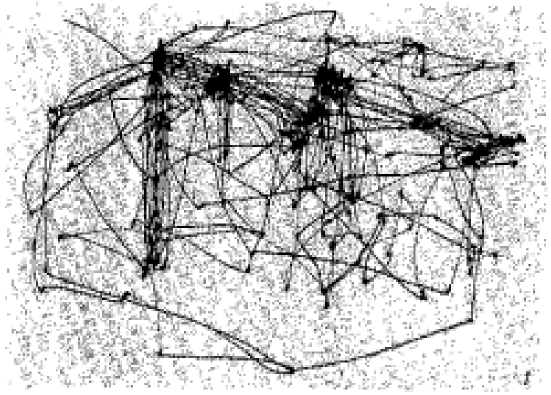
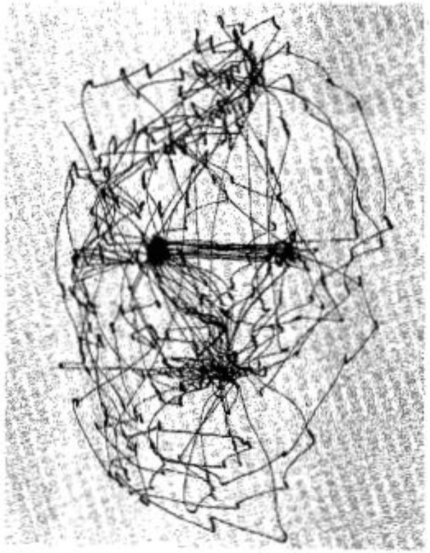
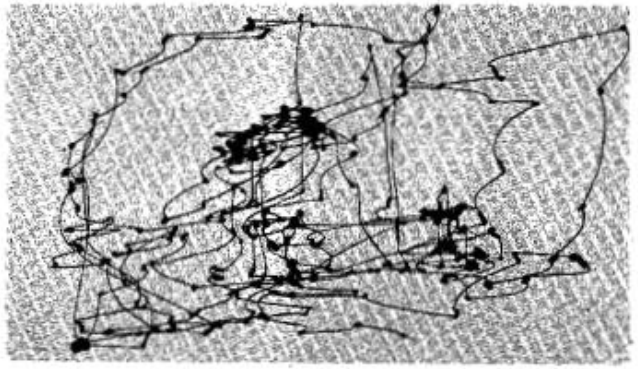
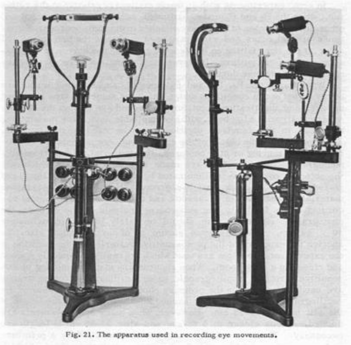


How do we define attention?





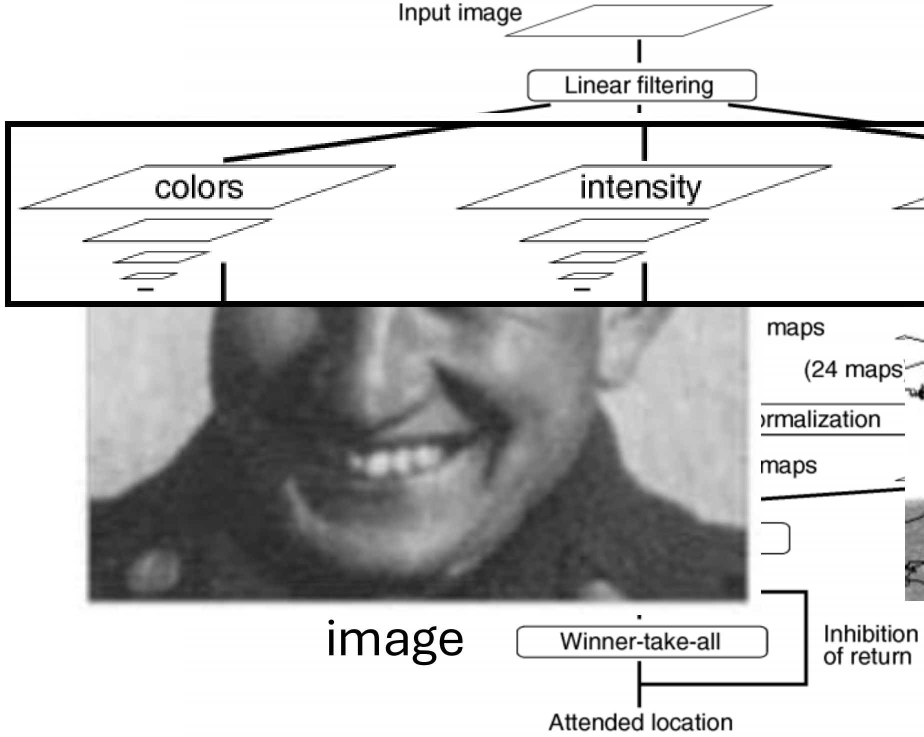




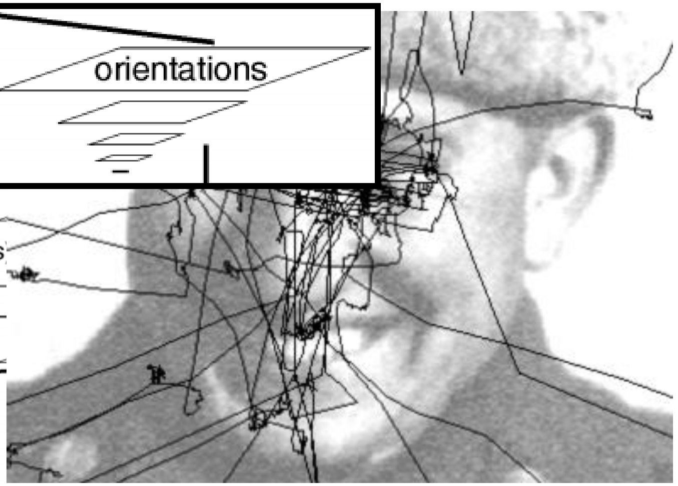
Yarbus, Alfred L. "Eye movements during perception of complex objects." *Eye movements and vision*. Springer, Boston, MA, 1967. 171-211.

Cool, but feature extraction is not enough

What is a saliency map ?



image



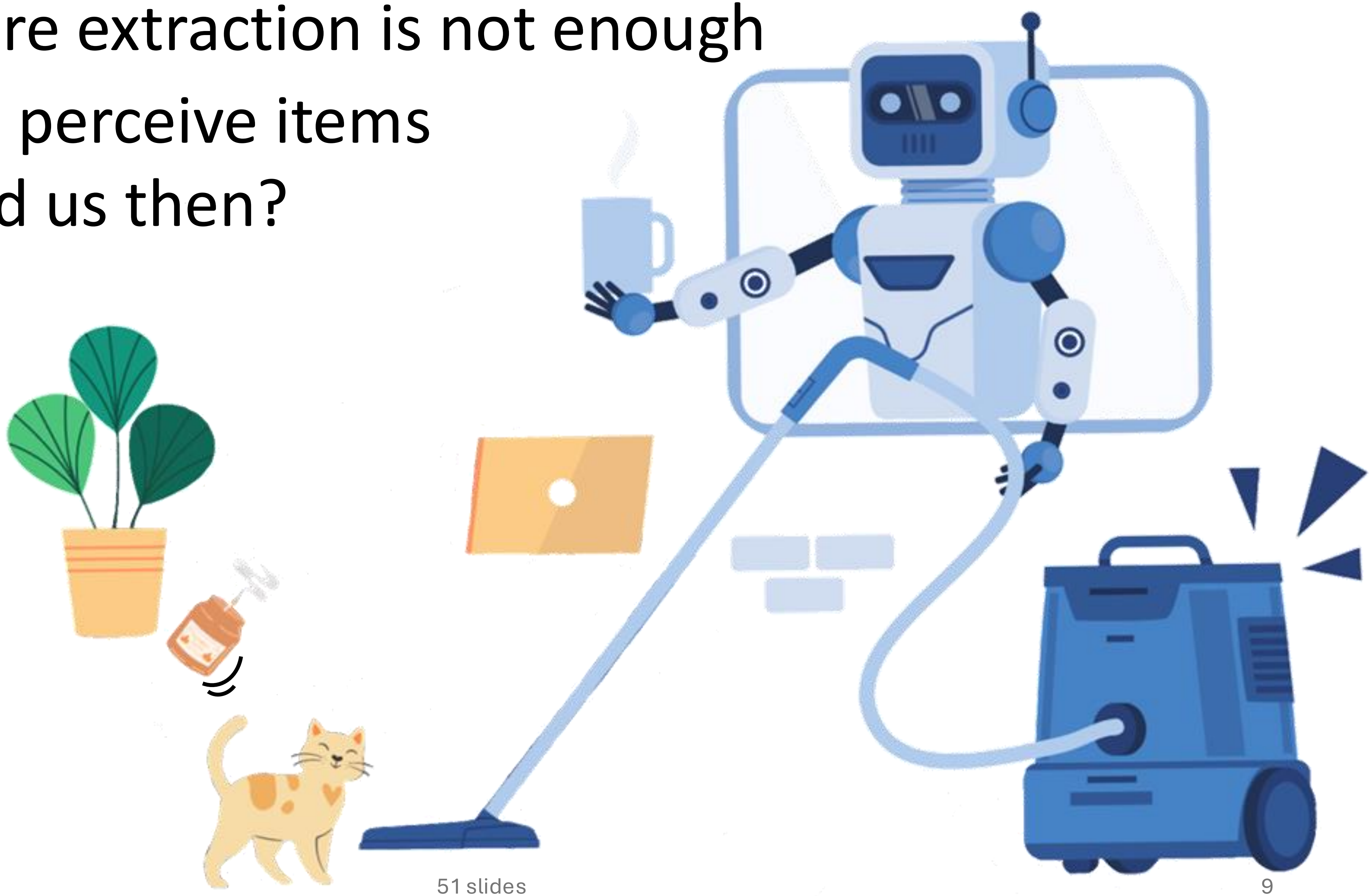
scan path

saliency map

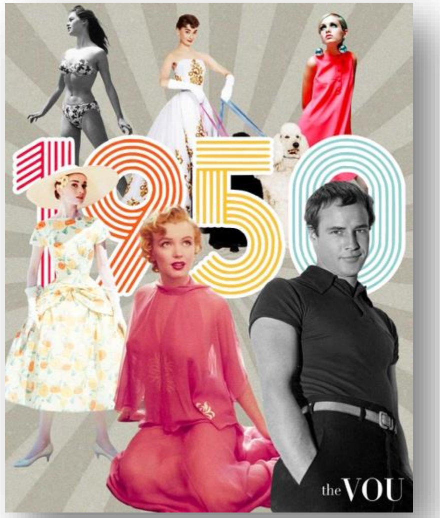
Itti, Laurent, Christof Koch, and Ernst Niebur. "A model of saliency-based visual attention for rapid scene analysis." *IEEE Transactions on Pattern Analysis & Machine Intelligence* 11 (1998): 1254-1259.

Cool, but feature extraction is not enough

How do we perceive items around us then?



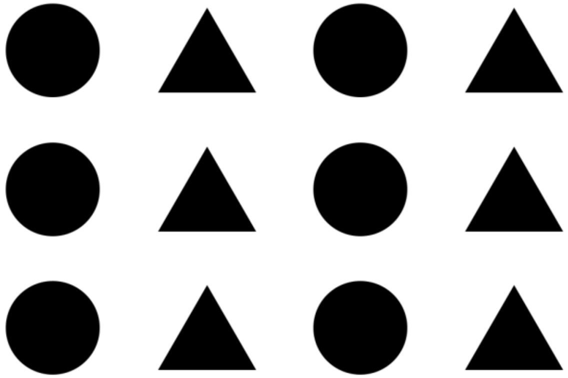
Gestalt Principles



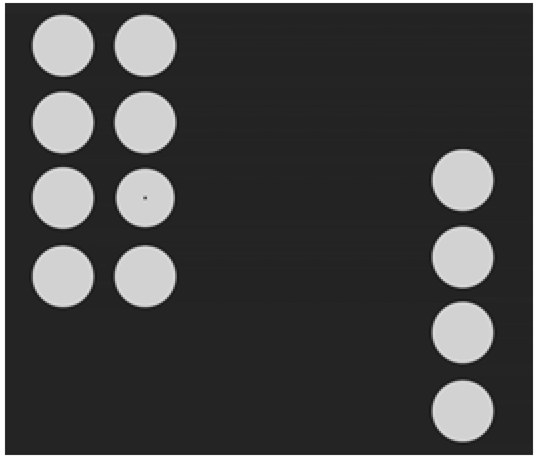
closure

figure-ground organisation

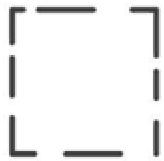
similarity

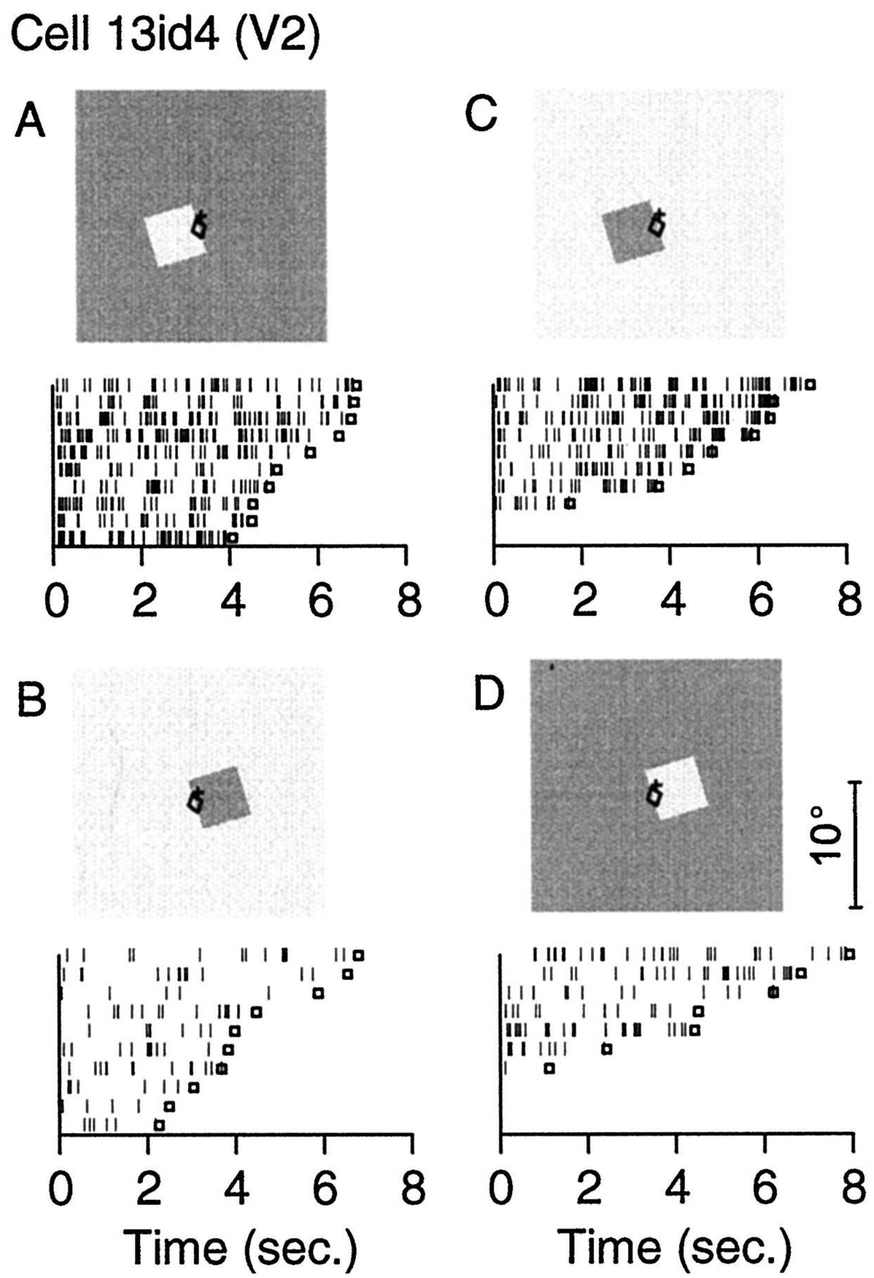


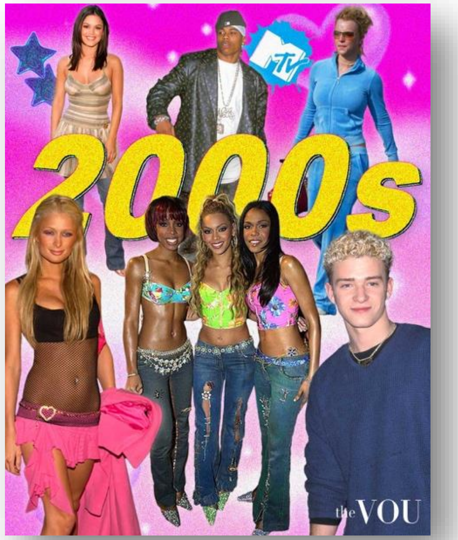
proximity



closure



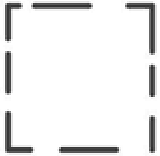


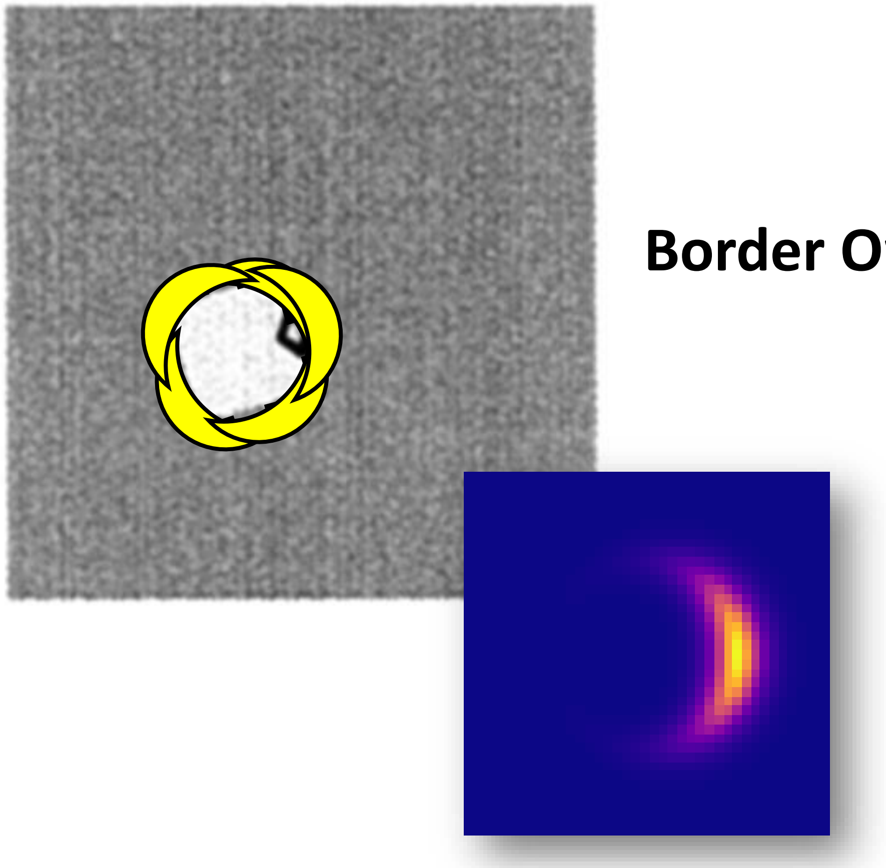


Zhou, Hong, Howard S. Friedman, and Rüdiger Von Der Heydt. "Coding of border ownership in monkey visual cortex." *Journal of Neuroscience* 20.17 (2000): 6594-6611.

Proto-object is an 'object to be'

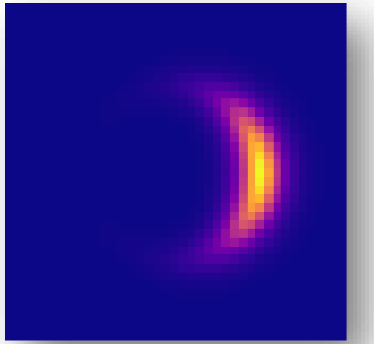
closure

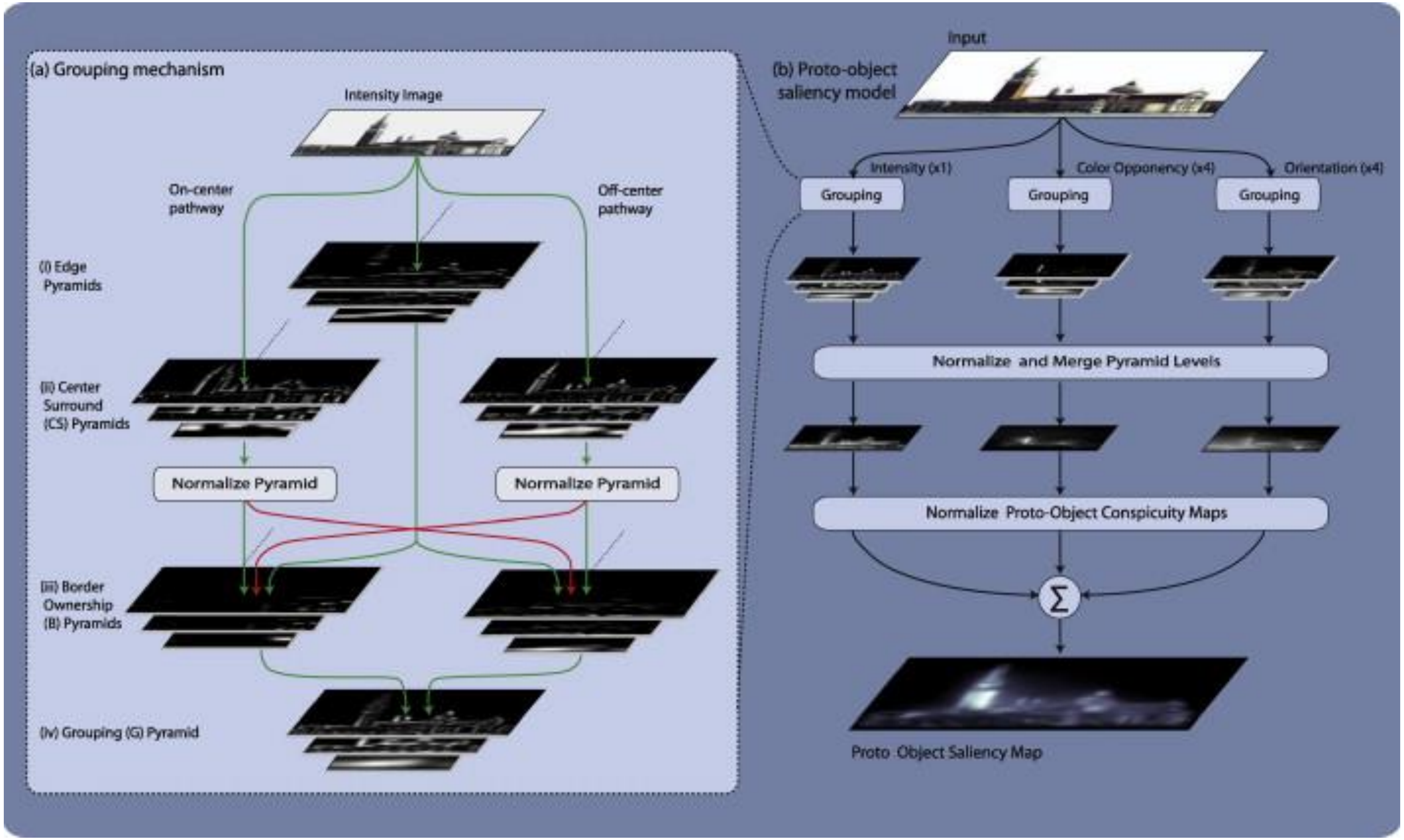




Border Ownership cells

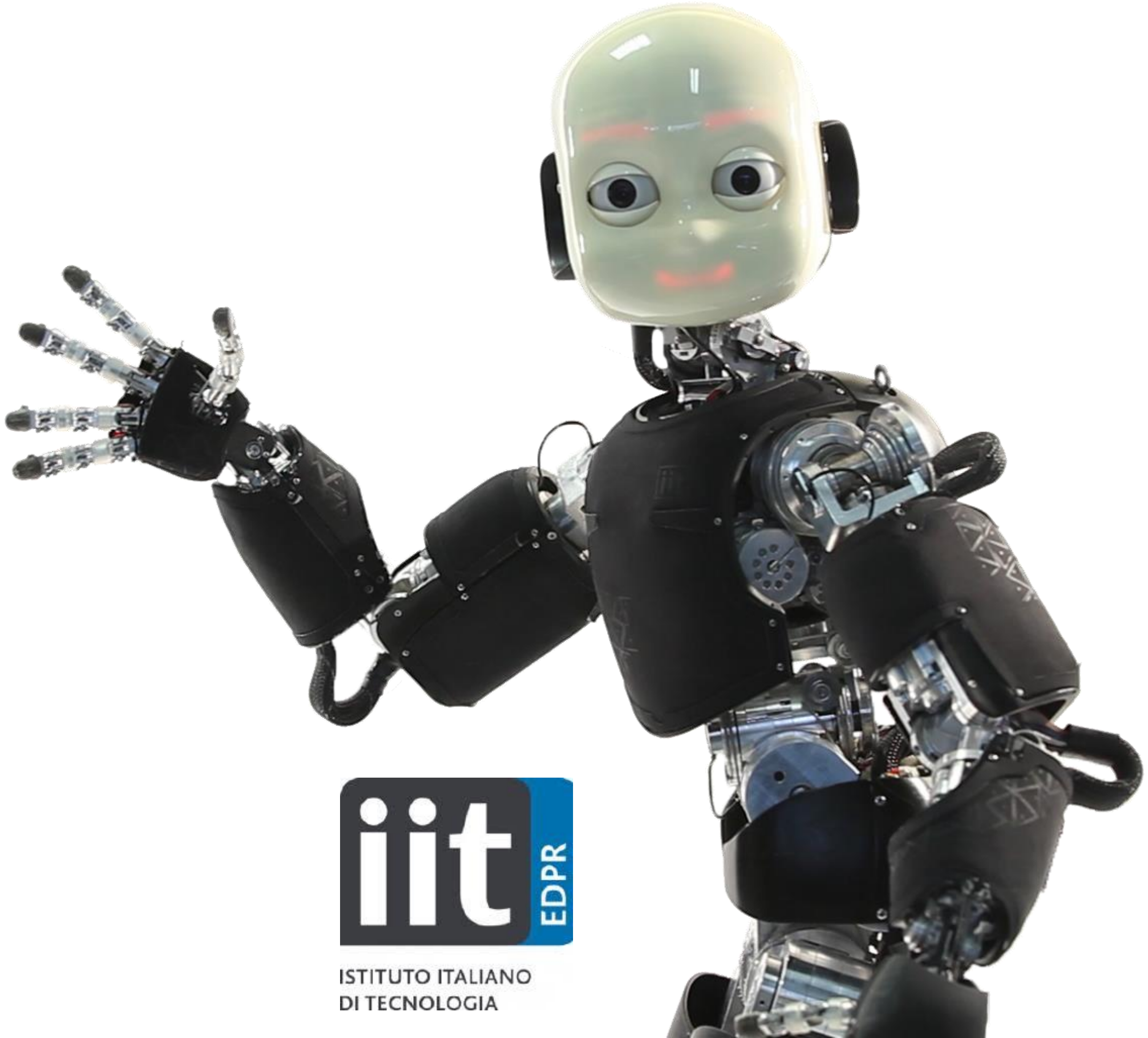
von Mises filter





Russell, Alexander F., et al. "A model of proto-object based saliency." *Vision research* 94 (2014): 1-15.

iCub



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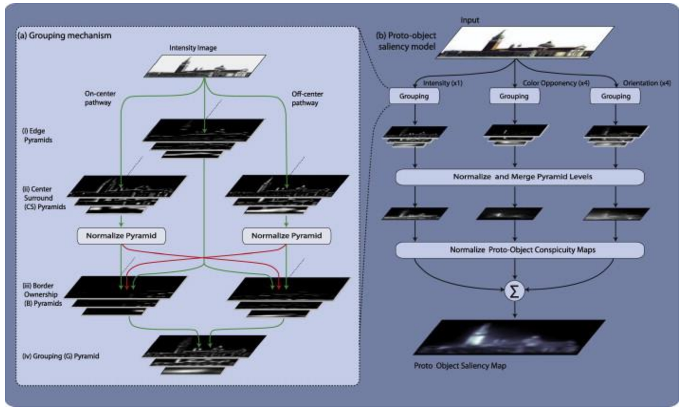
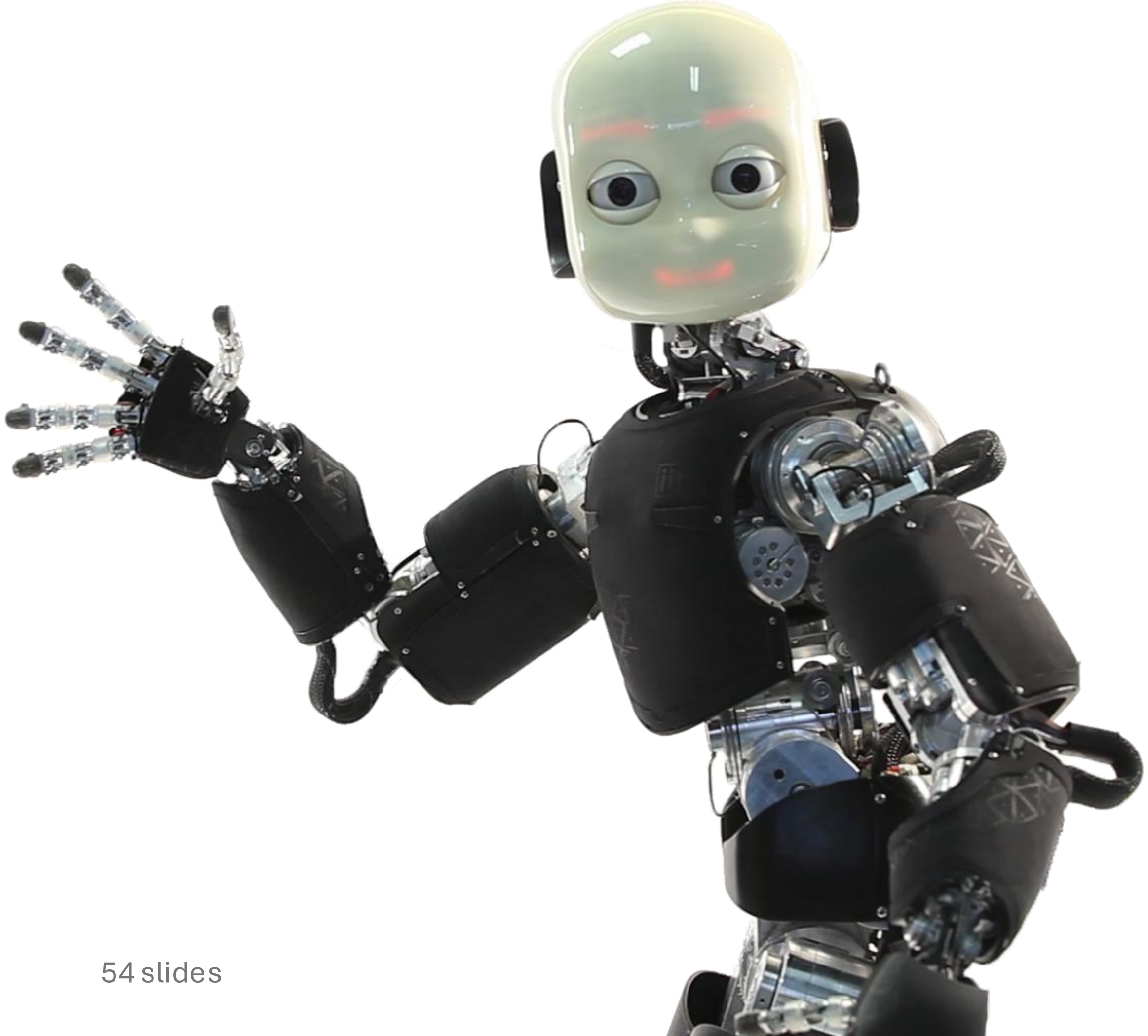


How do we perceive?

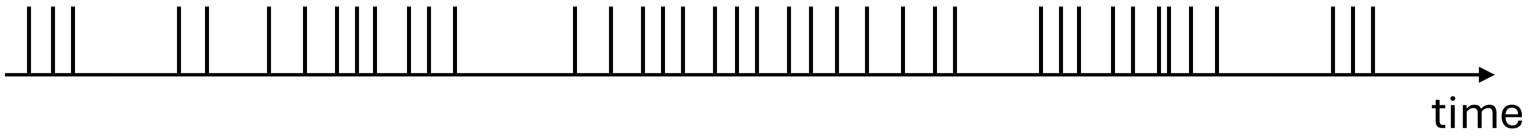


54 slides

How do we perceive?

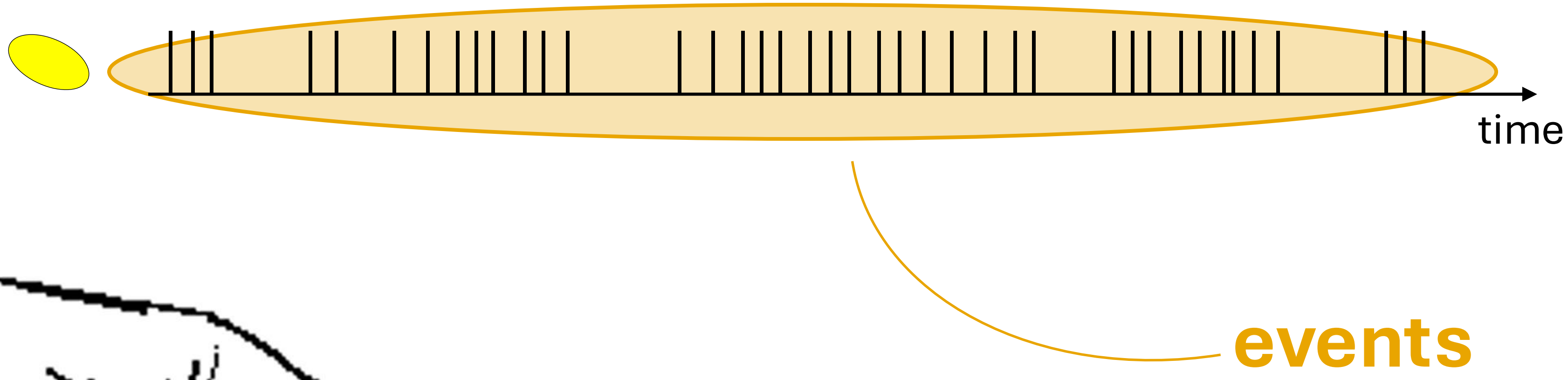
Visual Sensors
Auditory Sensors
Tactile Sensors
Proximity Sensors
Temperature Sensors
Force and Torque Sensors
Chemical Sensors

54 slides



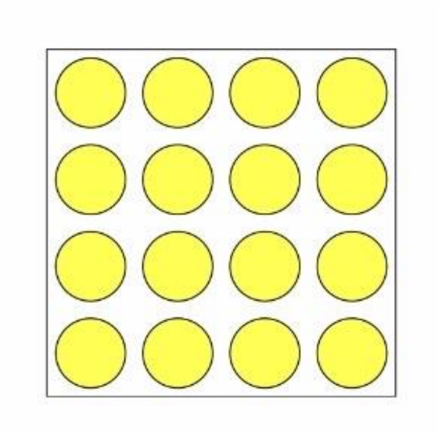
How do we perceive?

54 slides

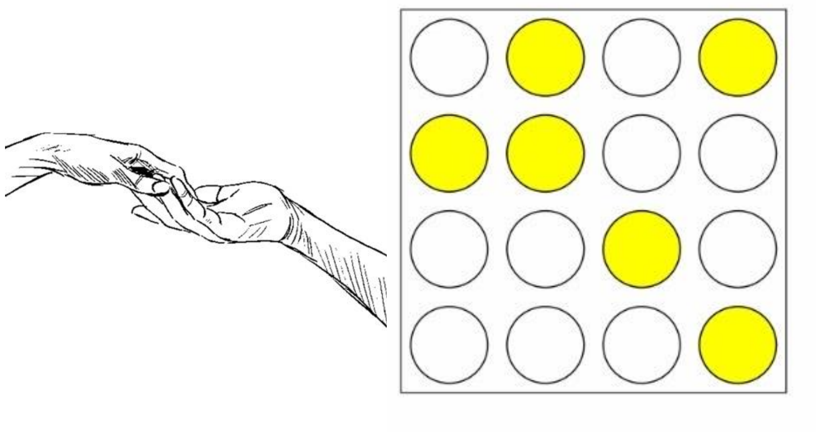


How do we perceive?

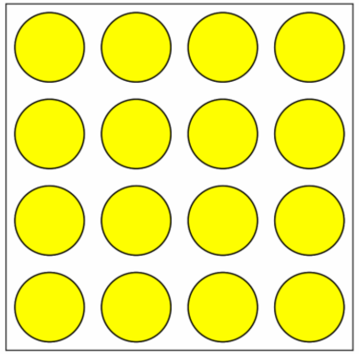
clock-driven



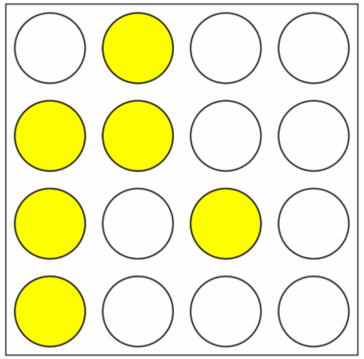
event-driven

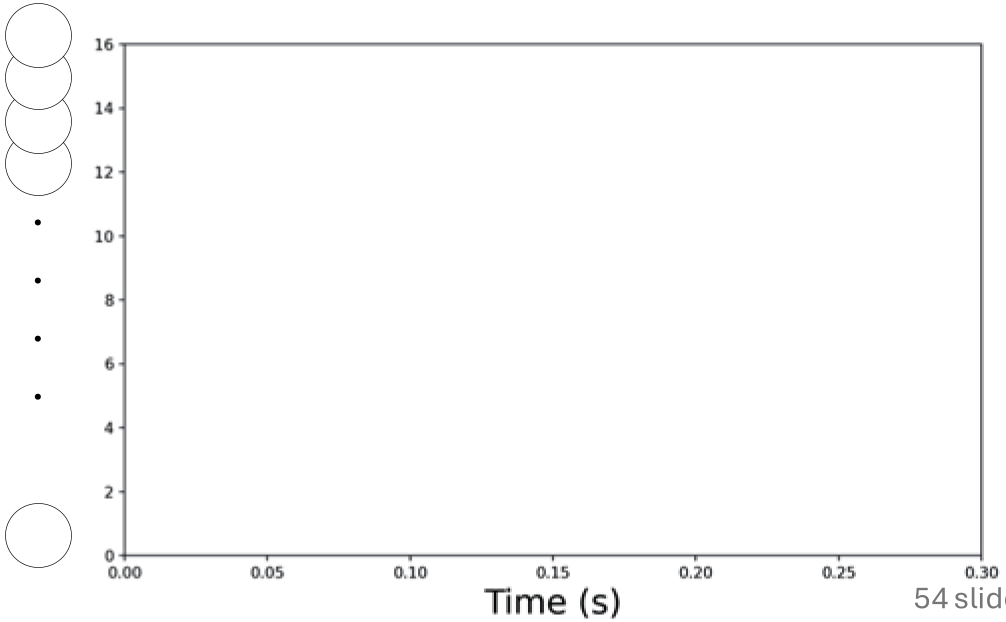


clock-driven

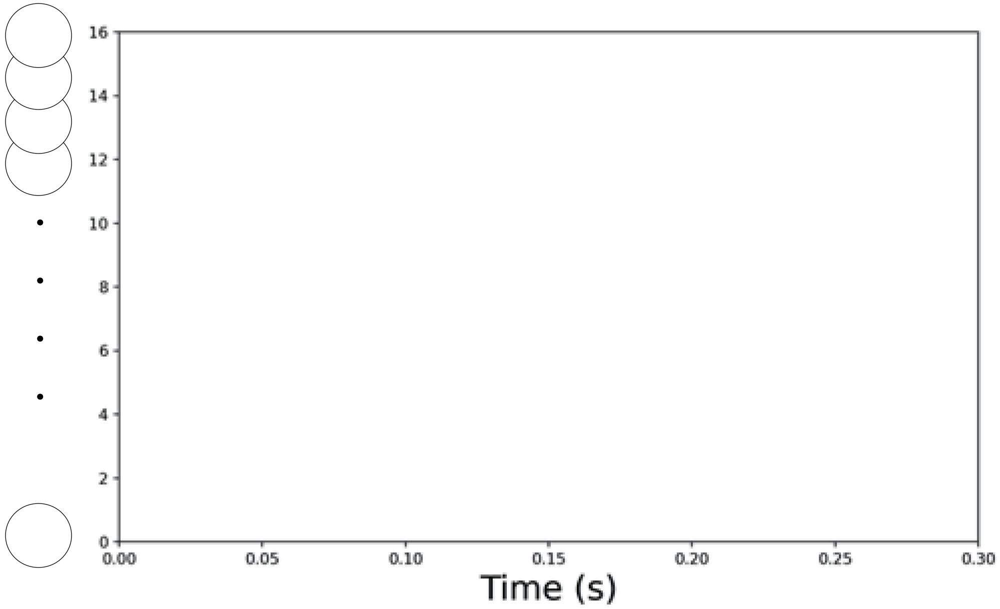


event-driven

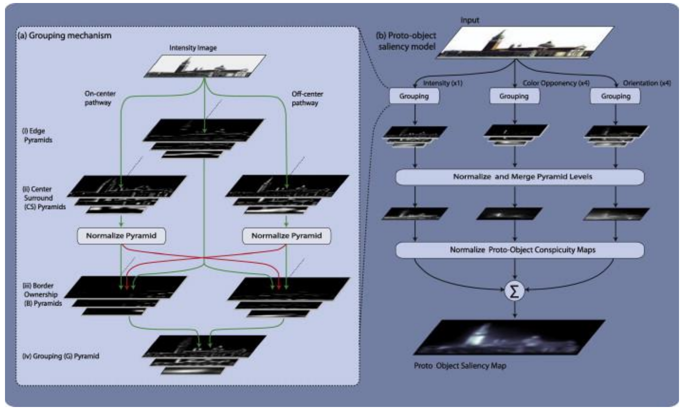


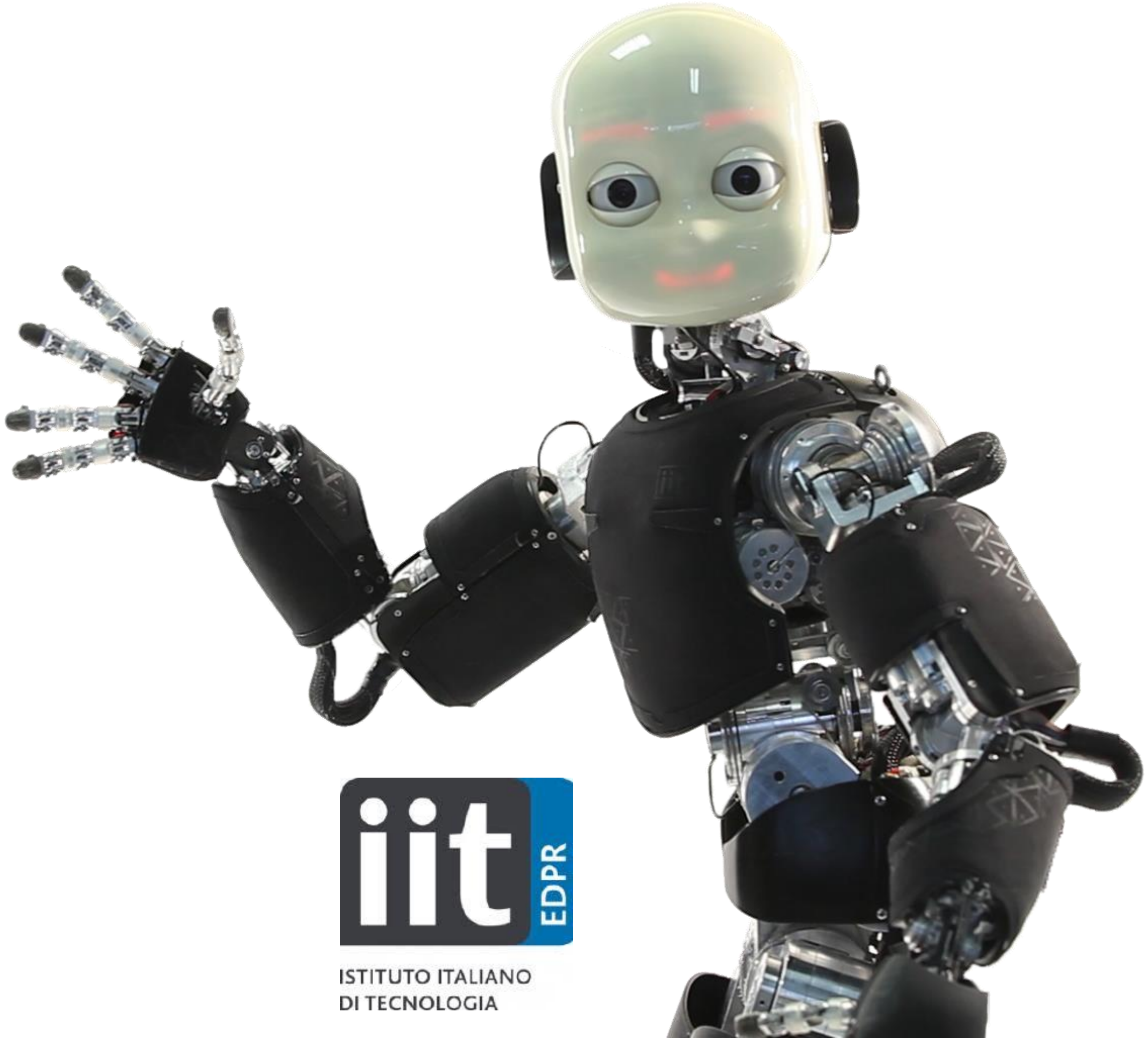


54 slides



Neuromorphic iCub





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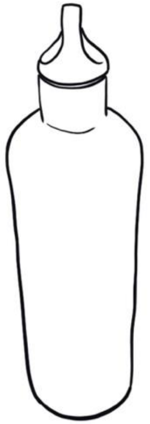
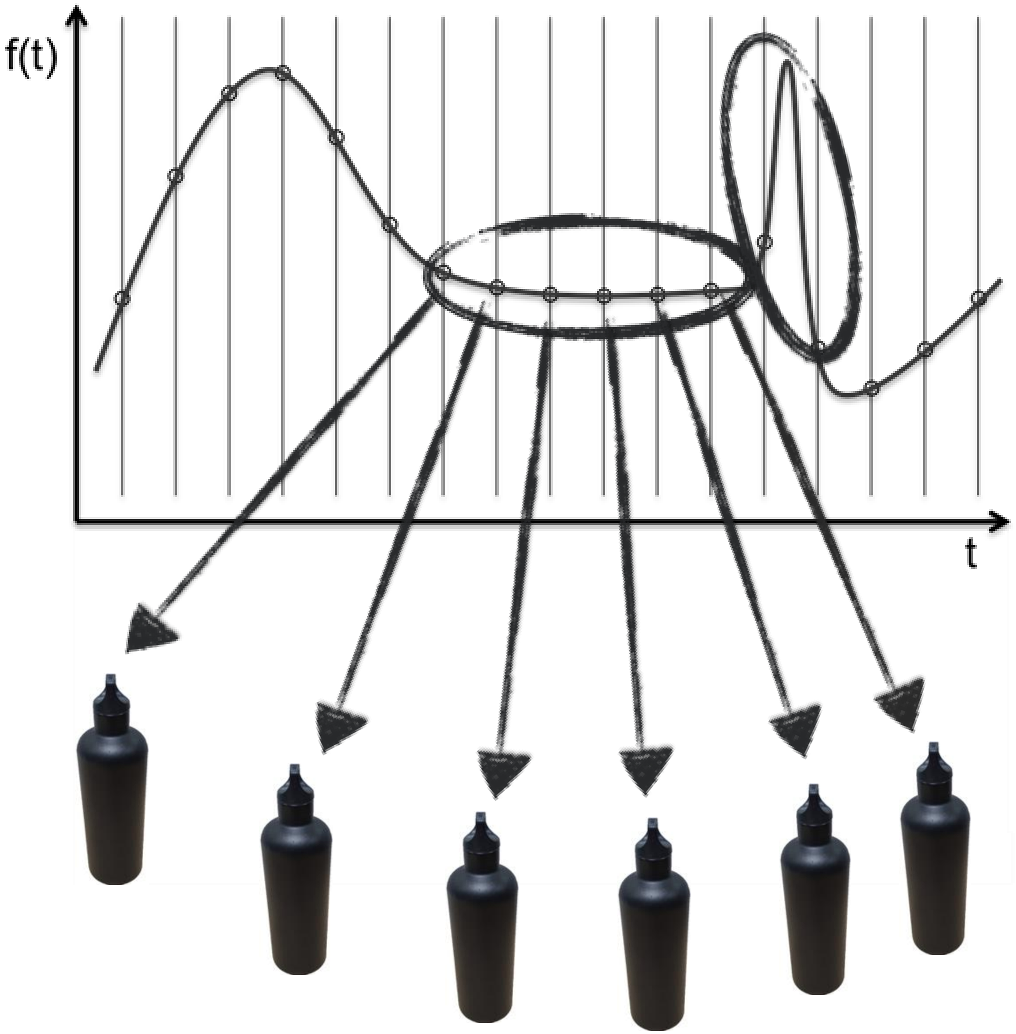
How does a neuromorphic camera work?

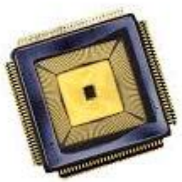
Let's start from a
frame-based camera!

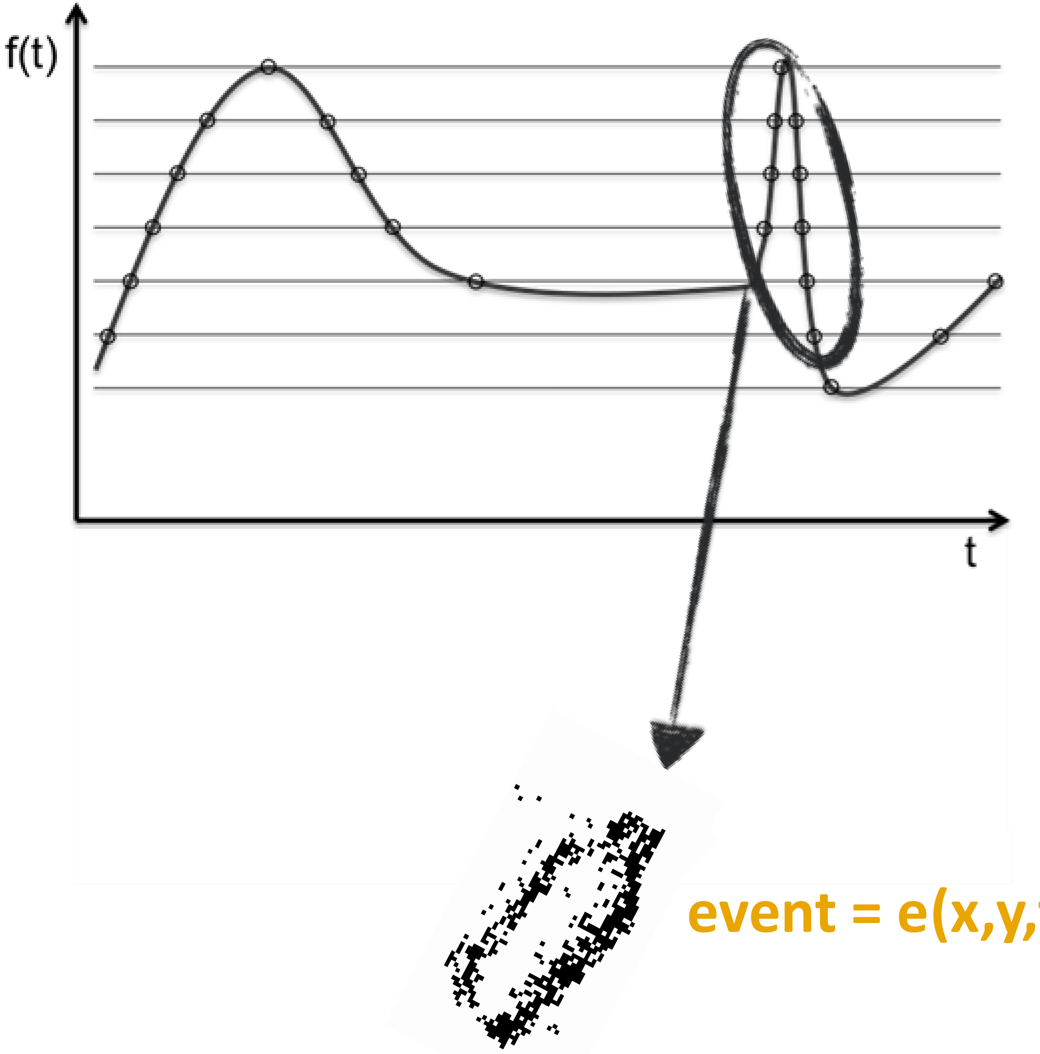


Clock-Based Sampling — fixed Δt



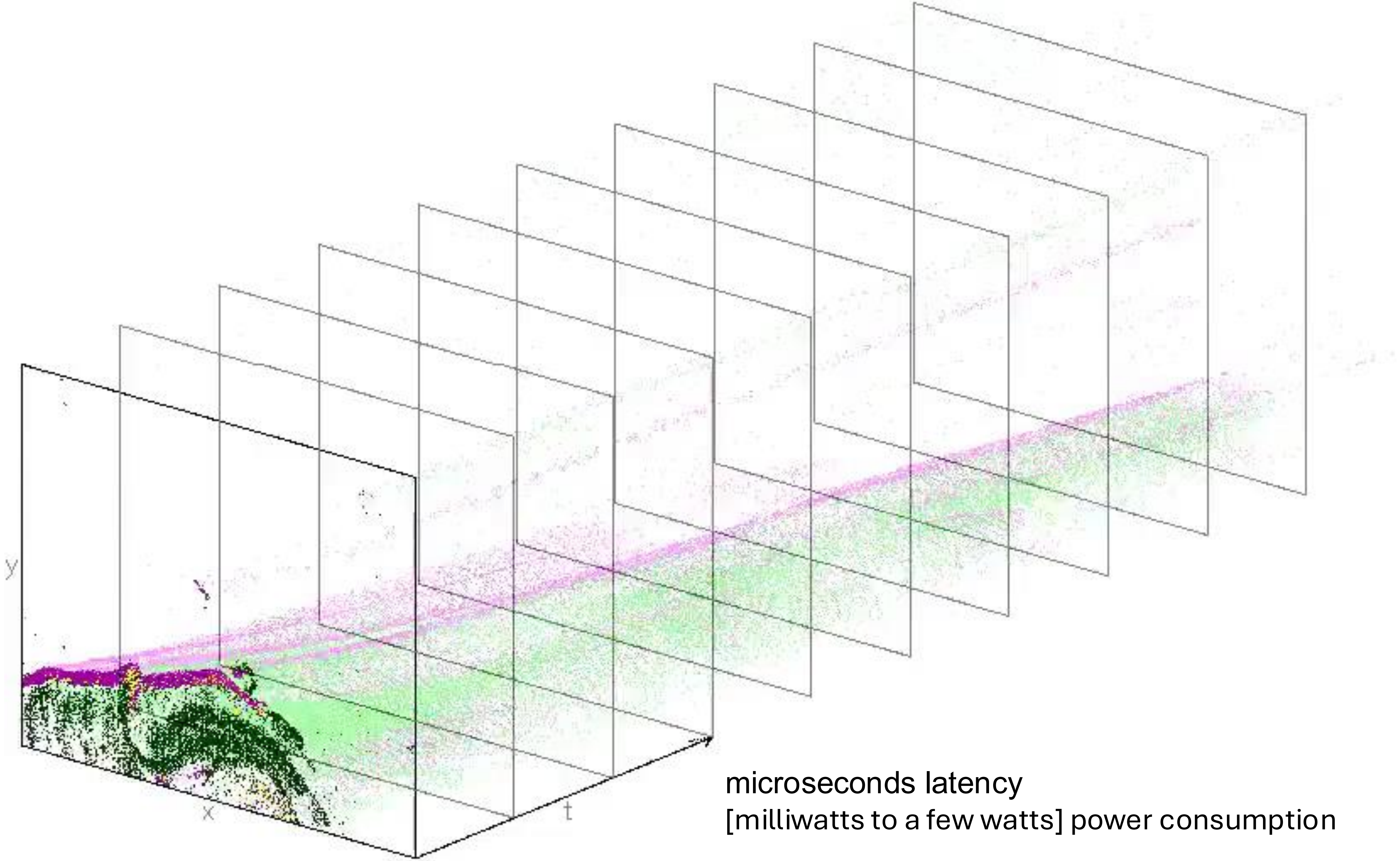
Data-Driven Sampling — fixed Δf (or Δf/f)





event = e(x,y,t,p)

44 slides

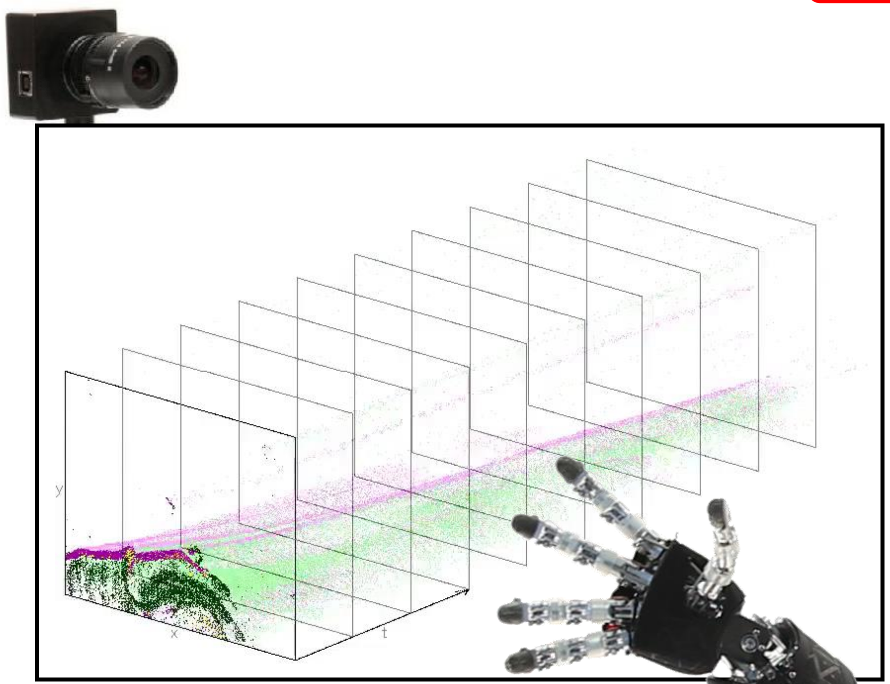


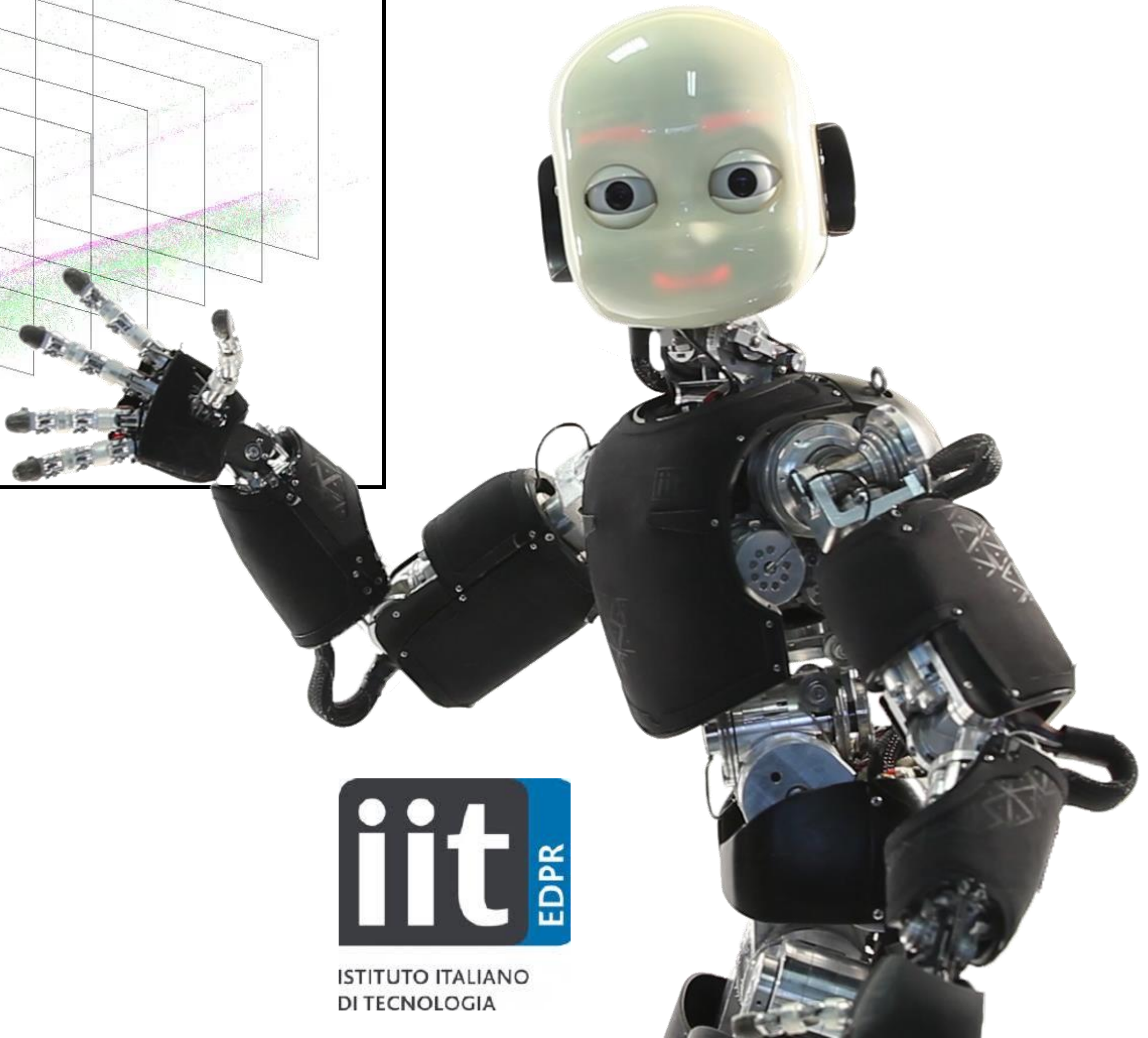
microseconds latency
[milliwatts to a few watts] power consumption

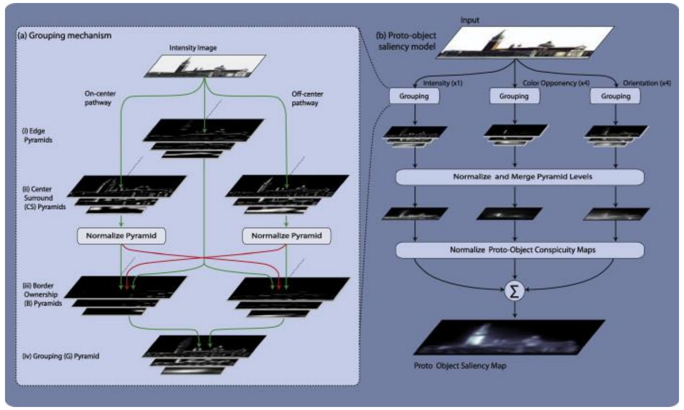
Intensity

Motion

Depth







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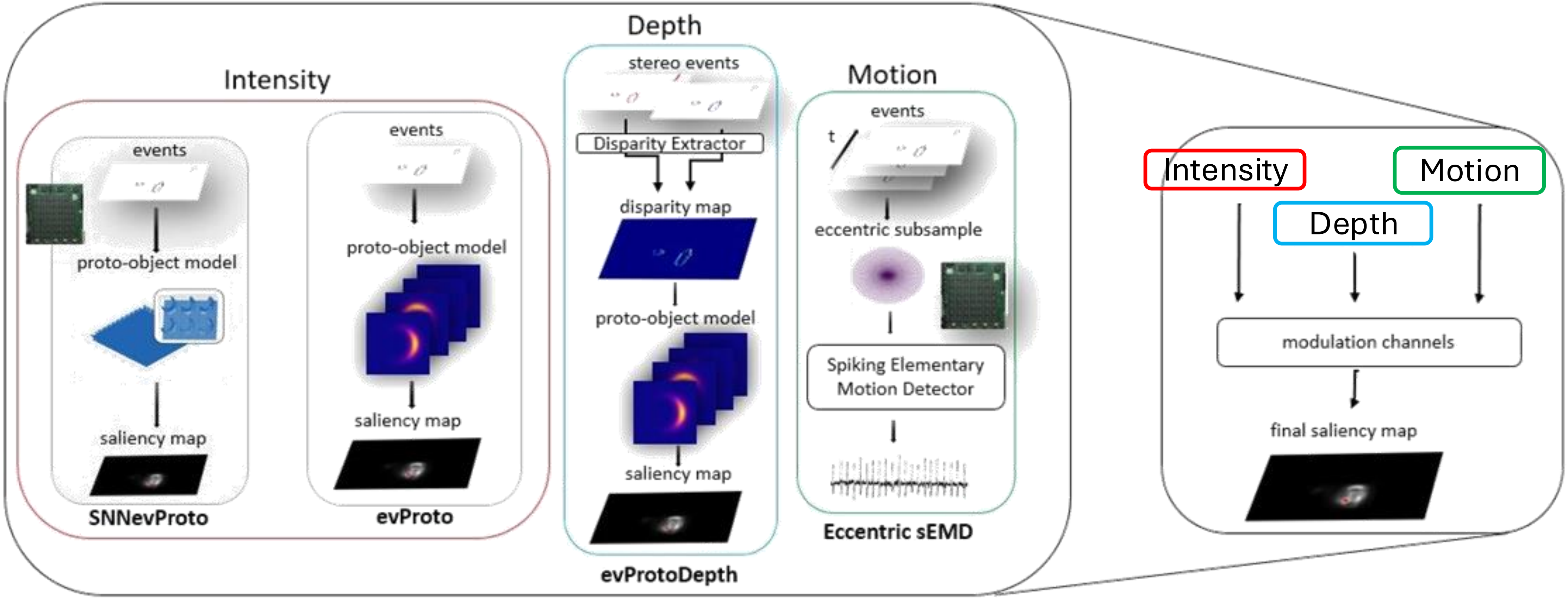
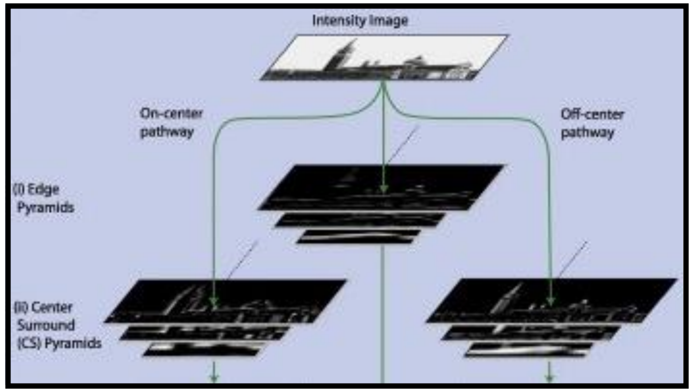
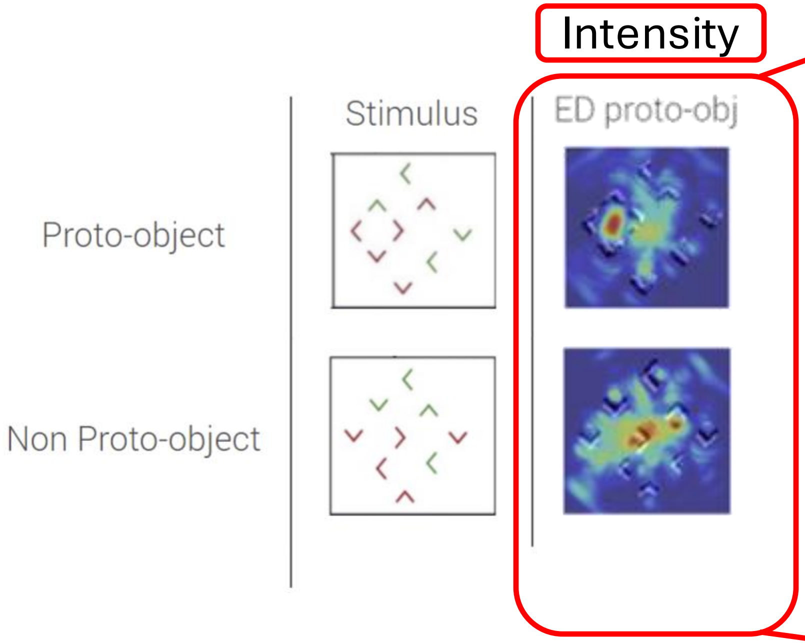
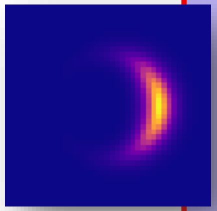
Bioinspired saliency-based attention model

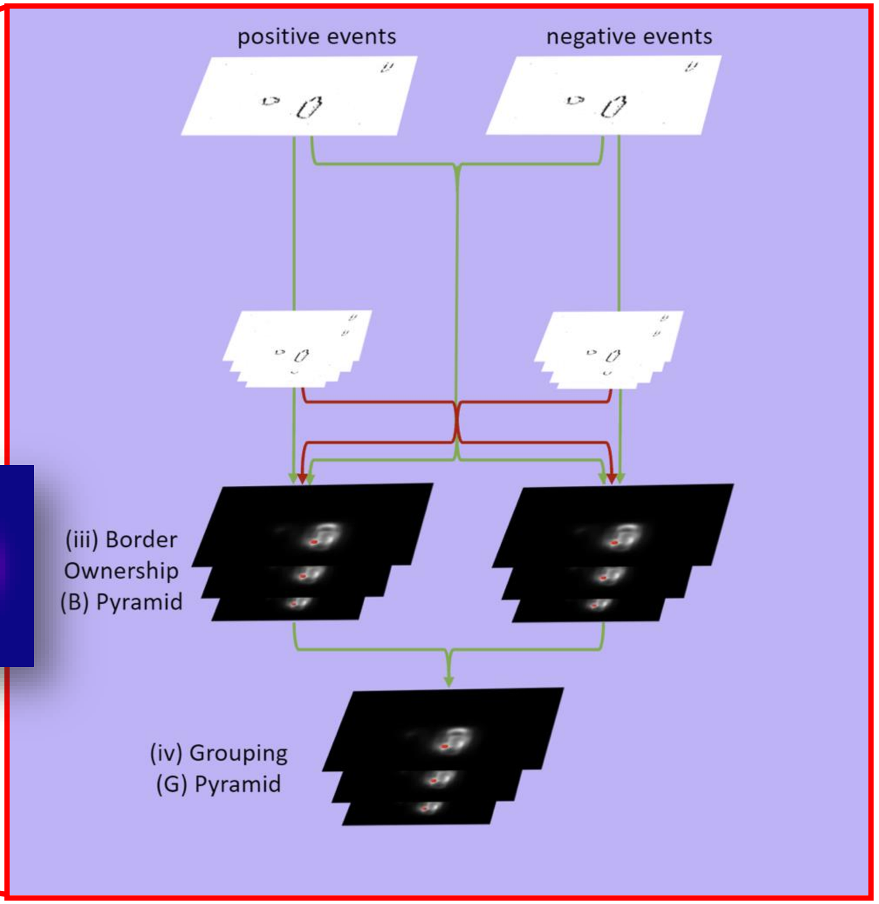


D'Angelo, G., Janotte, E., Schoepe, T., O'Keeffe, J., Milde, M. B., Chicca, E., & Bartolozzi, C. (2020). Event-based eccentric motion detection exploiting time difference encoding Front. Neuroscience
D'Angelo, G., Perrett, A., Iacono, M., Furber, S., & Bartolozzi, C. (2022). Event driven bio-inspired attentive system for the iCub humanoid robot on SpiNNaker. Neuromorphic Computing and Engineering
Ghosh, S & D'Angelo, G., Glover, A., Iacono, M., Niebur, E., & Bartolozzi, C. (2022). Event-driven proto-object based saliency in 3D space to attract a robot's attention. *Scientific reports*
Iacono, M., D'Angelo, G., Glover, A., Tikhanoff, V., Niebur, E., & Bartolozzi, C. (2019, November). Proto-object based saliency for event-driven cameras. In 2019 IEEE/RSJ International IROS









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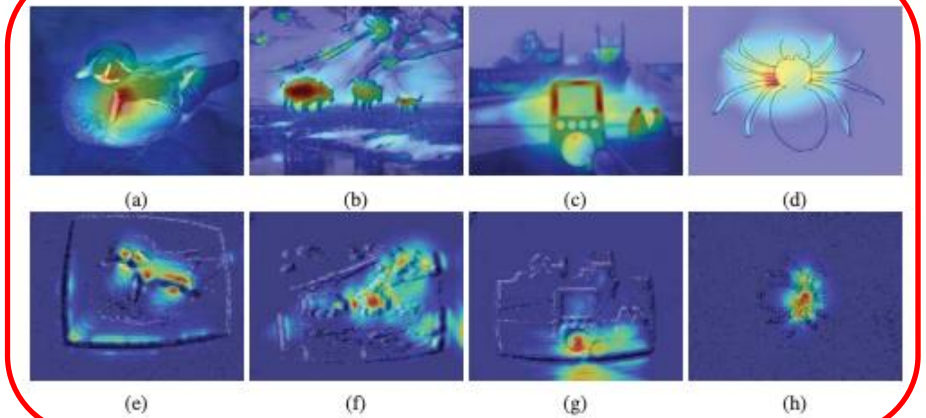
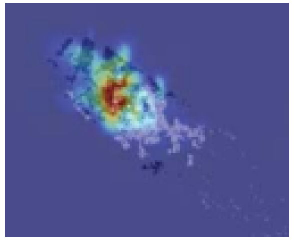
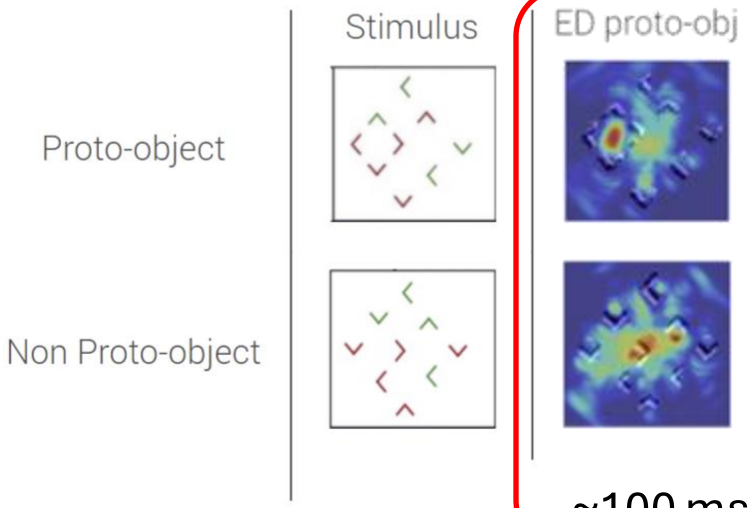


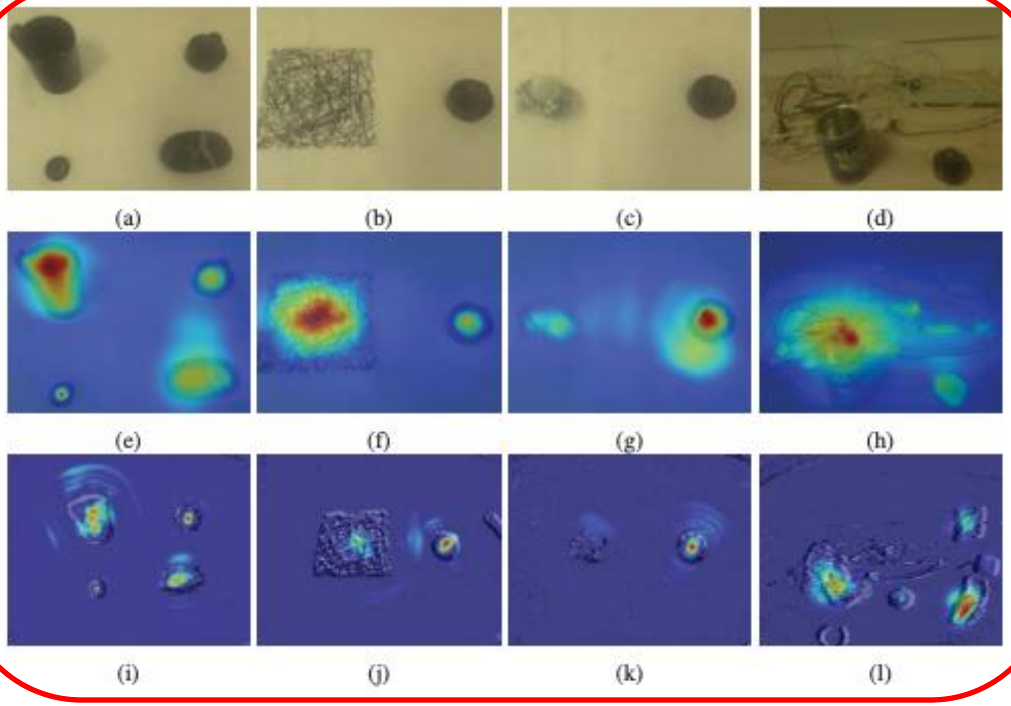


≈2000 px/s.

Intensity



~100 ms



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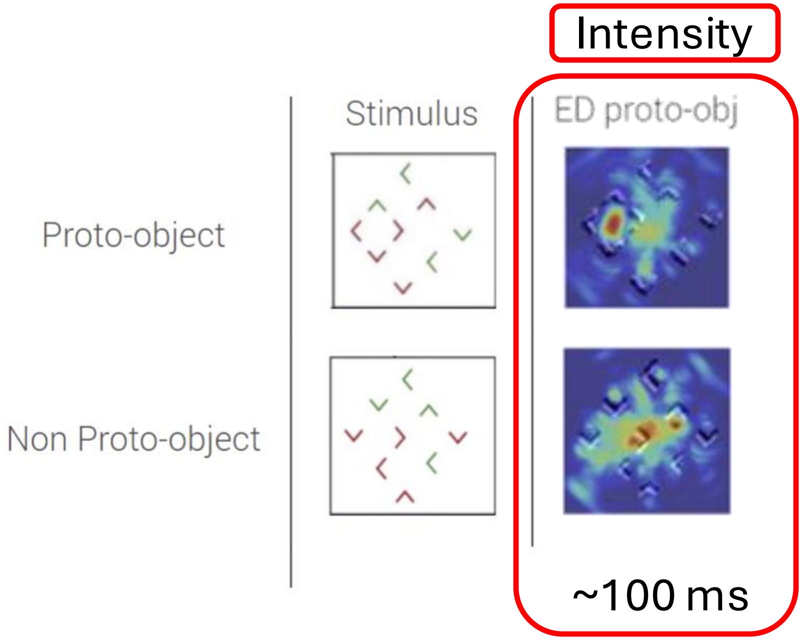

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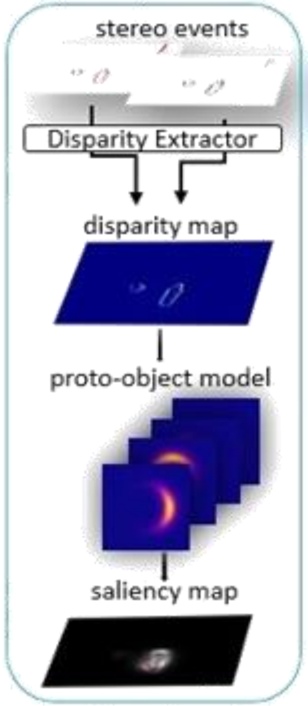
Depth



evProtoDepth

What interests a robot: Event-Driven Proto-object saliency in 3D space

Giulia D'Angelo and Suman Ghosh, Arren Glover, Massimiliano Iacono, Ernst Niebur, Chiara Bartolozzi

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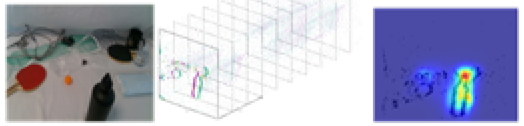
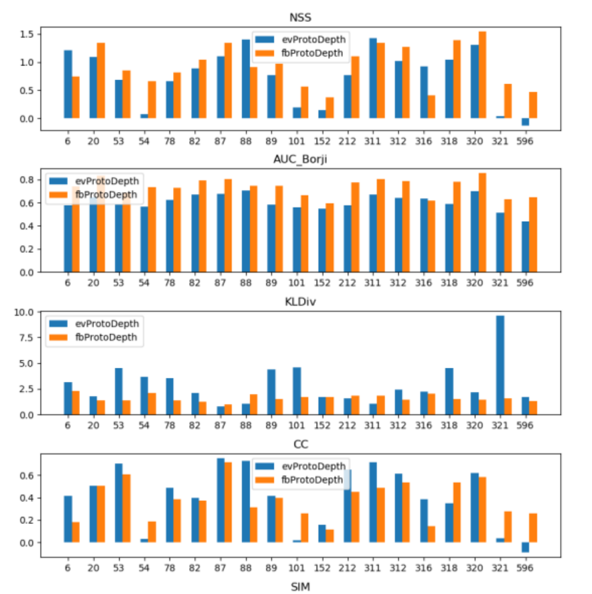
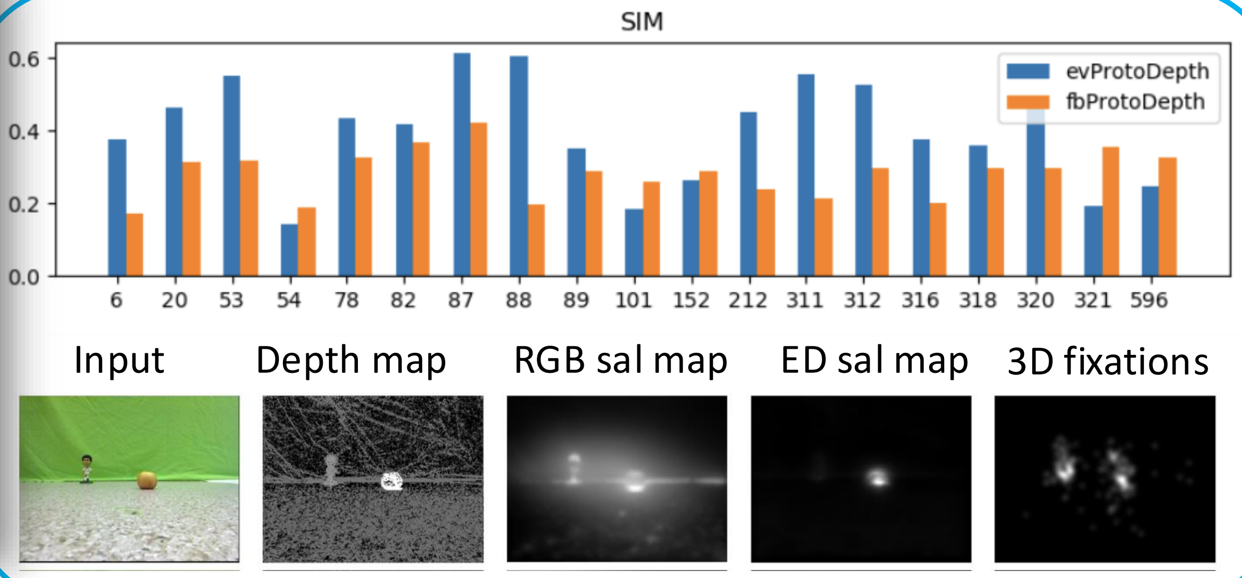
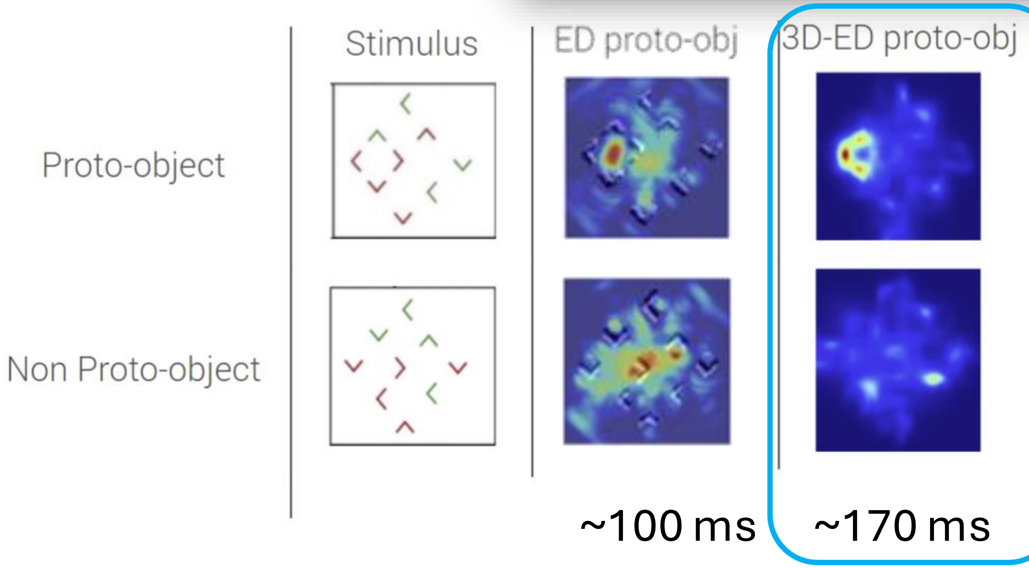
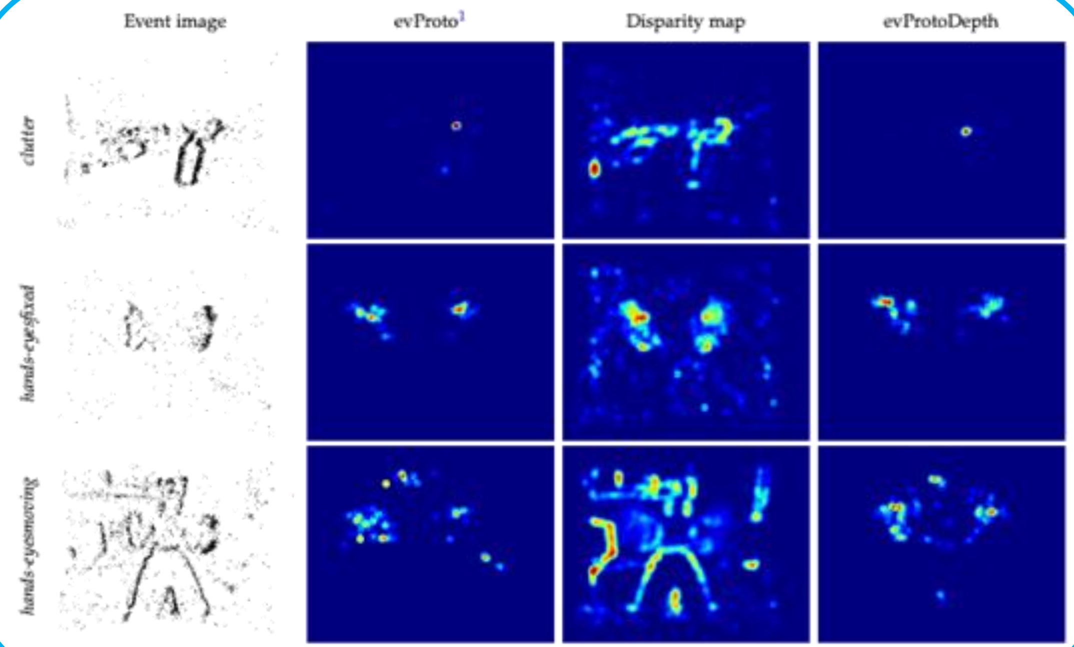
Ghosh, S & D'Angelo, G., Glover, A., Iacono, M., Niebur, E., & Bartolozzi, C. (2022). Event-driven proto-object based saliency in 3D space to attract a robot's attention. *Scientific reports*, *12*(1), 1-14.

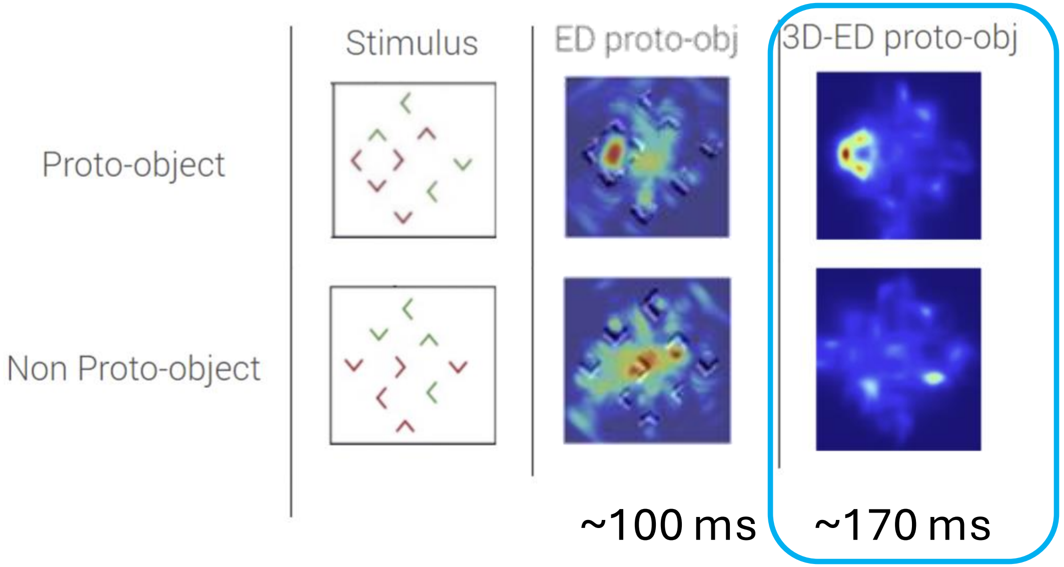


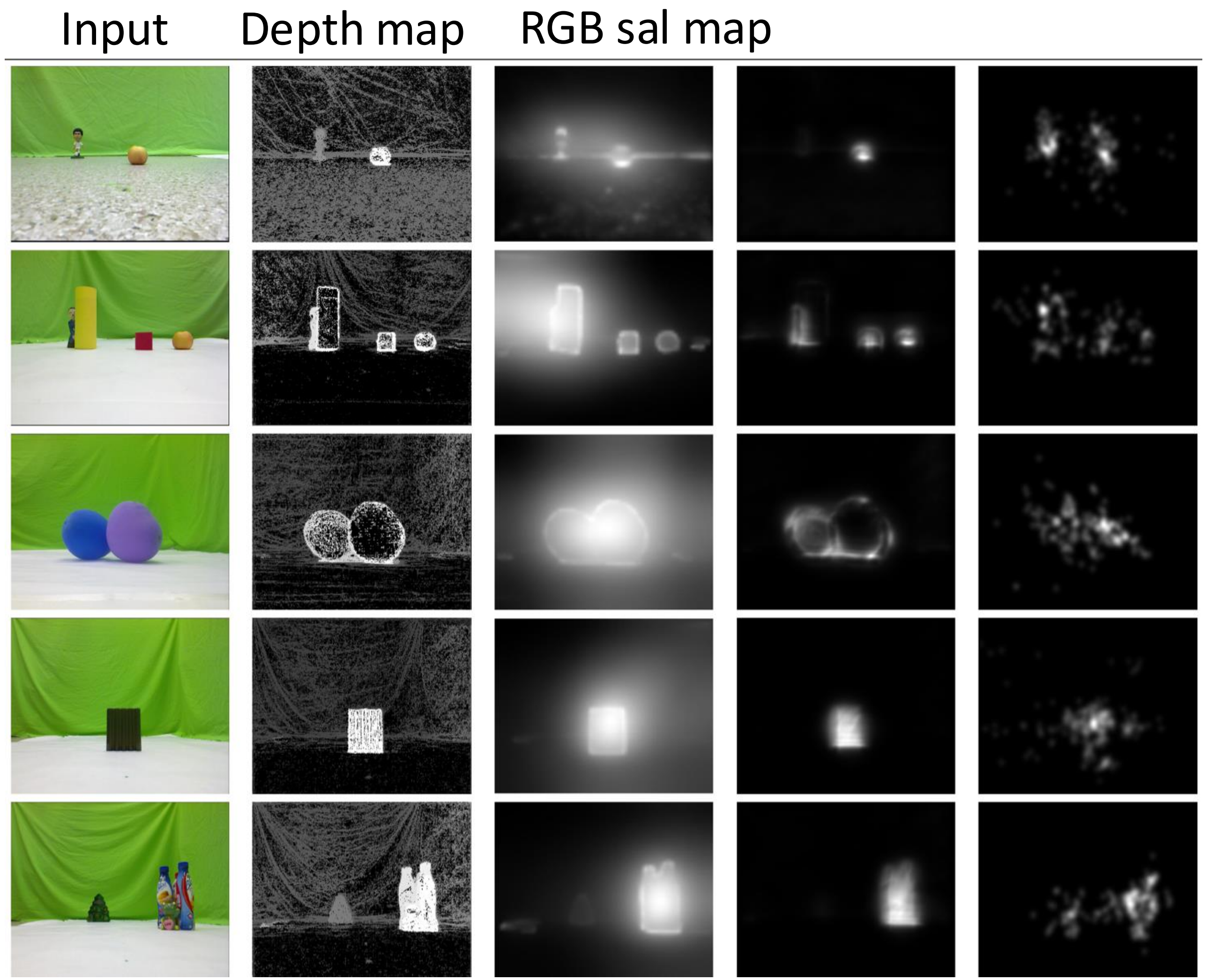

NSS
evProtoDepth
fbProtoDepth
AUC_Borji
KLDiv
CC
SIM


SIM
evProtoDepth
fbProtoDepth
Input
Depth map
RGB sal map
ED sal map
3D fixations

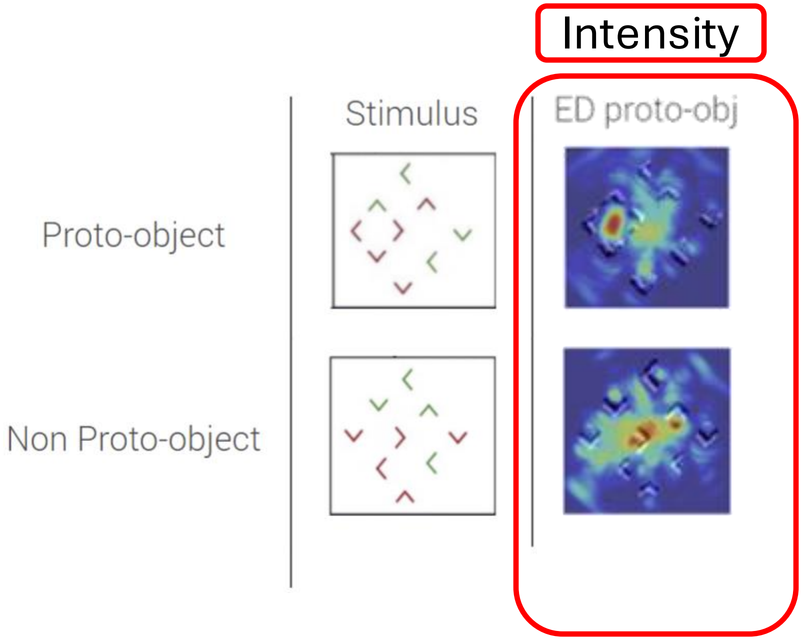

Stimulus
ED proto-obj
3D-ED proto-obj
Proto-object
Non Proto-object
~100 ms
~170 ms

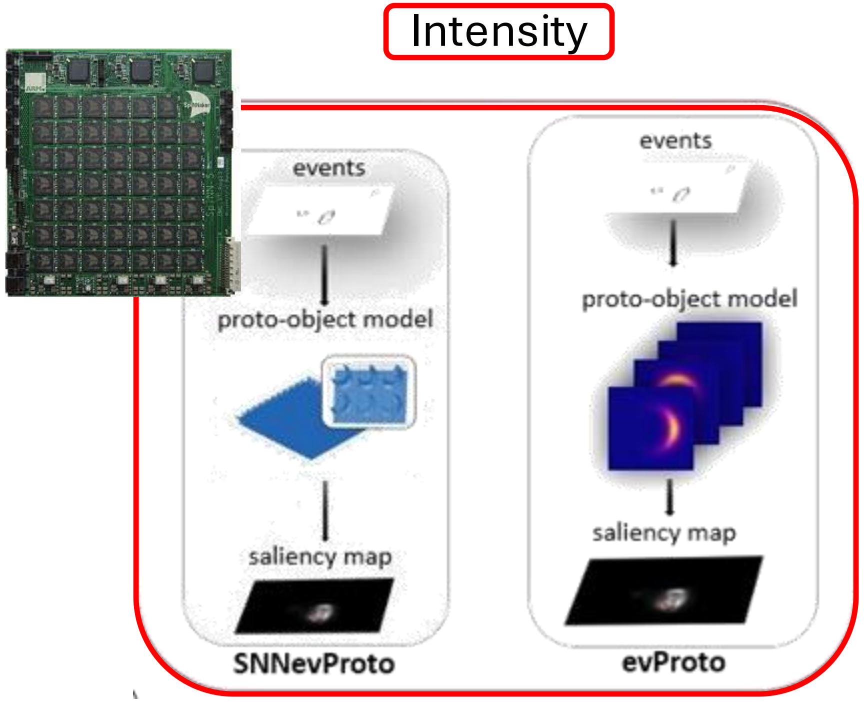

Event image
evProto[1]
Disparity map
evProtoDepth
clutter
hands-eyesfixed
hands-eyesmoving





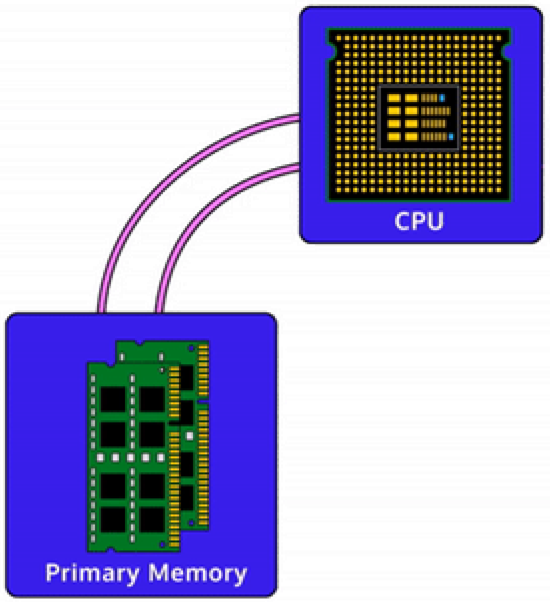
Ghosh, S & D'Angelo, G., Glover, A., Iacono, M., Niebur, E., & Bartolozzi, C. (2022). Event-driven proto-object based saliency in 3D space to attract a robot's attention. *Scientific reports*, *12*(1), 1-14.


Intensity
Stimulus
ED proto-obj
Proto-object
Non Proto-object

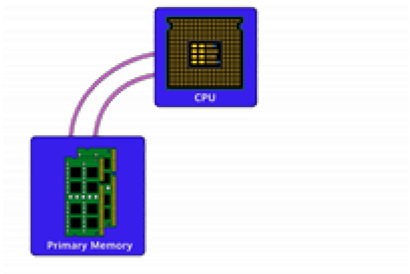

Intensity
events
proto-object model
saliency map
SNNevProto
events
proto-object model
saliency map
evProto

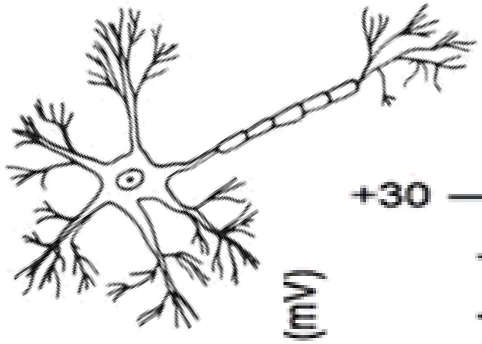
How does a neuromorphic platform work?

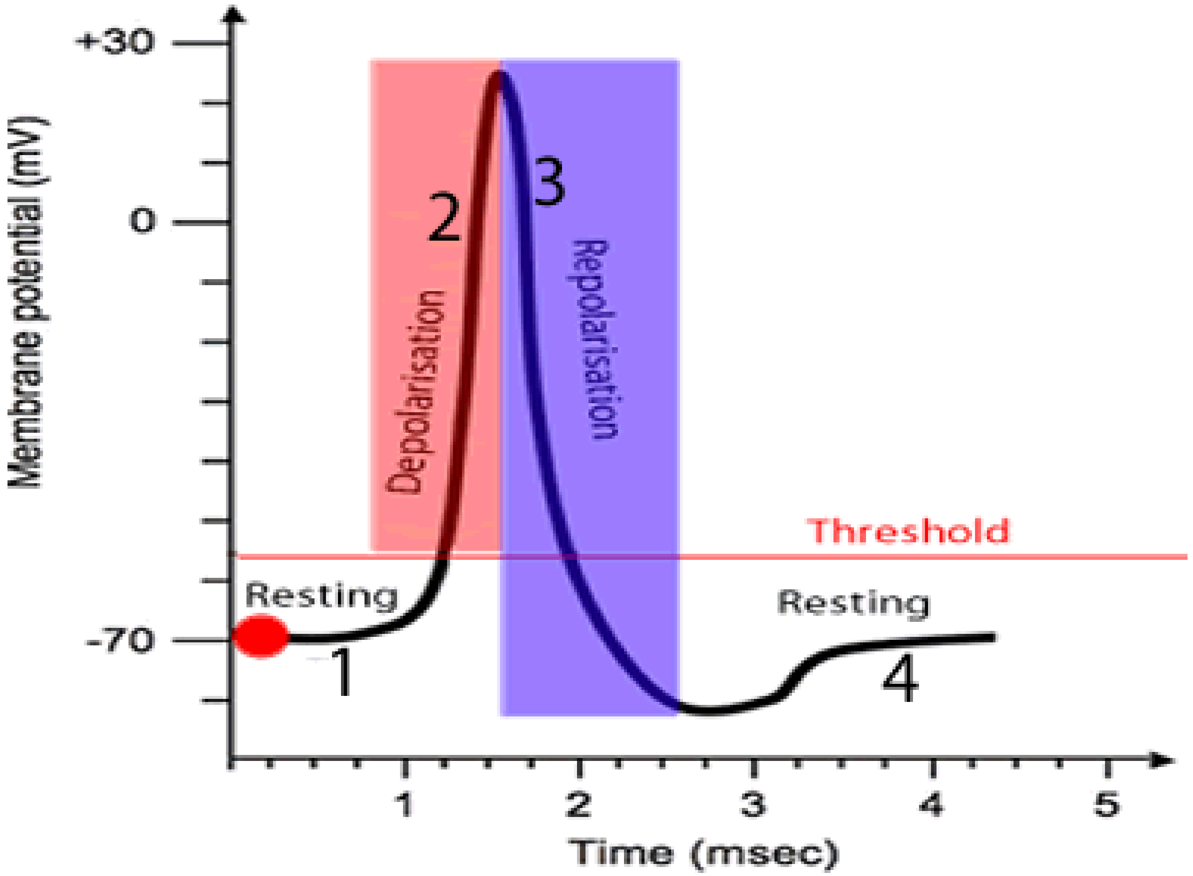
Let’s start from classic CPU!

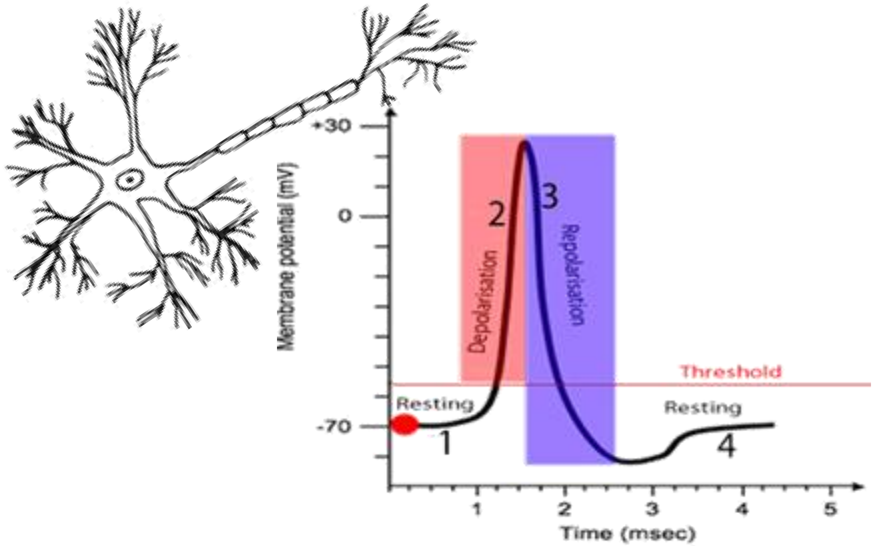


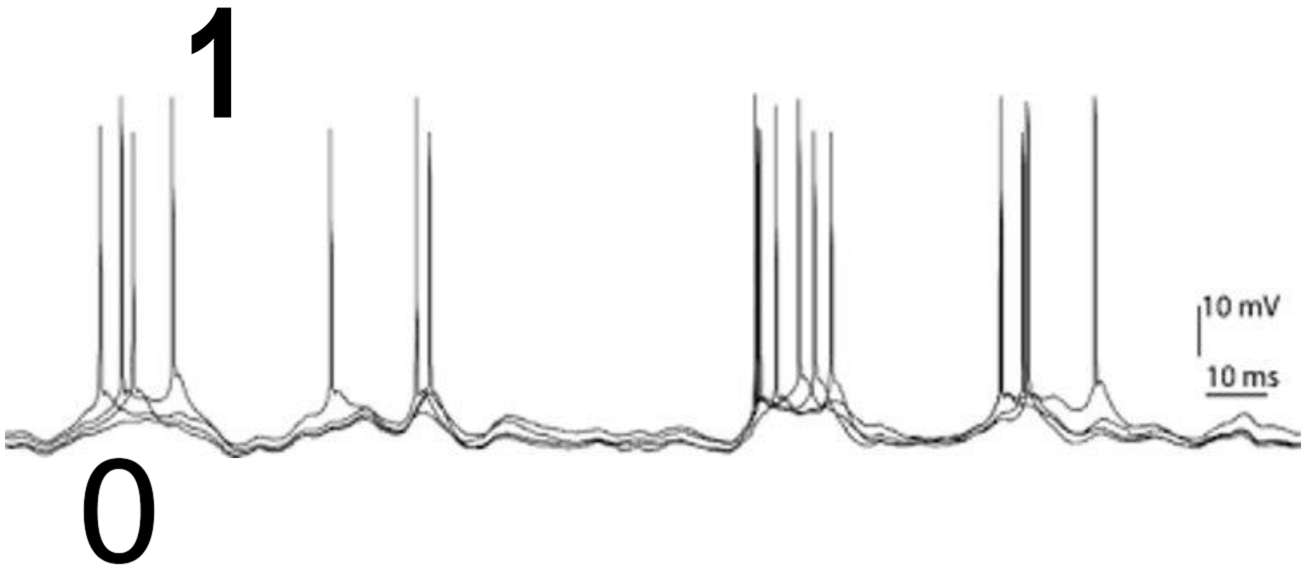
Let’s start from classic CPU!

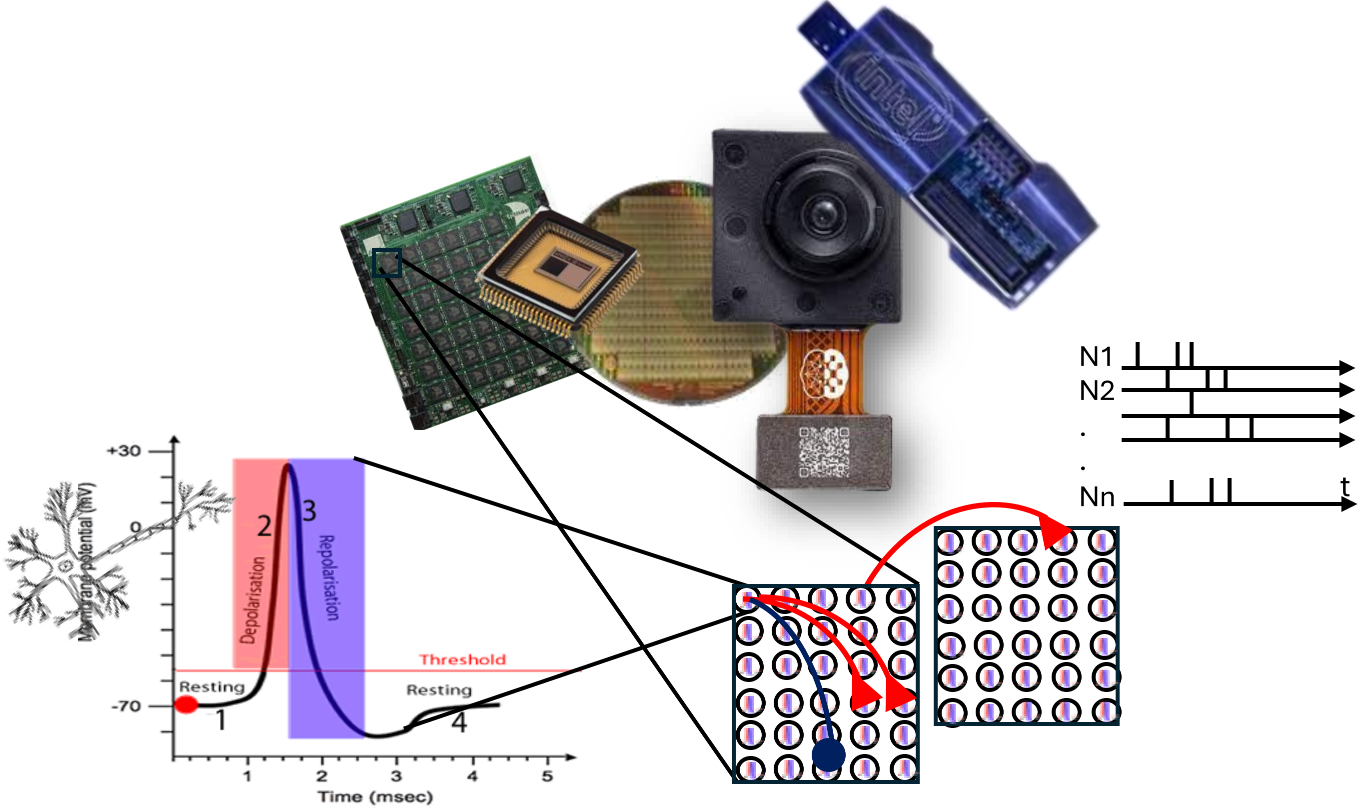


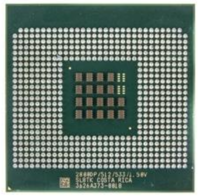





+30
0
-70
Membrane potential (mV)
Depolarisation
Repolarisation
2
3
Threshold
Resting
Resting
1
4
1
2
3
4
5
Time (msec)

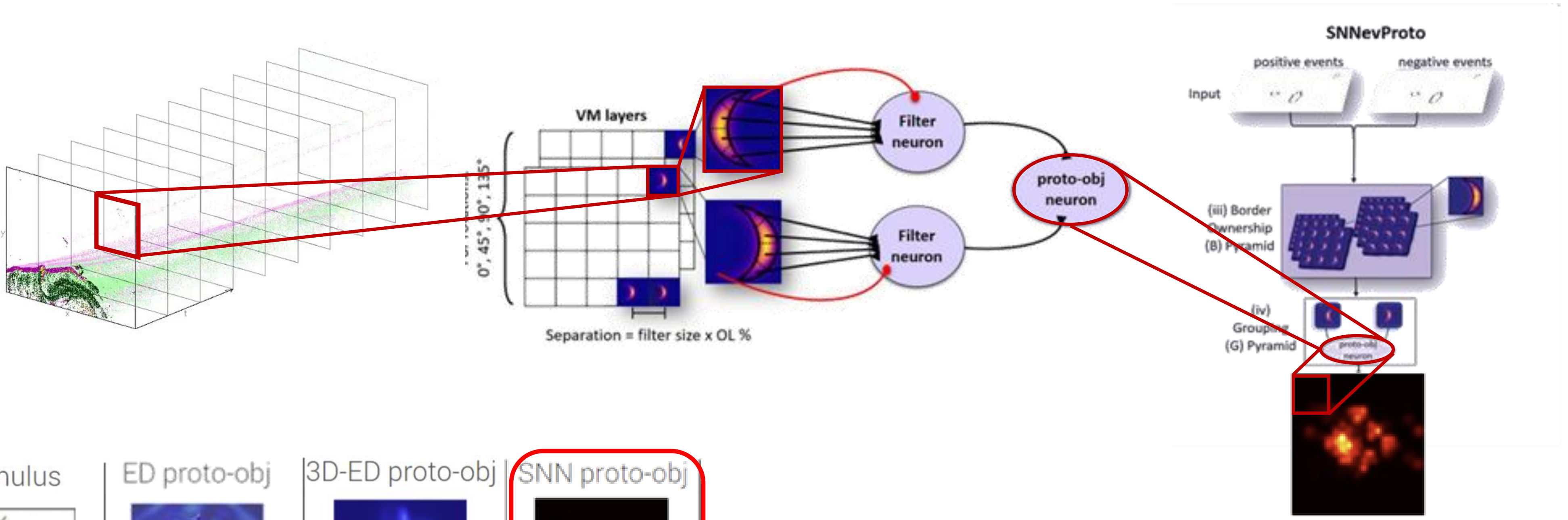

1
0
10 mV
10 ms

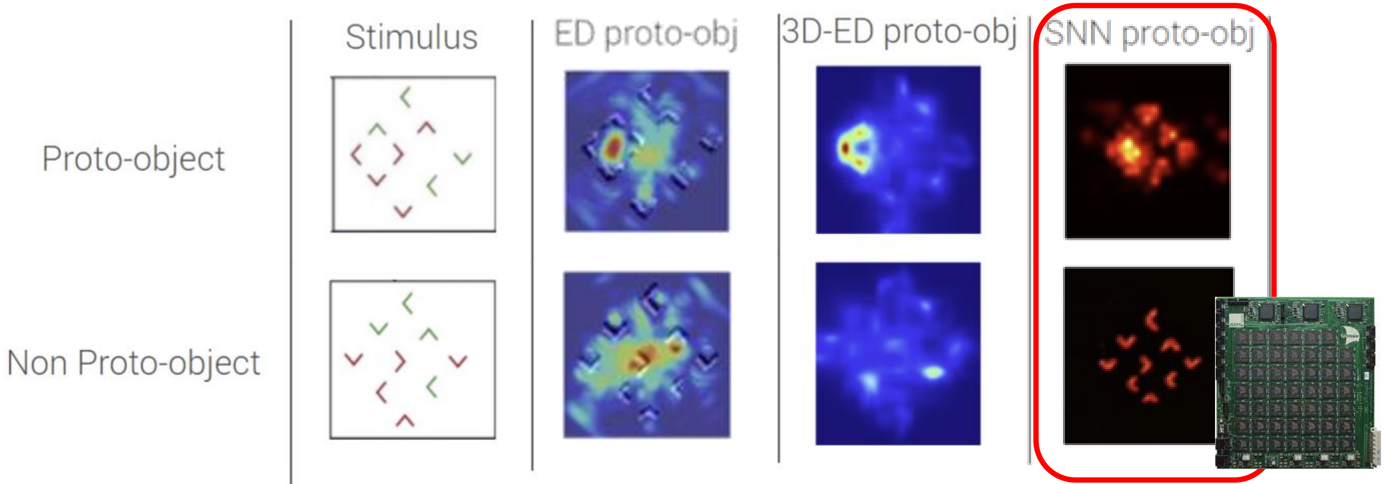




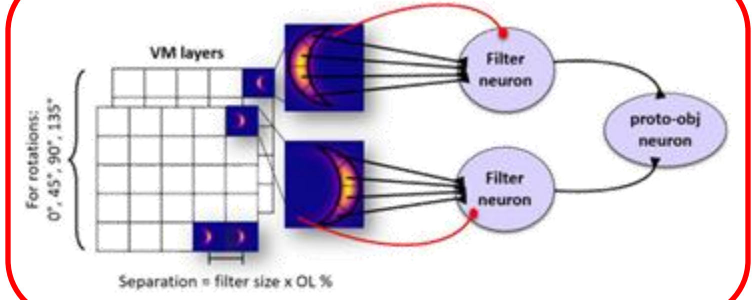
NON von Neumann architecture $e^{\frac{-\Delta T}{\tau}}$ LIF neuron
Connections among neurons • Exitatory and Inhibitory connections
DIGITAL: SpiNNaker (i.e. ARM cores; old 18 cores 1ms clock, new 256 Cortex M4 180 MHz; RISC) ANALOG: DYNAP-SE (asynchronous analog circuits, NO global clock)
~mW power consumption (even less)

von Neumann architecture	NON strictly von Neumann
Single core	NO connections among cores
CISC 1 to 3 GHz	CISC 1.4 to 2.5 GHz
125 to 250 W	300 to 400 W

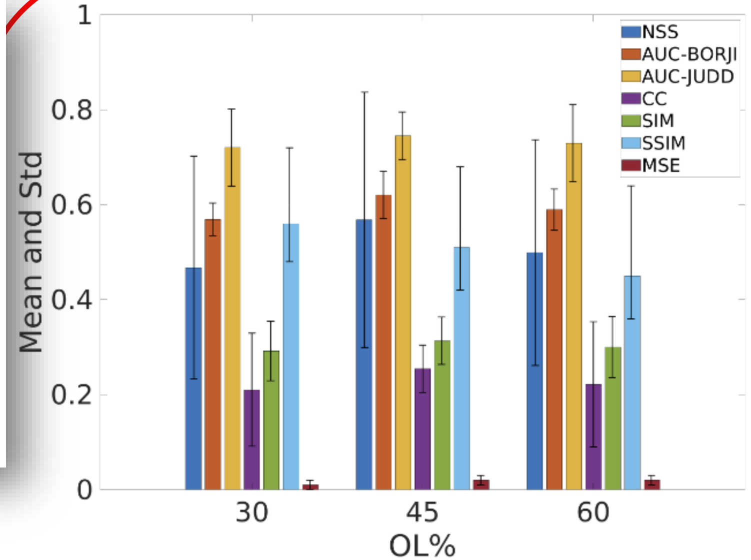

VM layers
0°, 45°, 90°, 135°
Separation = filter size x OL %
Filter neuron
Filter neuron
proto-obj neuron
SNNevProto
positive events
negative events
Input
(iii) Border Ownership (B) Pyramid
(iv) Grouping (G) Pyramid


Stimulus
ED proto-obj
3D-ED proto-obj
SNN proto-obj
Proto-object
Non Proto-object

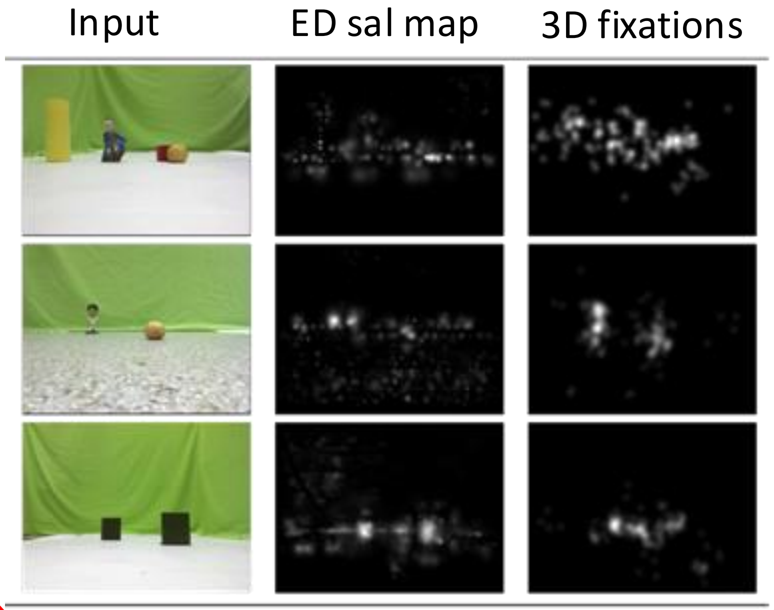
~100 ms ~170 ms

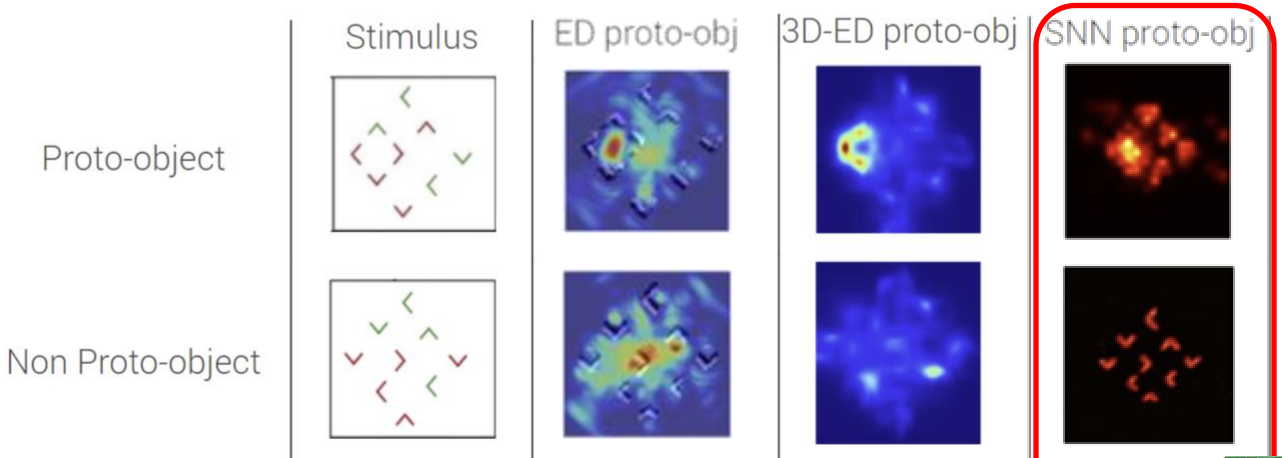


OL%	# of neurons	# of SpiNNaker boards
10%	10 428	3
20%	12 000	3
30%	15 801	3
40%	22 266	3
50%	30 306	6
60%	48 878	6
70%	82 084	12
80%	176 248	24

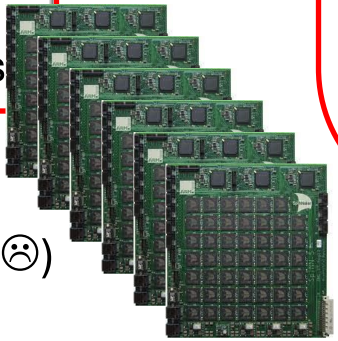


Dataset #	First sample latency (ms)	Second sample latency (ms)
Average	16 ± 2.44	19.2 ± 3.37



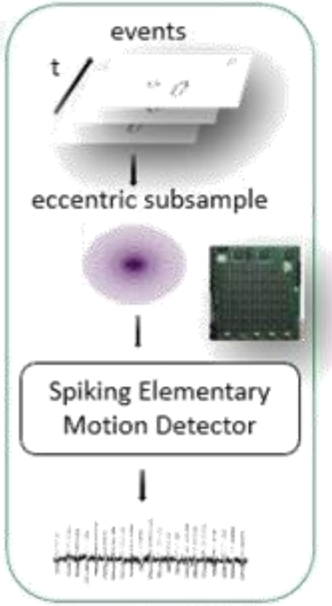


~100 ms ~170 ms ~16 ms

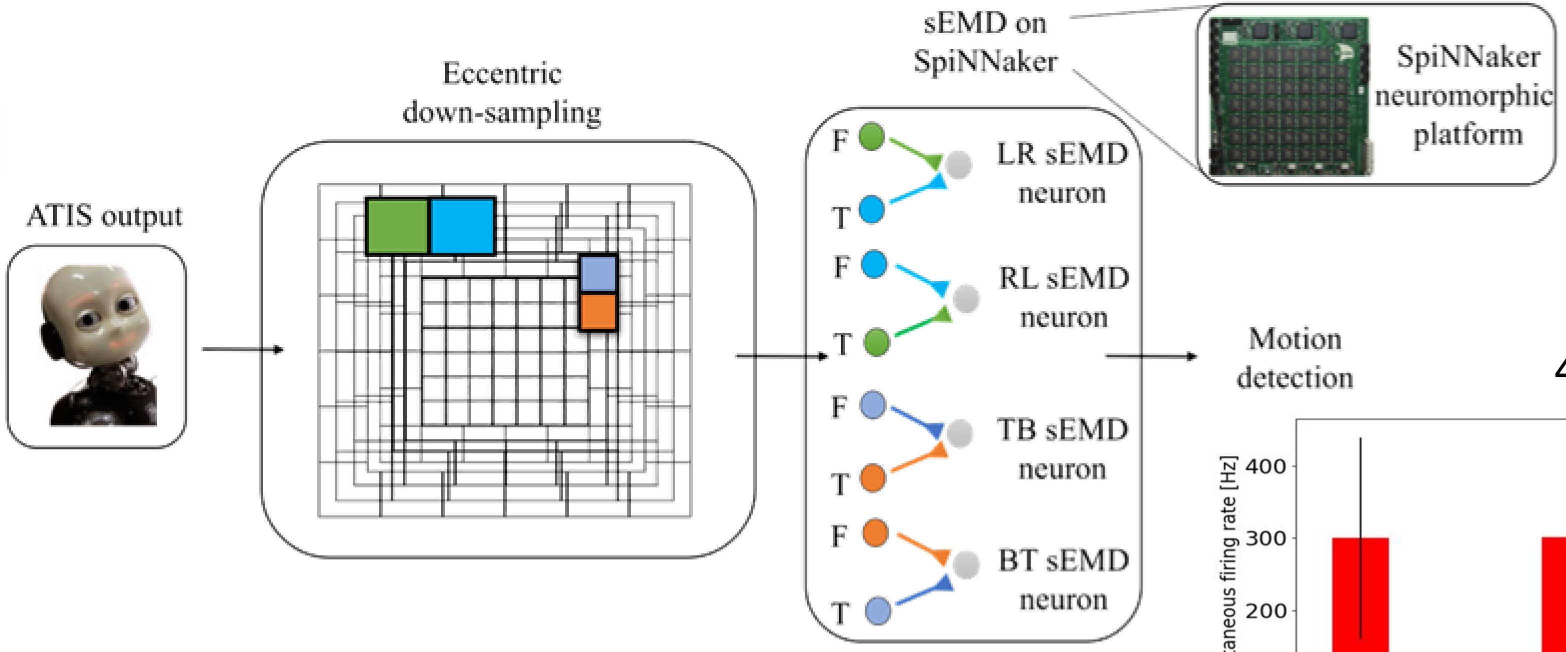


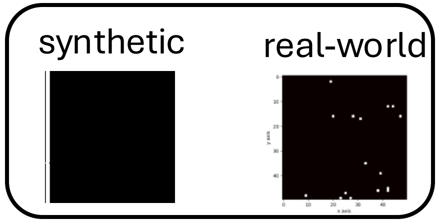
(6 SpiNNaker boards ☹)

Motion

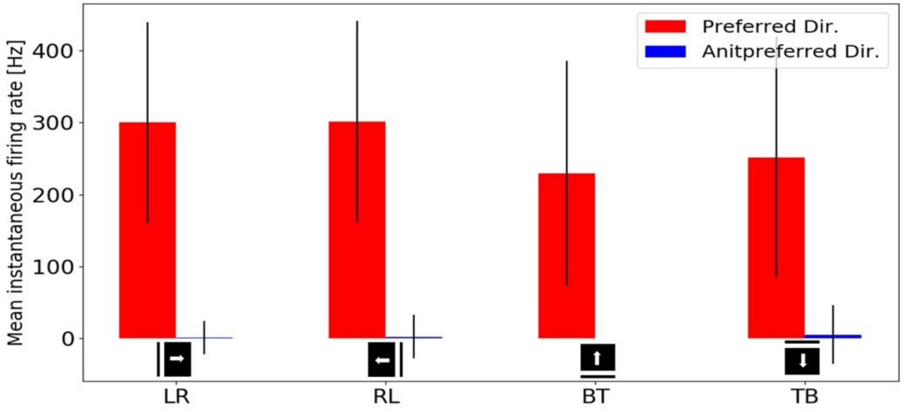


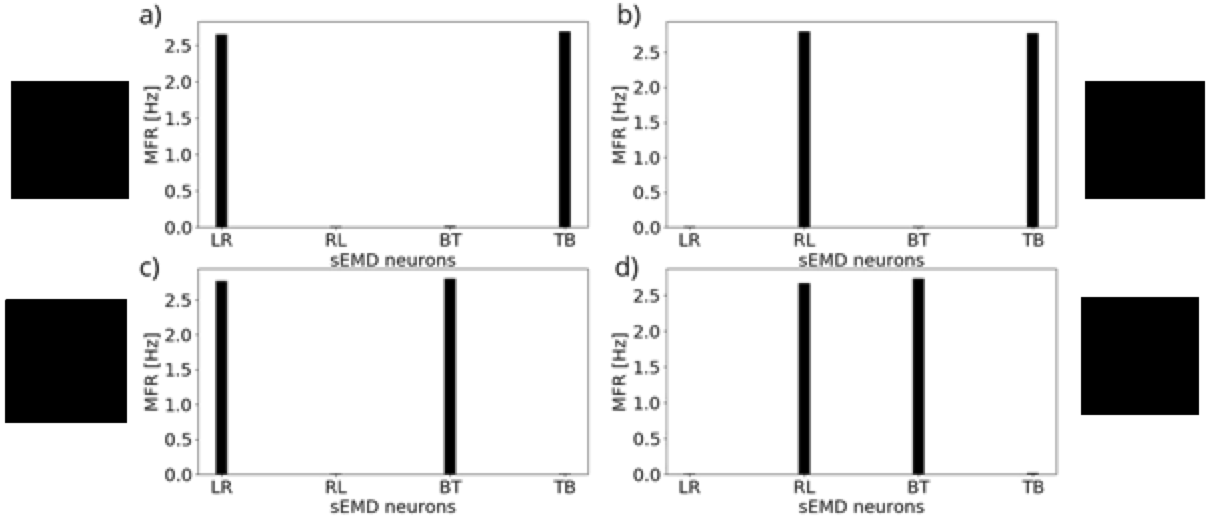
Eccentric sEMD

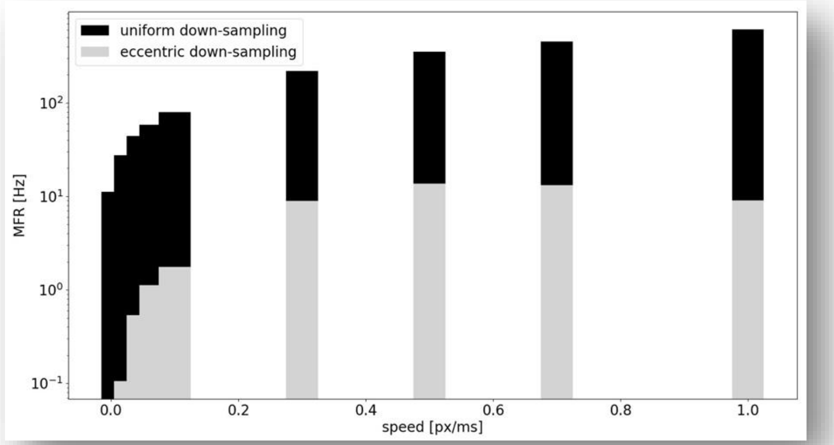




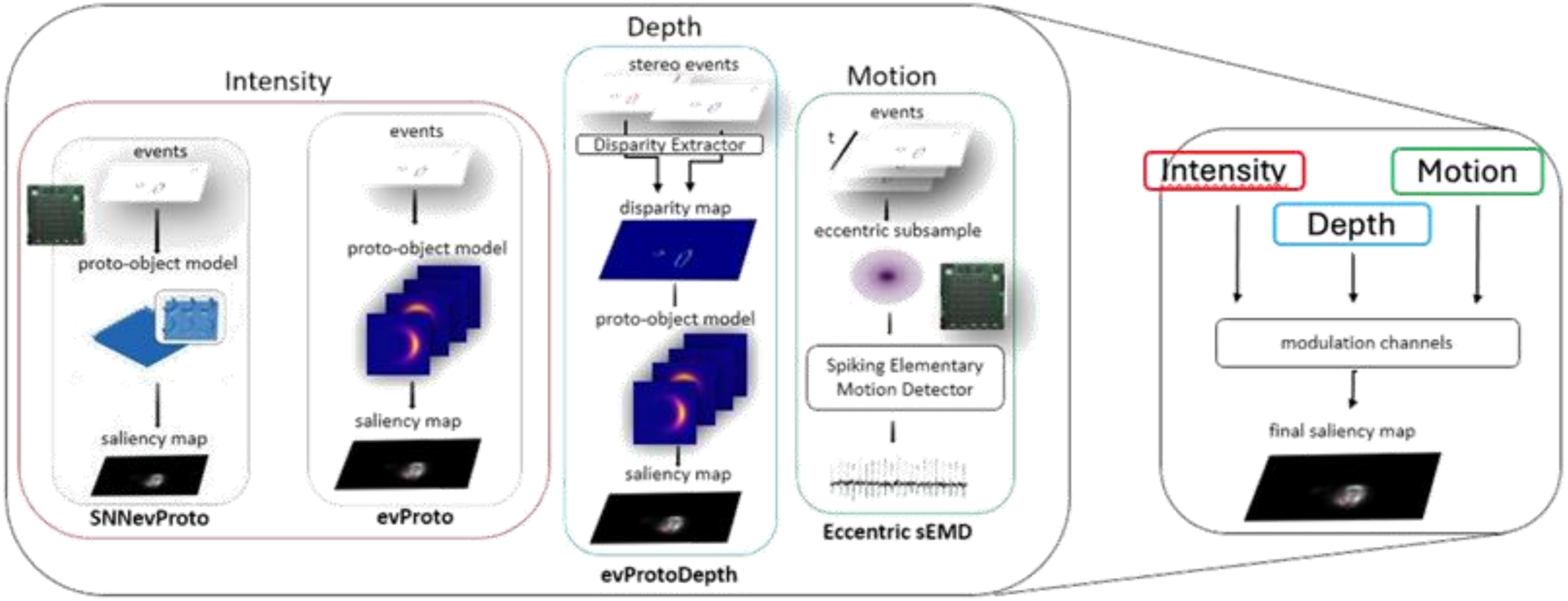
4 ms latency





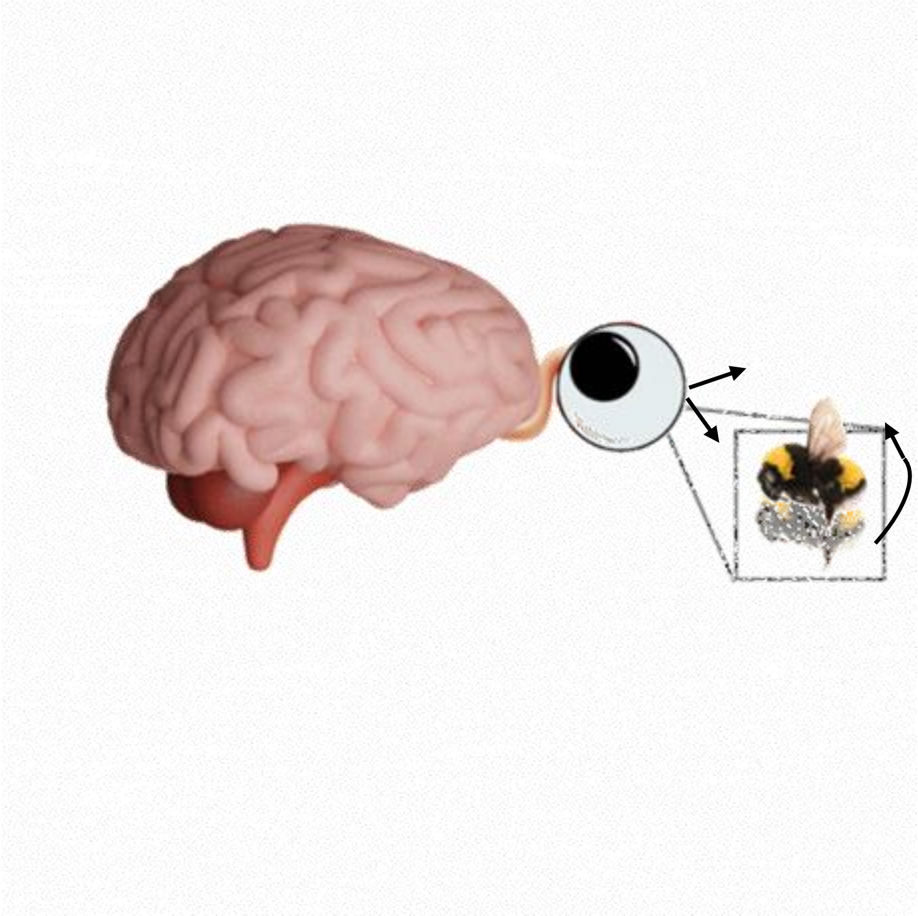


D'Angelo, G., Janotte, E., Schoepe, T., O'Keeffe, J., Milde, M. B., Chicca, E., & Bartolozzi, C. (2020). Event-based eccentric motion detection exploiting time difference encoding. *Frontiers in neuroscience*, *14*, 451.



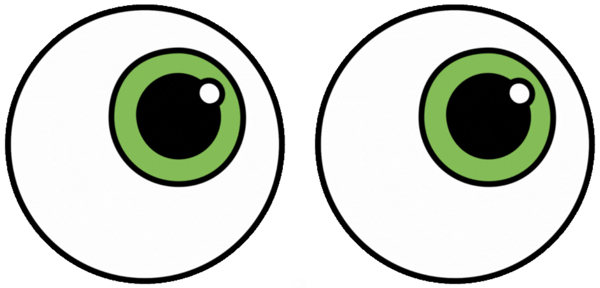
Is there any saliency map in the brain?

Is there any saliency map in the brain?

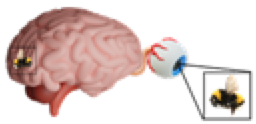


Is there any saliency map in the brain?

Is the active interaction with the world the response?



Embodiment refers to the concept of experiencing the world through a physical body or form.

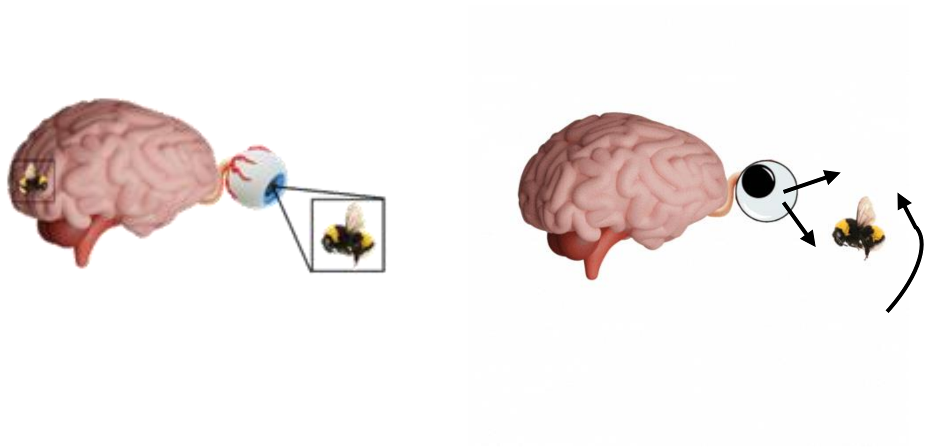


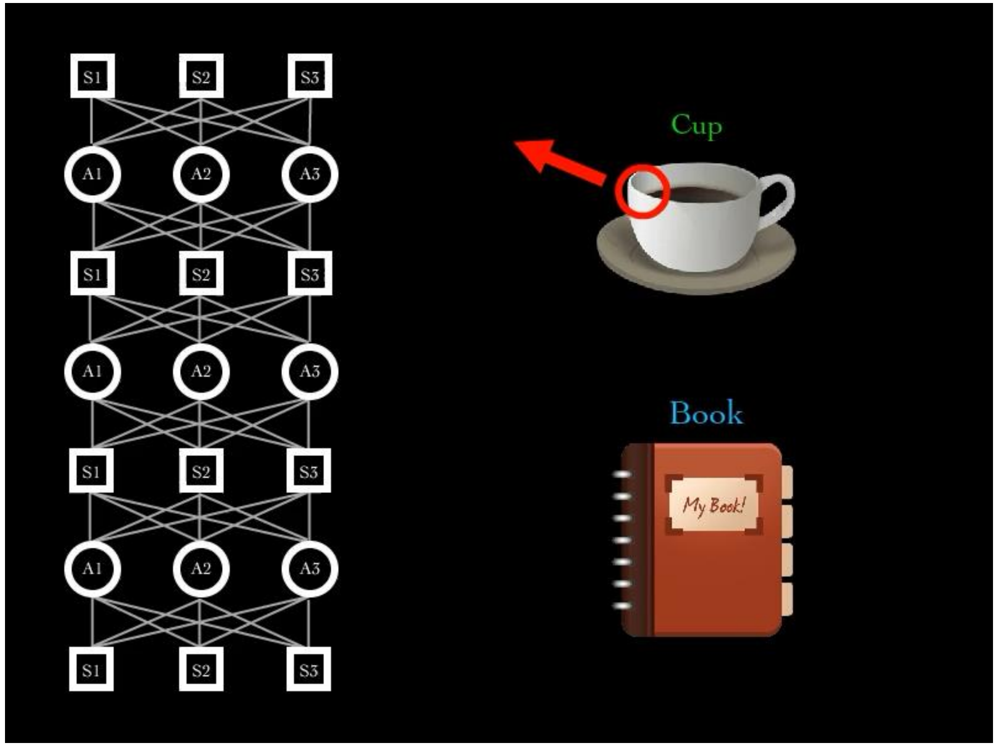
Is there any saliency map in the brain?
Is the active interaction with the world the response?

Sensorimotor contingencies

standard view

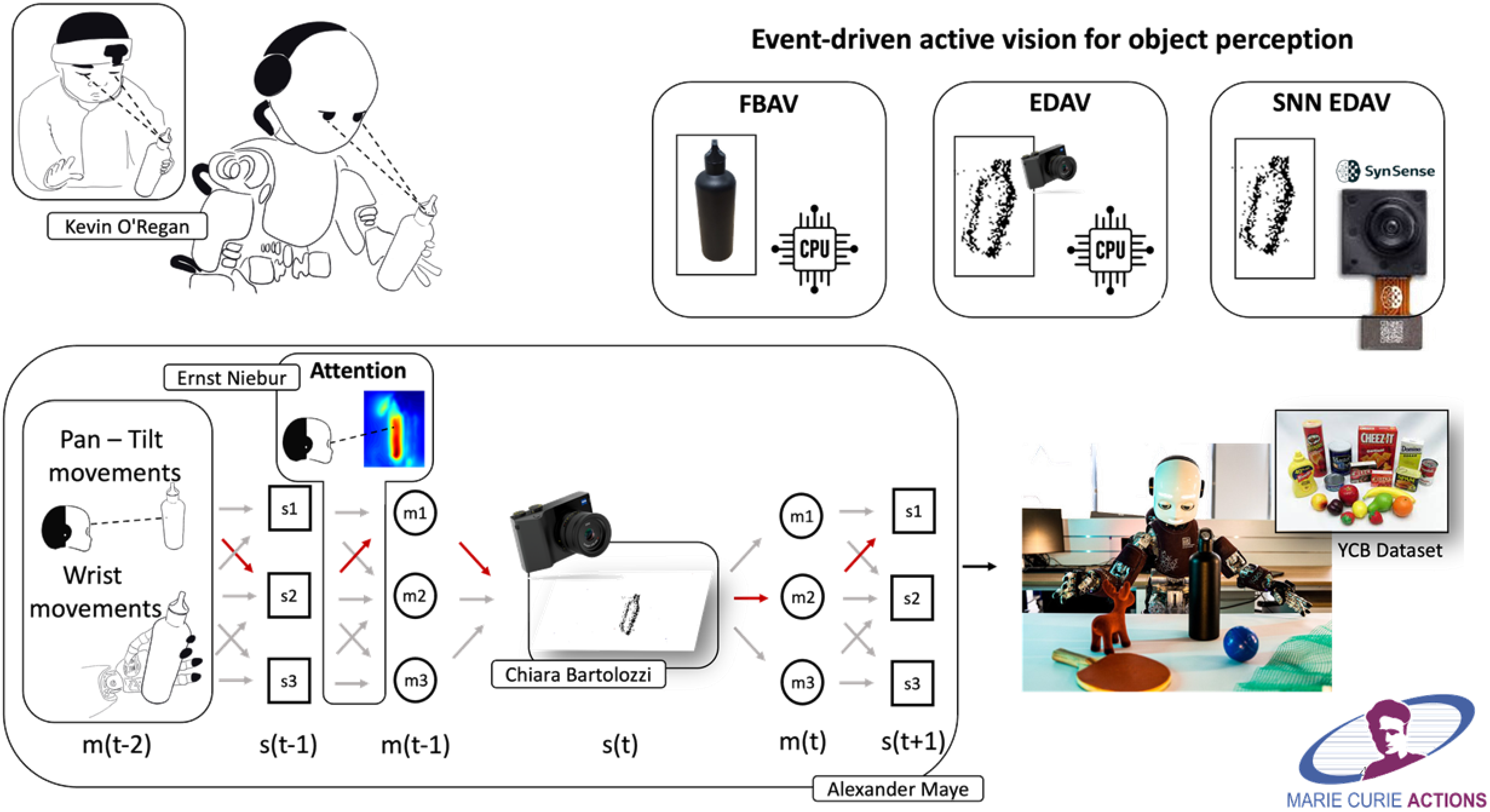
sensorimotor view



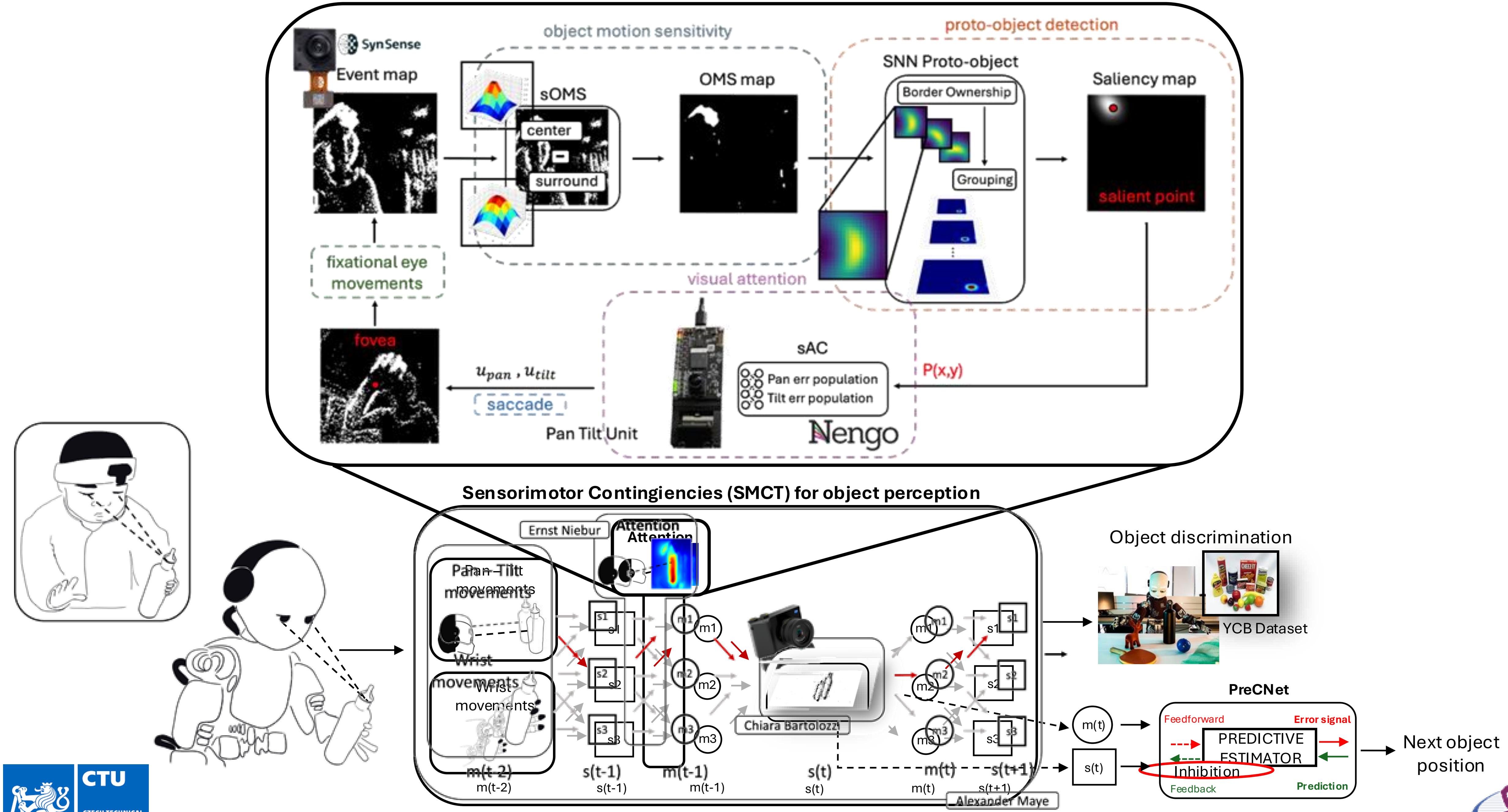


Engel, Andreas K., et al. "Where's the action? The pragmatic turn in cognitive science." *Trends in cognitive sciences* 17.5 (2013): 202-209.

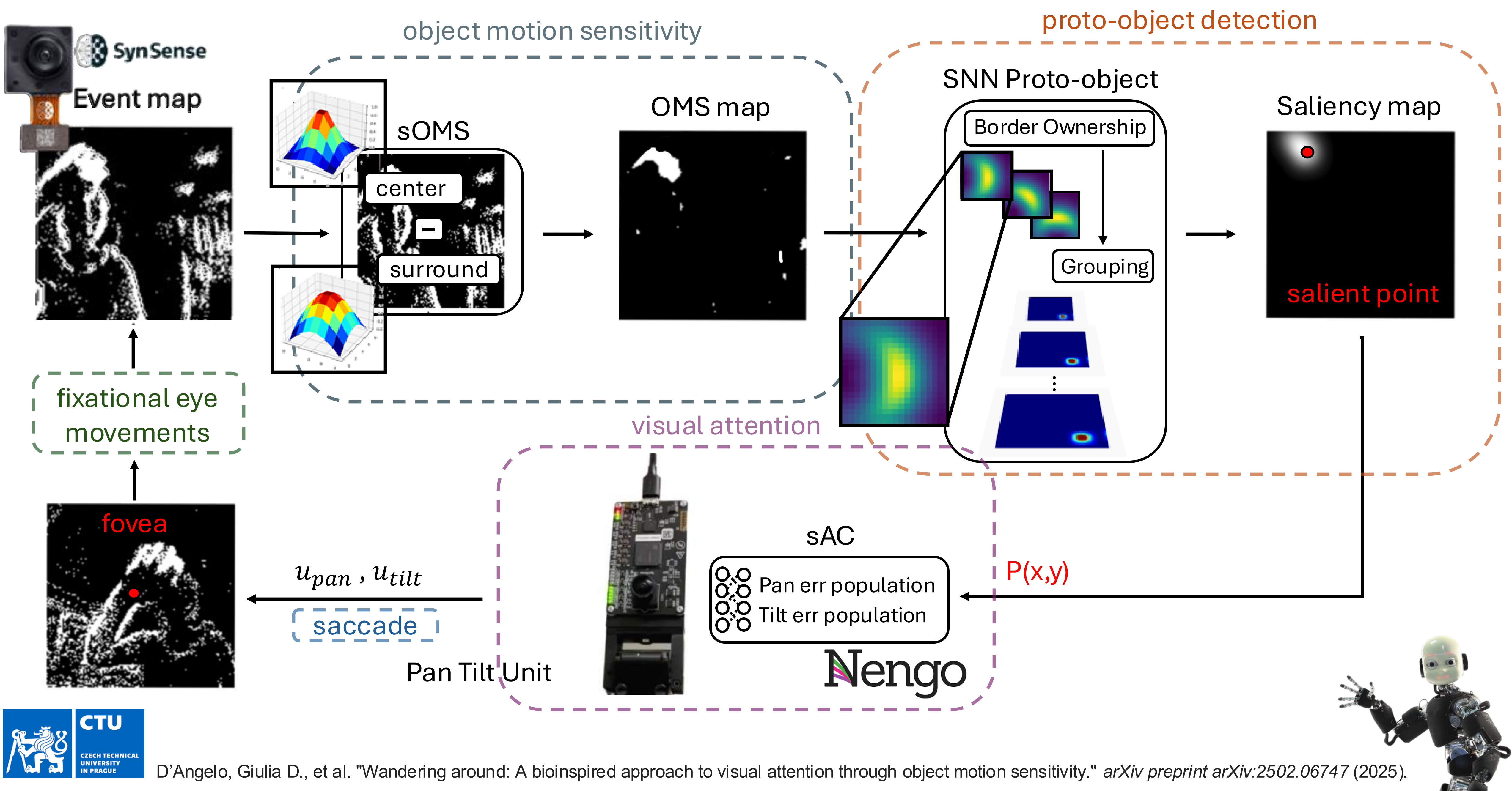
Maye, Alexander, and Andreas K. Engel. "A discrete computational model of sensorimotor contingencies for object perception and control of behavior." *2011 IEEE International Conference on Robotics and Automation*. IEEE, 2011.


Event-driven active vision for object perception
Kevin O'Regan
FBAV
CPU
EDAV
CPU
SNN EDAV
SynSense
Ernst Niebur
Attention
Pan – Tilt movements
Wrist movements
s1
s2
s3
m1
m2
m3
Chiara Bartolozzi
m1
m2
m3
s1
s2
s3
m(t-2)
s(t-1)
m(t-1)
s(t)
m(t)
s(t+1)
Alexander Maye
YCB Dataset
MARIE CURIE ACTIONS

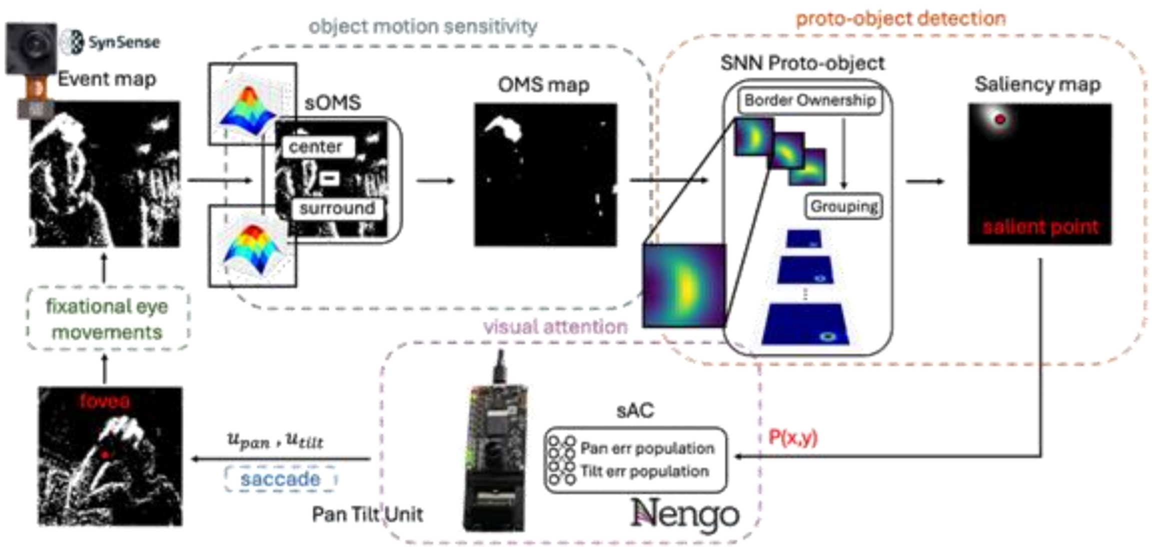
Attention



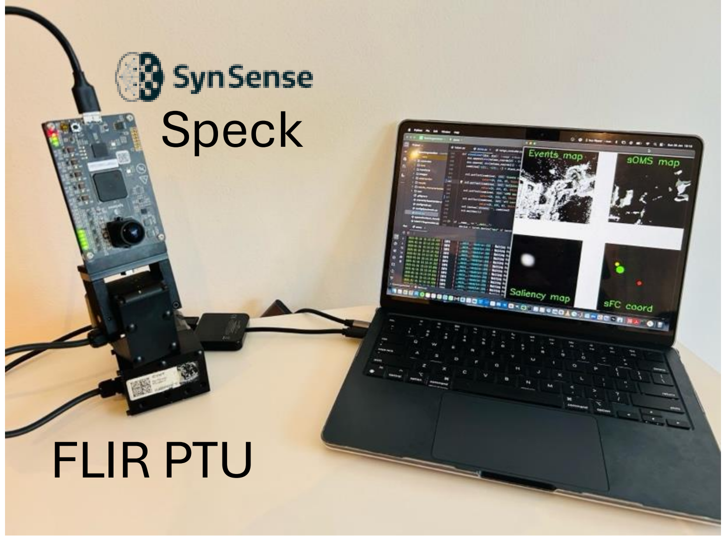
D'Angelo, Giulia D., et al. "Wandering around: A bioinspired approach to visual attention through object motion sensitivity." *arXiv preprint arXiv:2502.06747* (2025).

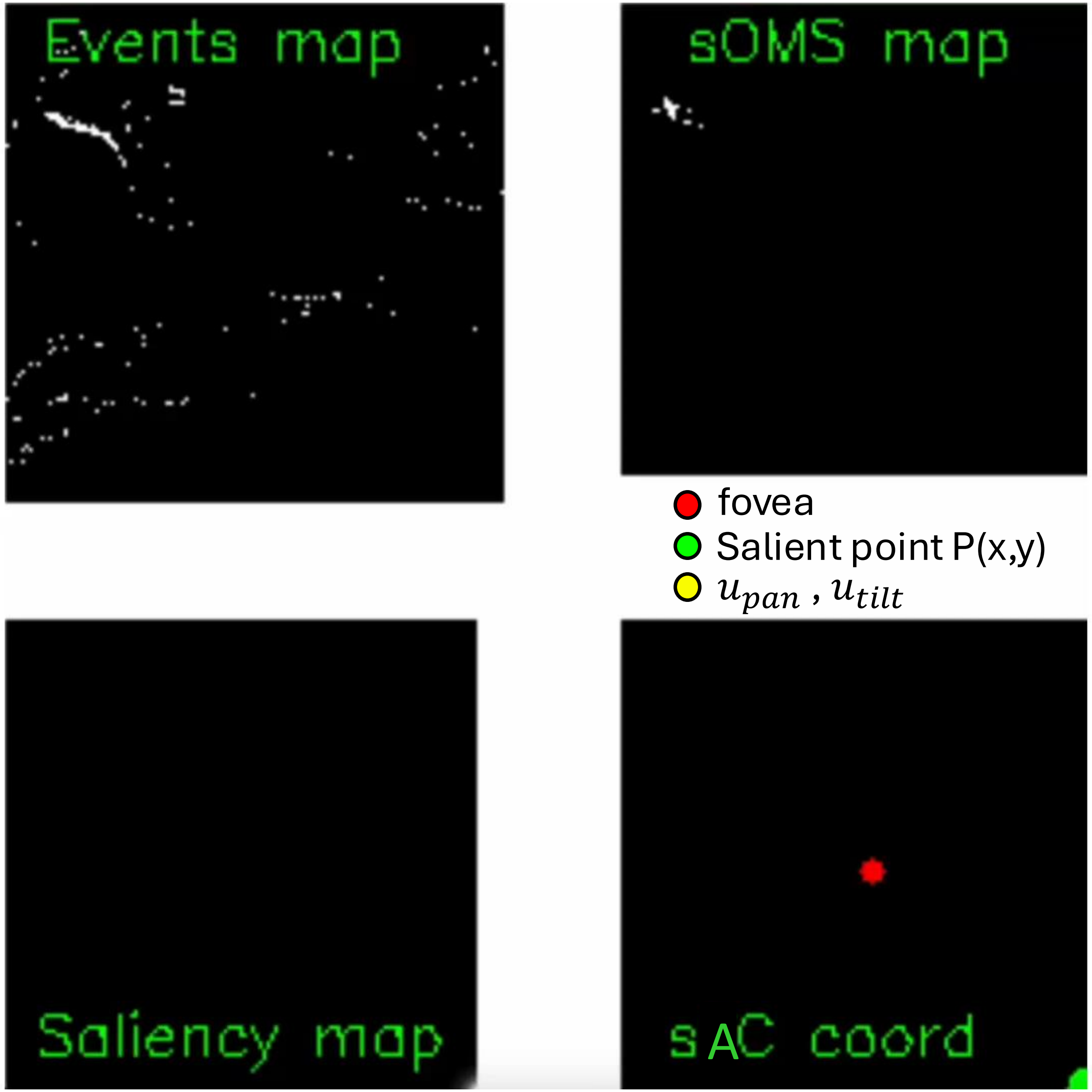


D'Angelo, Giulia D., et al. "Wandering around: A bioinspired approach to visual attention through object motion sensitivity." *arXiv preprint arXiv:2502.06747* (2025).

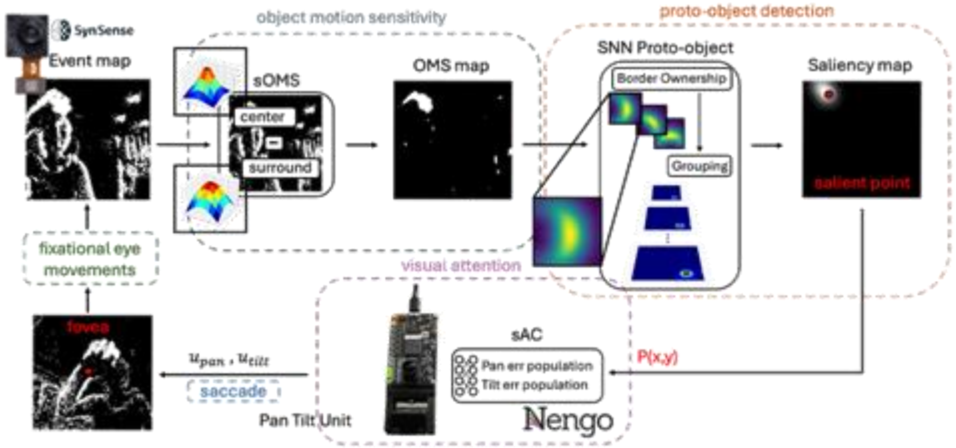


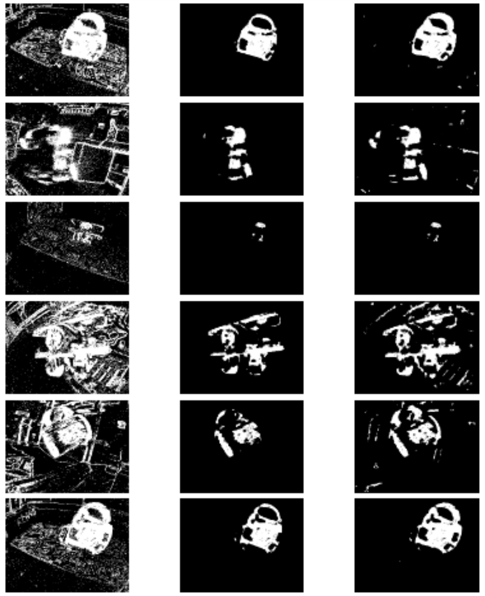
Setup



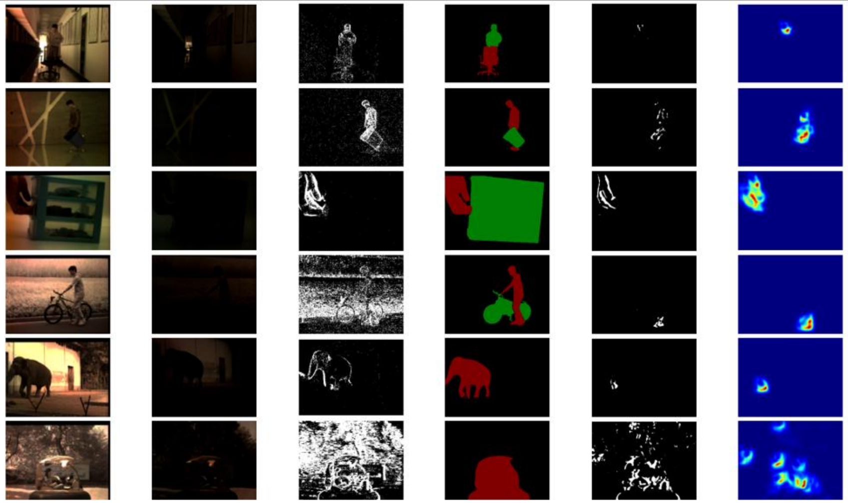


D'Angelo, Giulia D., et al. "Wandering around: A bioinspired approach to visual attention through object motion sensitivity." *arXiv preprint arXiv:2502.06747* (2025).





Sub-dataset	Event map	Ground Truth	OMS map	mean IoU % [8]	mean IoU %	mean SSIM %
Box				72 ± 16	**64.79 ± 0.02**	**89 ± 0.08**
Fast				69 ± 3	**69.85 ± 0.15**	**90 ± 0.06**
Floor				94	**63.21 ± 0.22**	**94± 0.22**
Table				88 ± 10	**73.59 ± 0.22**	**89 ± 0.11**
Tabletop				72 ± 14	**82.24 ± 0.18**	**96 ± 0.06**
Wall				82±6	**64.49 ± 0.07**	**84 ± 0.04**



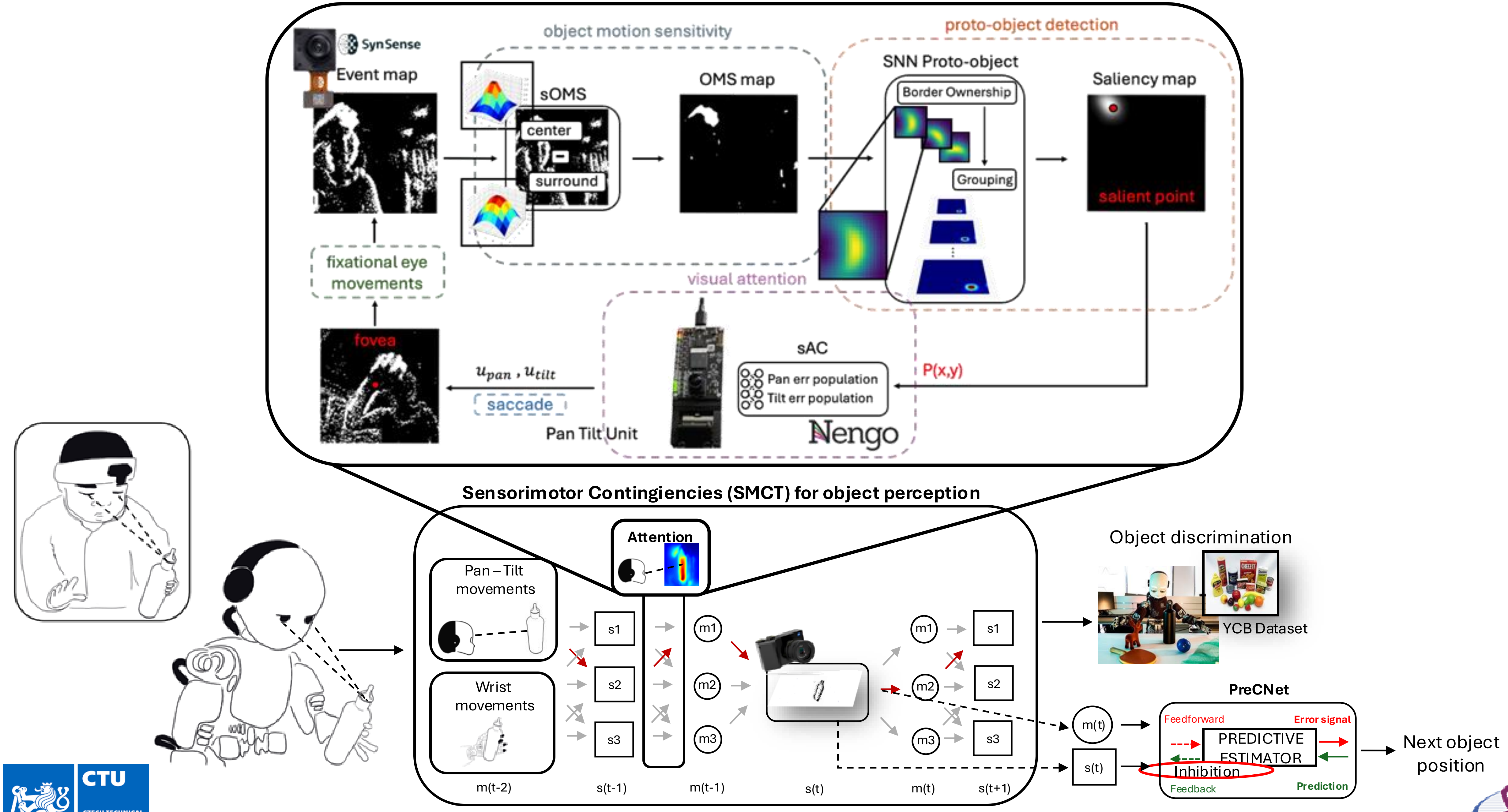
Sub-dataset	Normal-light RGB [48]	Low-light RGB [48]	Event map [48]	Annotation [48]	OMS map	Saliency map	Accuracy %
00002							84.13
00011							89.88
00064							87.47
00033							72.96
00031							55.55
00025							47.84

Wandering around: A bioinspired approach to visual attention through object motion sensitivity

Giulia D'*Angelo*[1], Victoria Clerico[2], Chiara *Bartolozzi*[3], Matej Hoffmann[1], Michael *Furlong*[4], and Alexander *Hadjiivanov*[5,6]

1 Department of Cybernetics, Faculty of Electrical Engineering, Czech Technical University in Prague, Czech Republic
2 IBM Research Europe, Zurich, Switzerland
3 Event-Driven Perception for Robotics, Italian Institute of Technology, Genoa, Italy
4 National Research Council of Canada & Systems Design Engineering, University of Waterloo, Canada
5 Advanced Concepts Team, European Space Agency, Noordwijk, The Netherlands
6 Adapsent Research, Leiden, The Netherlands

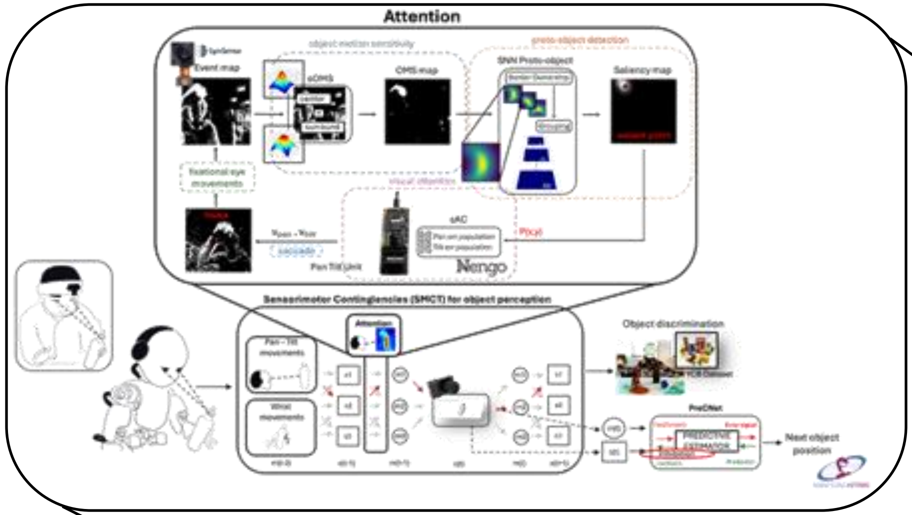
Attention

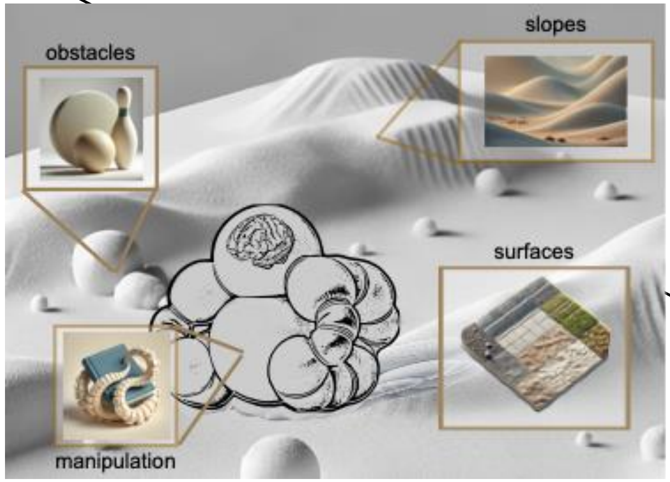


D'Angelo, Giulia D., et al. "Wandering around: A bioinspired approach to visual attention through object motion sensitivity." *arXiv preprint arXiv:2502.06747* (2025).

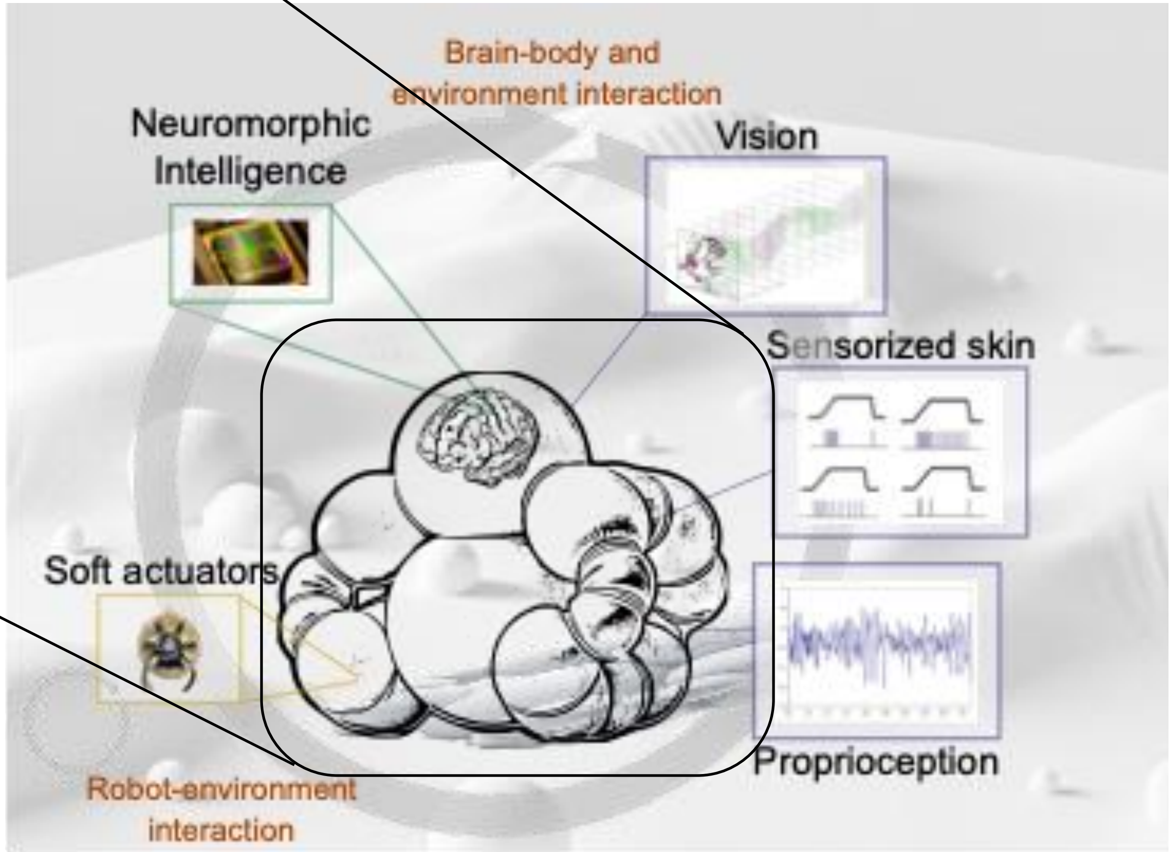
A Benchmarking Framework for Embodied Neuromorphic Agents

Co-designing “**brain**” and “**body**” unlocks new levels of *efficiency*, *resilience*, and *adaptability*





Set of **Tasks** and **Metrics** for evaluation and benchmark



Giulia D’Angelo, Jens E. Pedersen, Taimoor Hassan, Matteo Cianchetti, Josh Bongard, Fumiya Iida, Giacomo Indiveri, Matej Hoffmann, Cecilia Laschi, Chiara De Luca, Chiara Bartolozzi, and Elisa Donati

Not only attention…

Article

A neuromorphic electronic artist for robotic painting

Lioba Schürmann, Giulia D'Angelo, Giacomo Indiveri, Chiara Bartolozzi, and 1 more

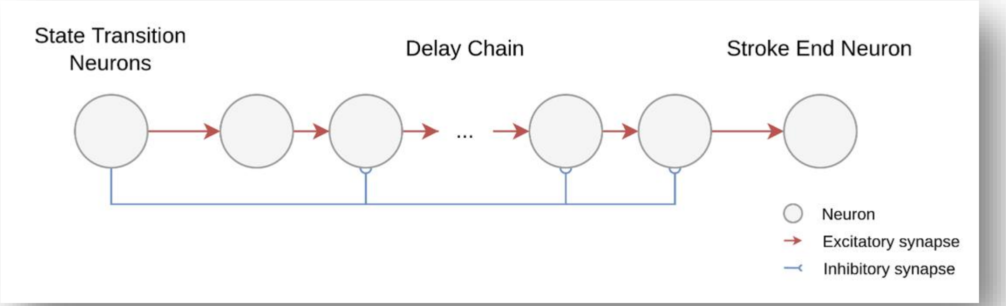
This is a preprint; it has not been peer reviewed by a journal.

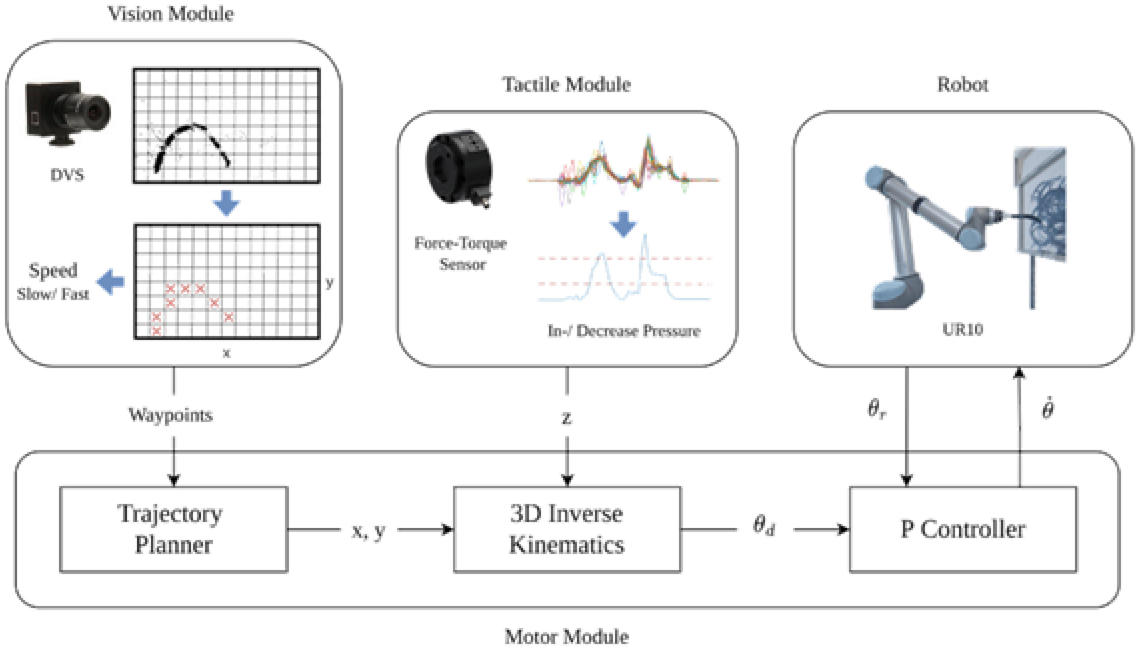
https://doi.org/10.21203/rs.3.rs-4528779/v1

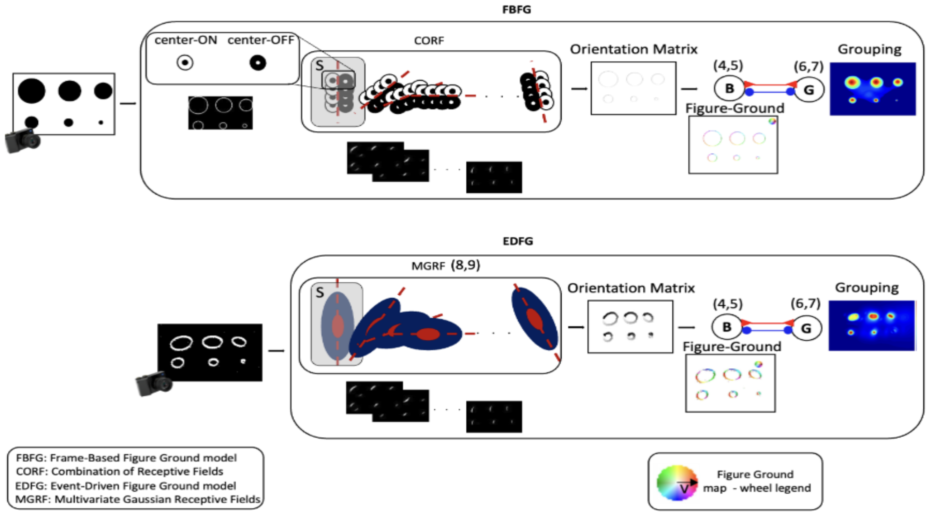
scientific reports

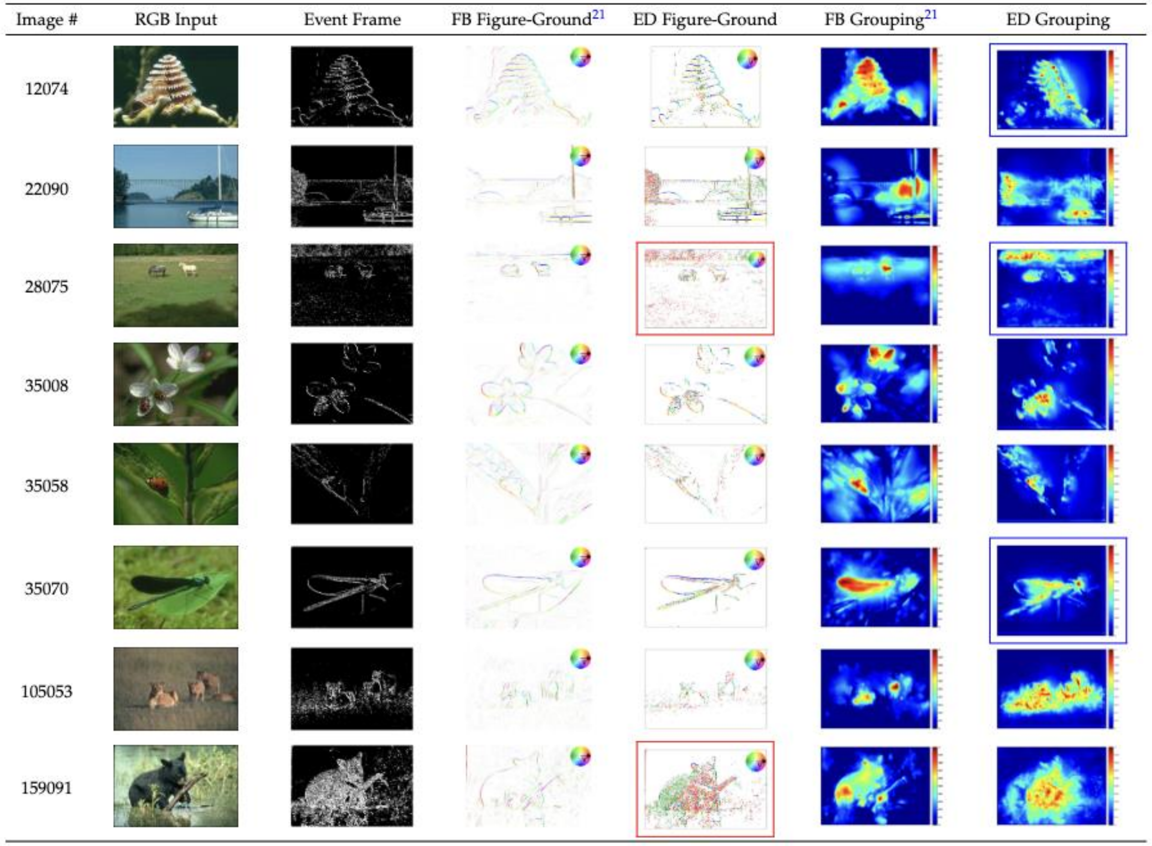
Abstract

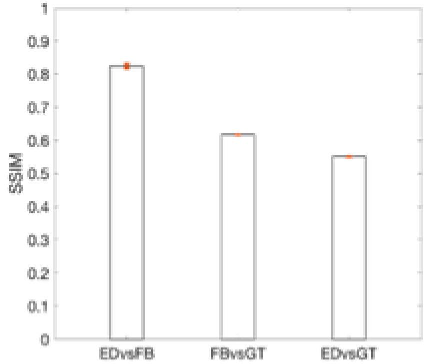
Recent advances in computer vision and deep learning have led to a surge of interest in the field of AI-generated art, including digital image creation and robot-assisted painting. Traditional painting machines rely on static images and offline processing to incorporate visual feedback into their painting process. However, this approach does not consider the dynamic nature of painting and fails to decompose complex











nature communications

Article https://doi.org/10.1038/s41467-025-56904-9

Event-driven figure-ground organisation model for the humanoid robot iCub

Received: 25 January 2024

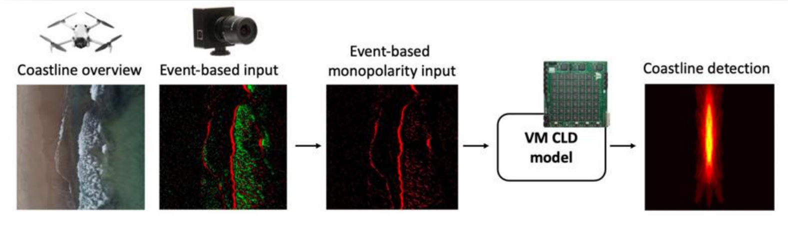
Accepted: 5 February 2025

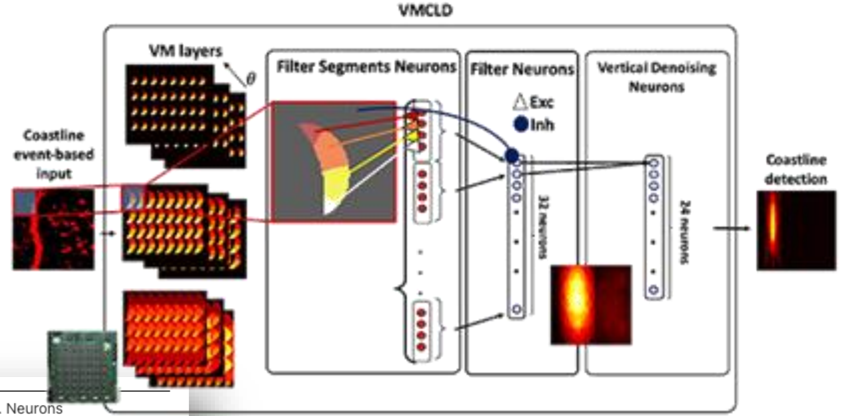
Published online: 22 February 2025

Check for updates

Giulia D'Angelo[1,3], Simone Voto[1], Massimiliano Iacono[1], Arren Glover[1], Ernst Niebur[2] & Chiara Bartolozzi[1]

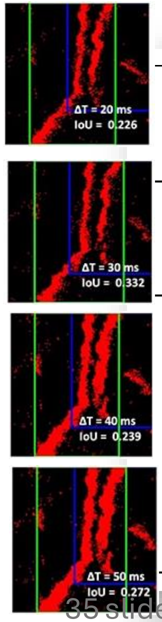
Figure-ground organisation is a perceptual grouping mechanism for detecting objects and boundaries, essential for an agent interacting with the environment. Current figure-ground segmentation methods rely on classical computer vision or deep learning, requiring extensive computational resources, especially during training. Inspired by the primate visual system, we developed



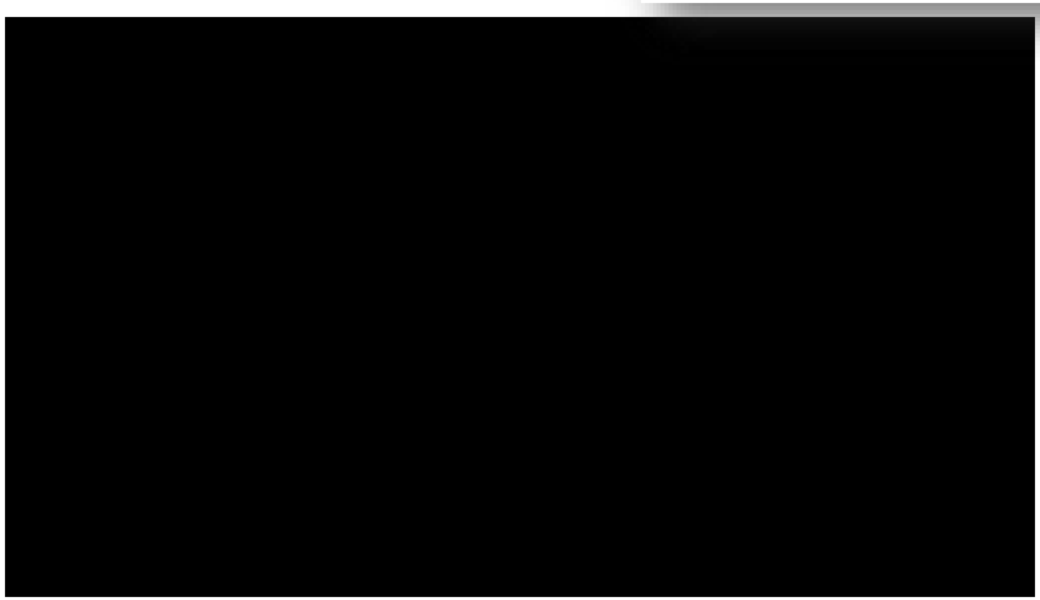


Populations	No. Neurons
Input Population	16 384 (128×128)
Filter Segments Neurons Population	128 (32×4)
Filter Neurons Population	32
Vertical Denoising Population	24
Total	$16\,384 + 184 \times 9 = 18\,040$

Average consumption ΔT=20 ms is 0.3756 mW



ΔT	Average of IoU	Accuracy (%) (Threshold = 0.80)	Accuracy (%) (Threshold = 0.70)	Accuracy (%) (Threshold = 0.60)	Accuracy (%) (Threshold = 0.50)	Accuracy (%) (Threshold = 0.40)	Accuracy (%) (Threshold = 0.30)
20	61.68	18.69	37.88	57.07	73.23	85.35	92.93
30	65.66	22.78	49.44	67.78	78.89	90.56	**98.33**
40	67.06	**26.35**	55.69	70.66	82.04	89.82	95.81
50	**69.59**	24.64	**57.97**	**78.99**	**87.68**	**93.48**	96.38



Neuromorphic Computing and Engineering

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Event-driven nearshore and shoreline coastline detection on SpiNNaker neuromorphic hardware

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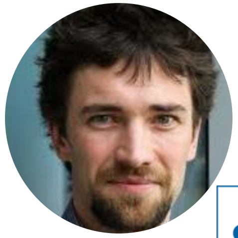


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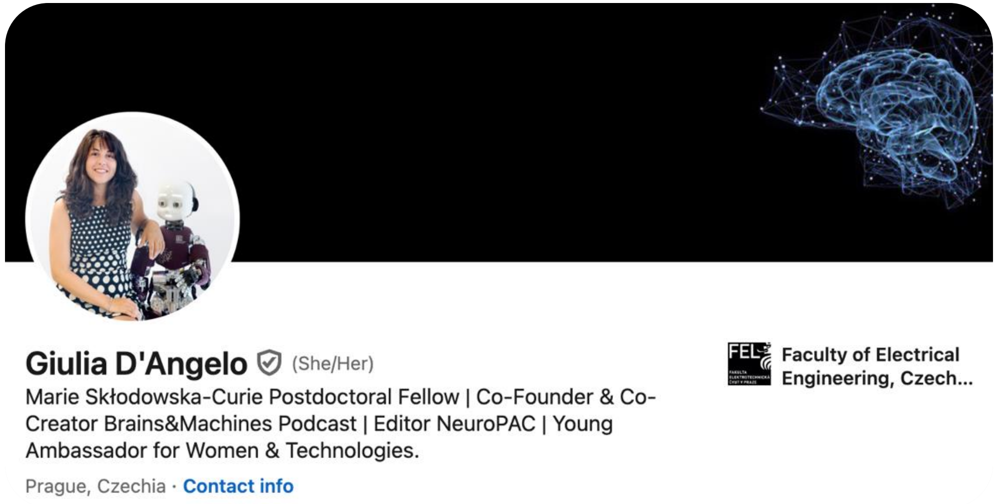

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