From spatial navigation in rodents to the autonomous vehicle: a neurorobotics perspective

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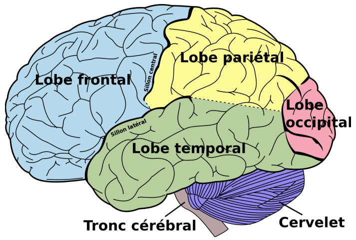
Engineering Science

Neurosciences Psychology

Autonomous robots

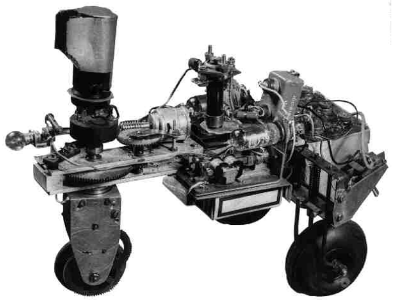


Animal (and Human) Understanding

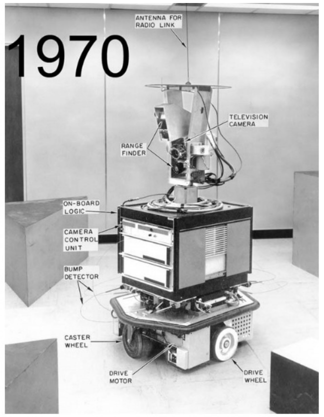
Sharc: Journée du GT4 - 09/07/21

Robot navigation

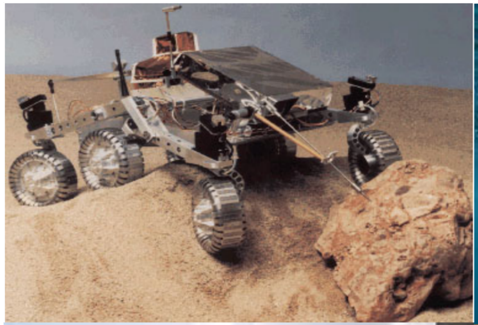
Electric Dog 1912



« Tortue »
W. Grey Walter
1949-53



« Shakey »
Stanford 1970





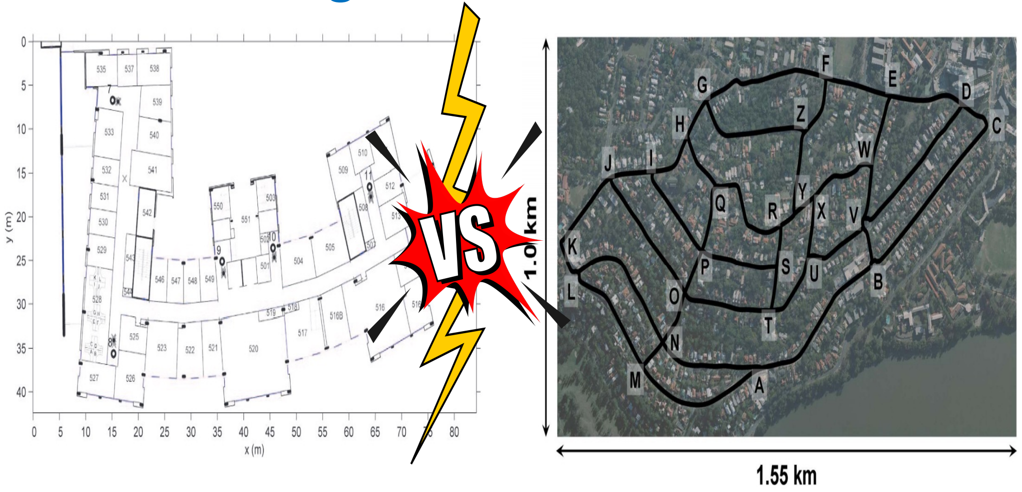



Challenge: Outdoor vision-based navigation

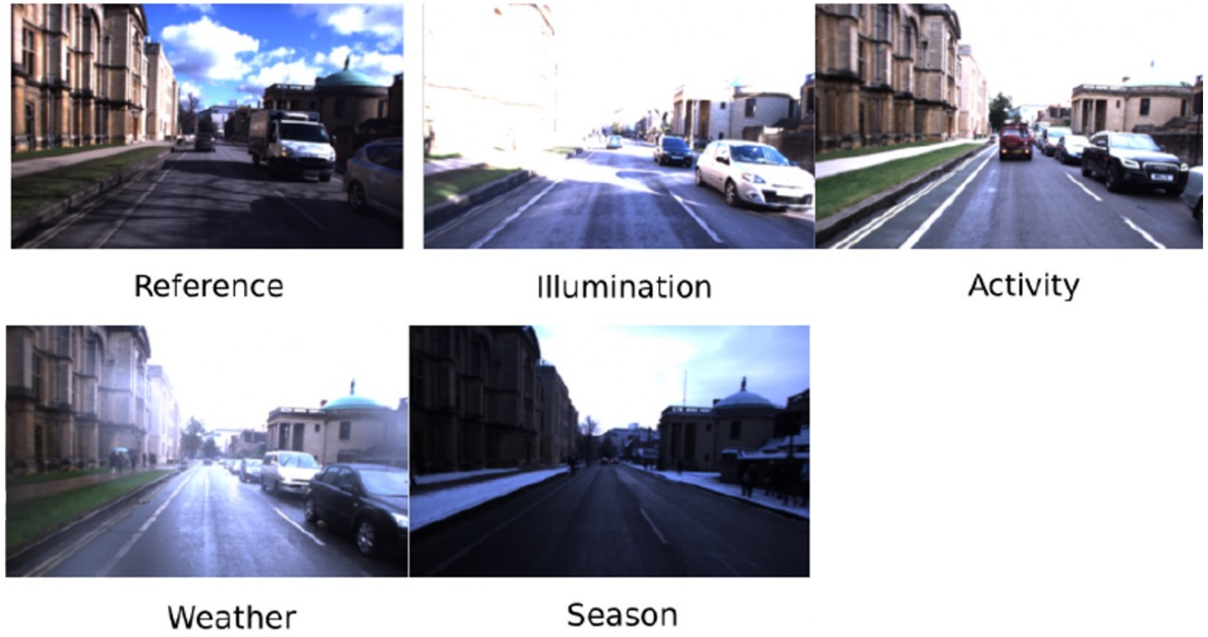
Autonomous vehicles (AV) face large and dynamic environments

Still unsolved !

Large volume of data



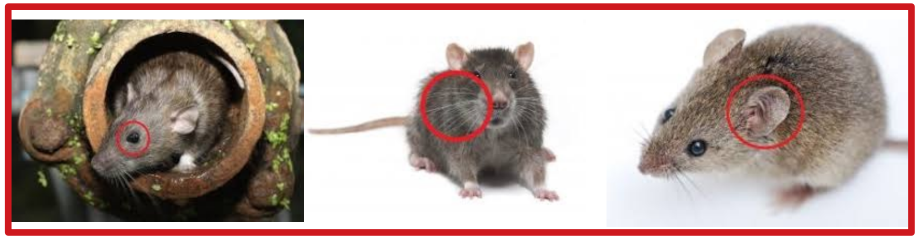
Changing conditions



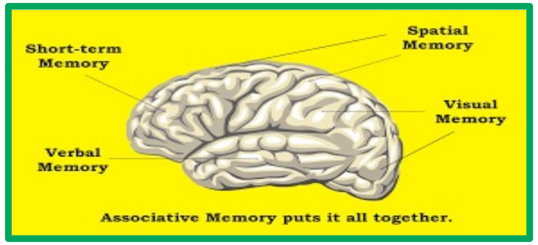
Spatial cognition and navigation

"how to extract (*perception*), to code (*memory*) and to process (*strategy and action selection*) useful **spatial information** from the environment?"

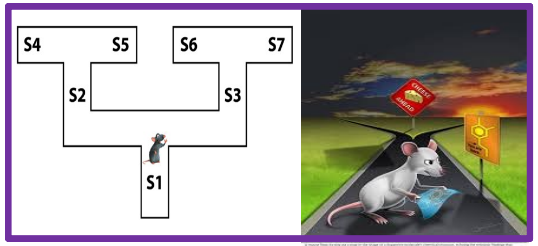
- Require **several cognitive processes**:
  - **Perception**



  - **Memory**



  - **Planning / action selection**

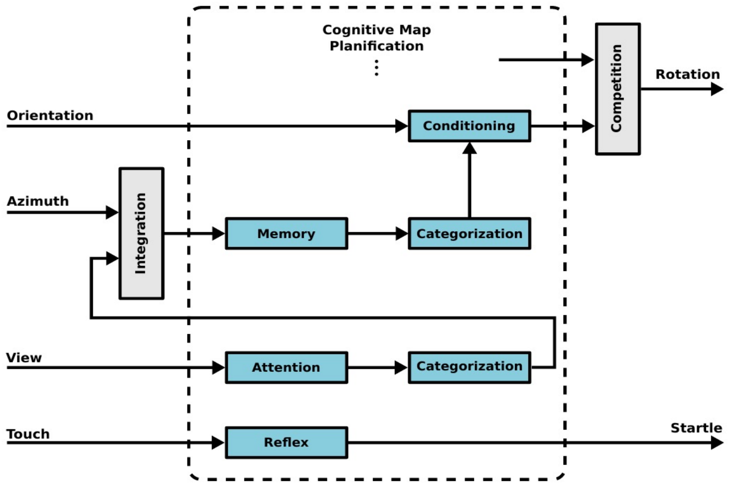


Toward autonomous mobile robots...

A neurorobotics approach to study **navigation**

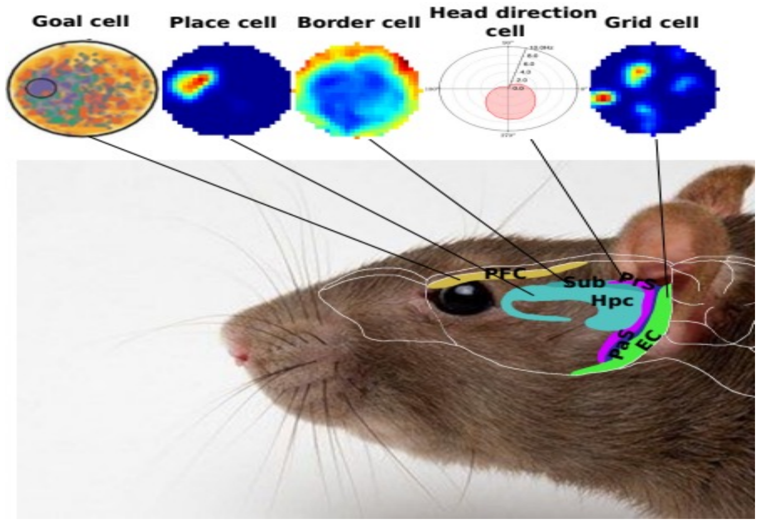
→ **To improve** our **understanding** of the mechanisms underlying spatial cognition

→ **To propose alternative solutions** for autonomous robotics

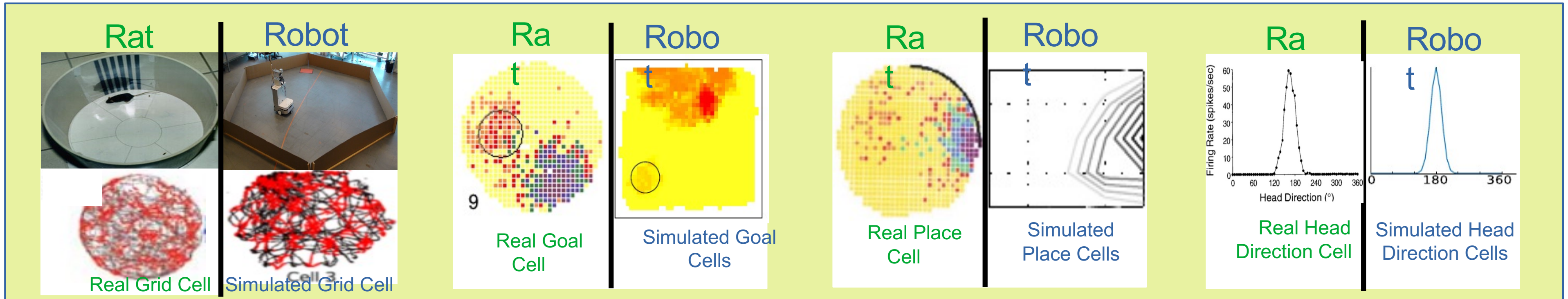


A neurorobotics approach

- Find a minimalist neural model (rate coding):
  - Accounting for the spatial behavior of mammals
  - Taking into account a minimum number of biological structures

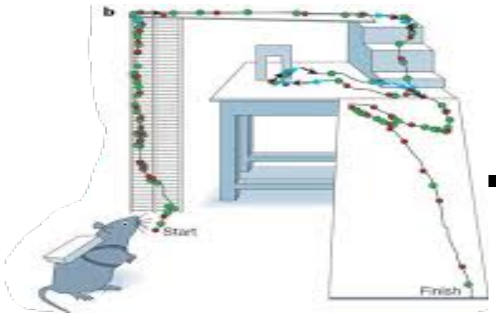


  - Explainable (not a black box), providing testable predictions



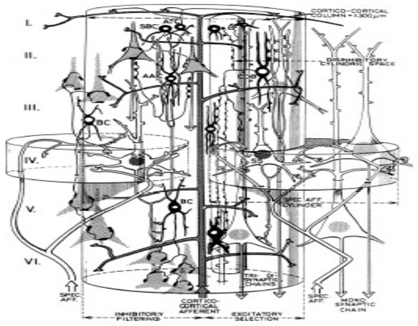
[Jauffret et al. 15] [Hirel et al. 11] [Gaussier et al. 02] [Mingda et al. 20]

A neurorobotics approach



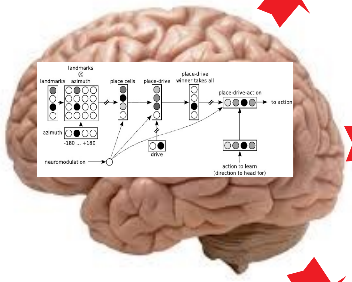
Behavioral
data

+

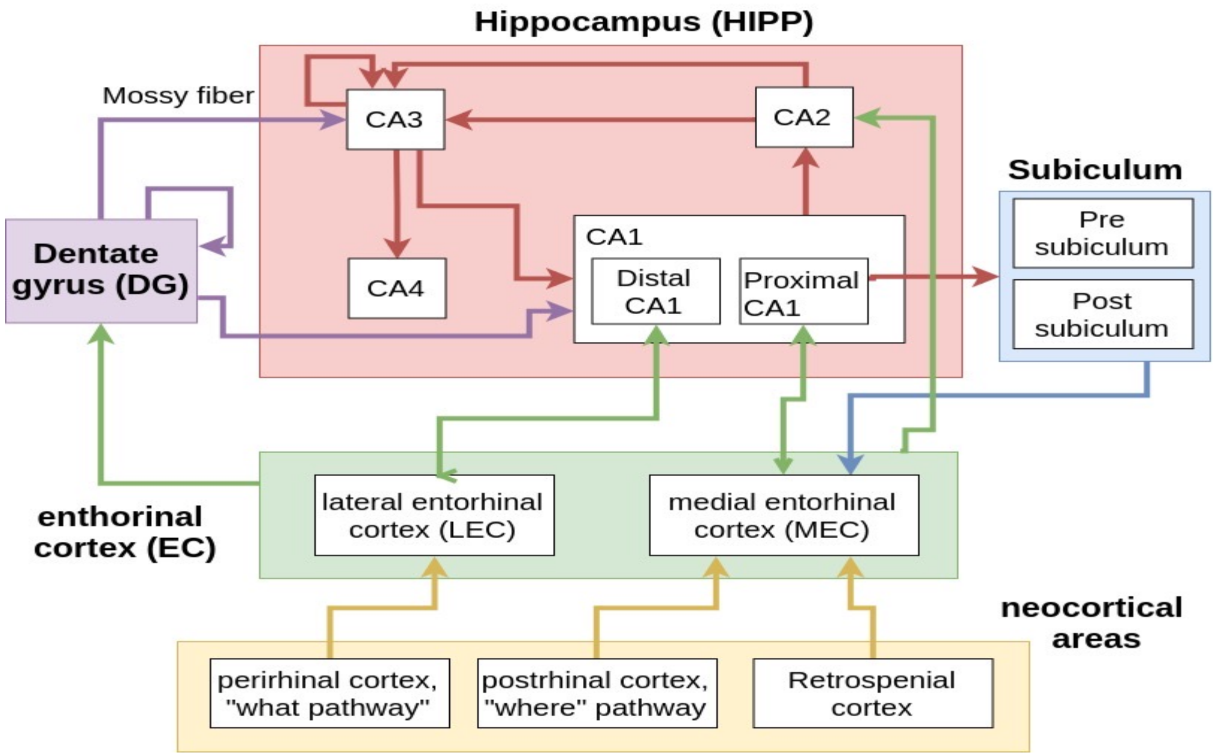


Neurobiological
data

=



Hippocampal Area



Beyond spatial cognition :

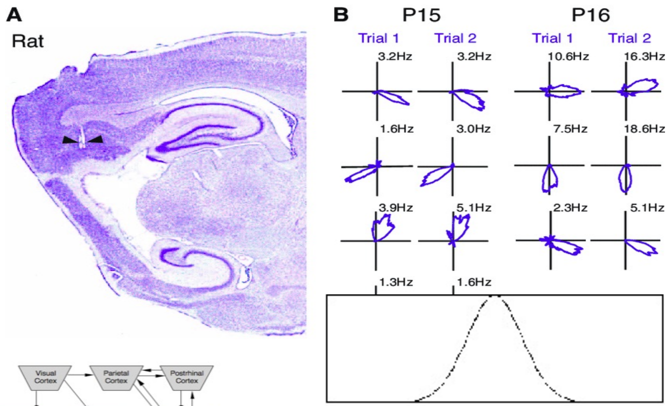
- Episodic memory (anterograde amnesia, Alzeimer…)

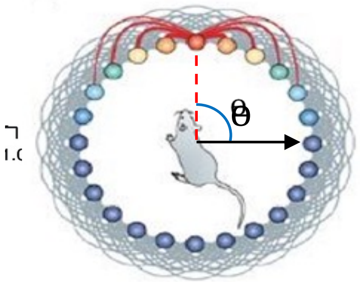
Spatial cells in mammals

Head direction cells (HD)

Discovered by Taube J. S., Muller R. U., Ranck J. B. [1990]

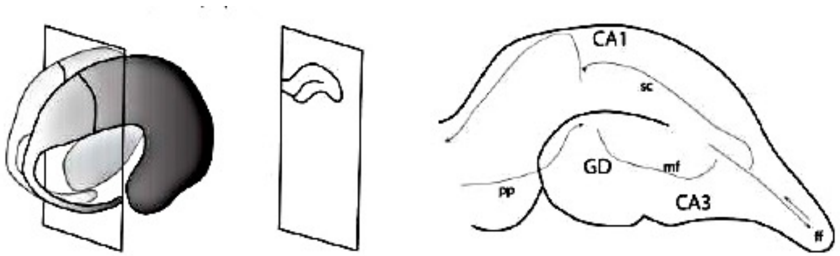
- **Fire only when the animal's head points in a specific direction**



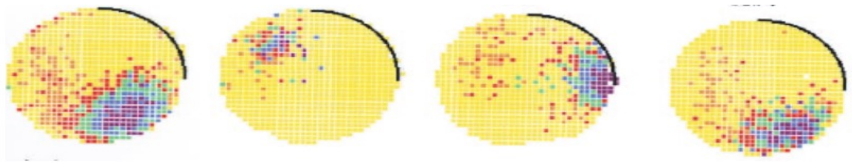


Place cells (PC)

- **Discovered by O'Keefe J, Dostrovsky J. [1971] in the hippocampus and the Dentate Gyrus**

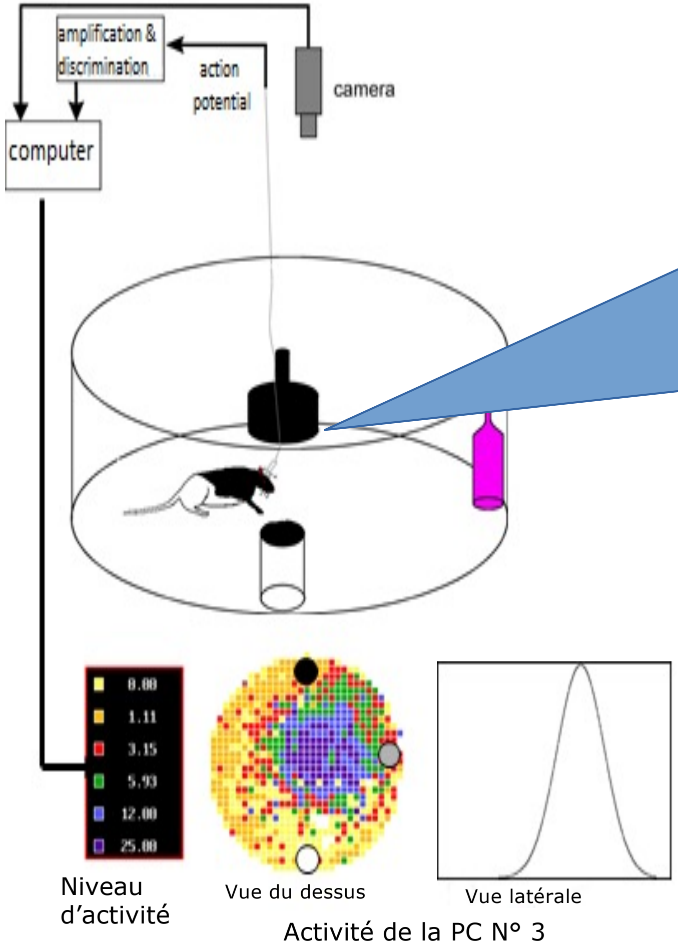


- **Respond only at a <u>given location</u> in the environment (place field).**

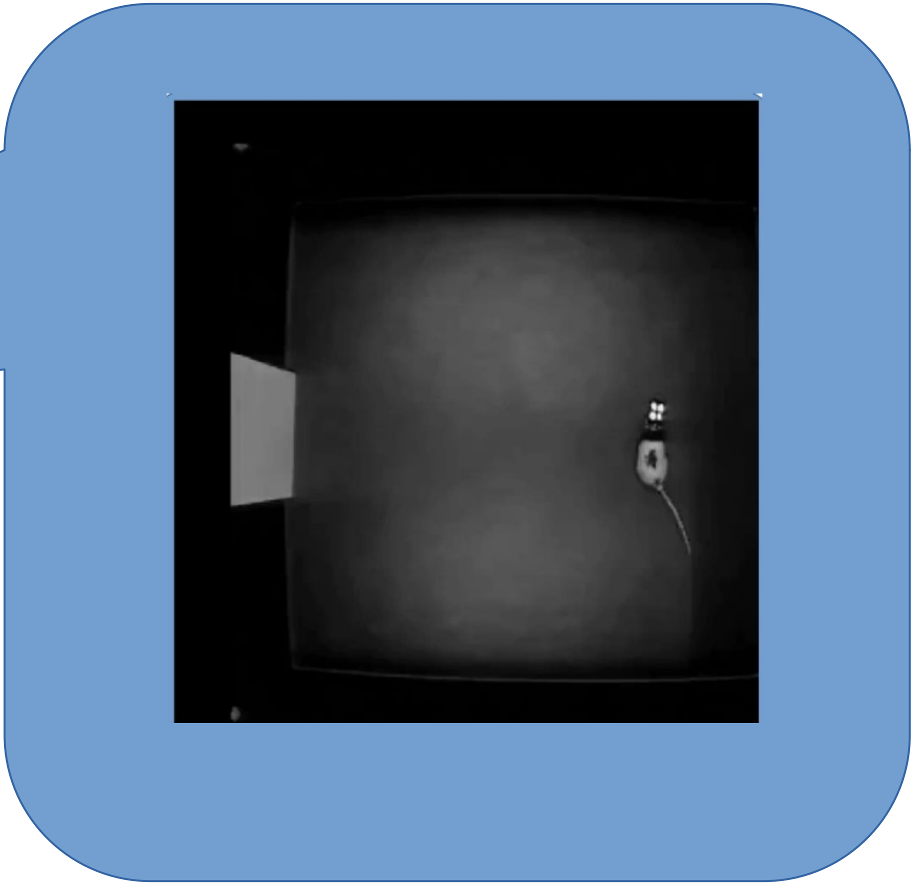


But <u>other cells</u>: Grid Cells, Border cells, Time cells, Speed cells, + **Conjunctive cells** …

Zoom on Place Cells (PC)

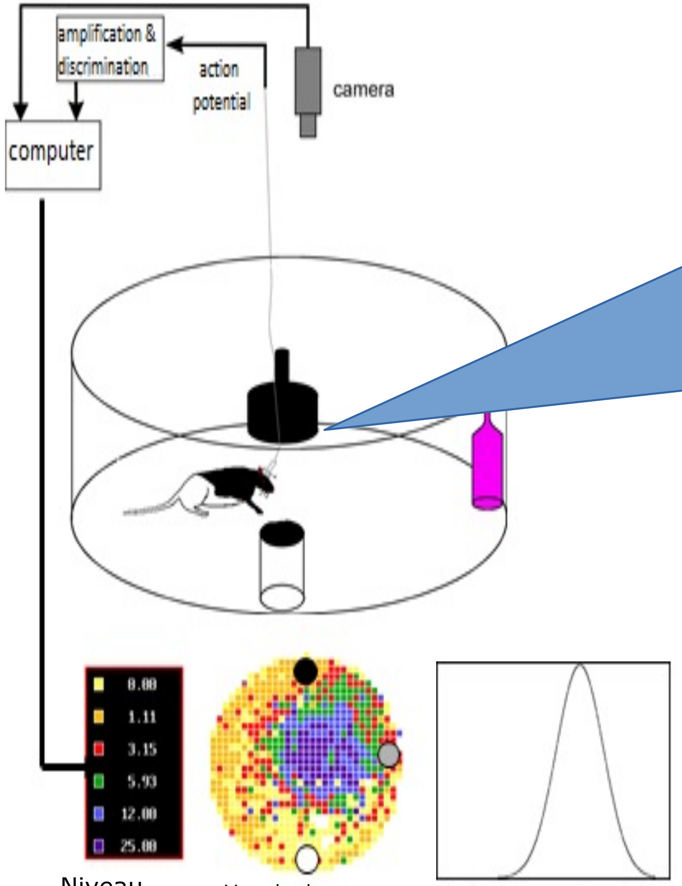


Une cellule de lieu dans l'hippocampe du rat
(Lab. B. Poucet – Marseille)



10 place cells (rat hippocampus CA1) recorded simultaneously over 50 minutes of foraging (Roddy Grieves)

Zoom on Place Cells (PC)



Niveau d'activité

Vue du dessus

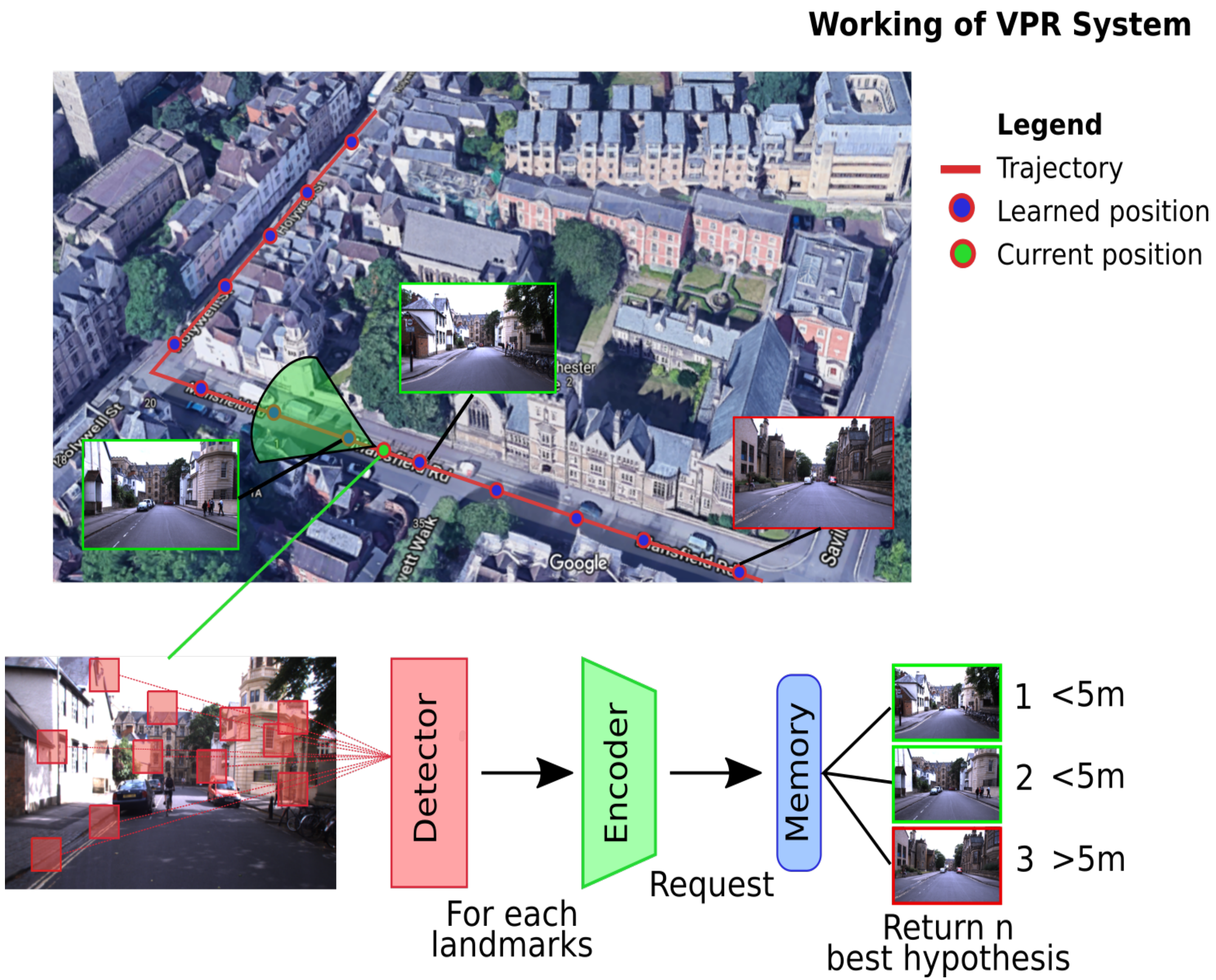
Vue latérale

Activité de la PC N° 3

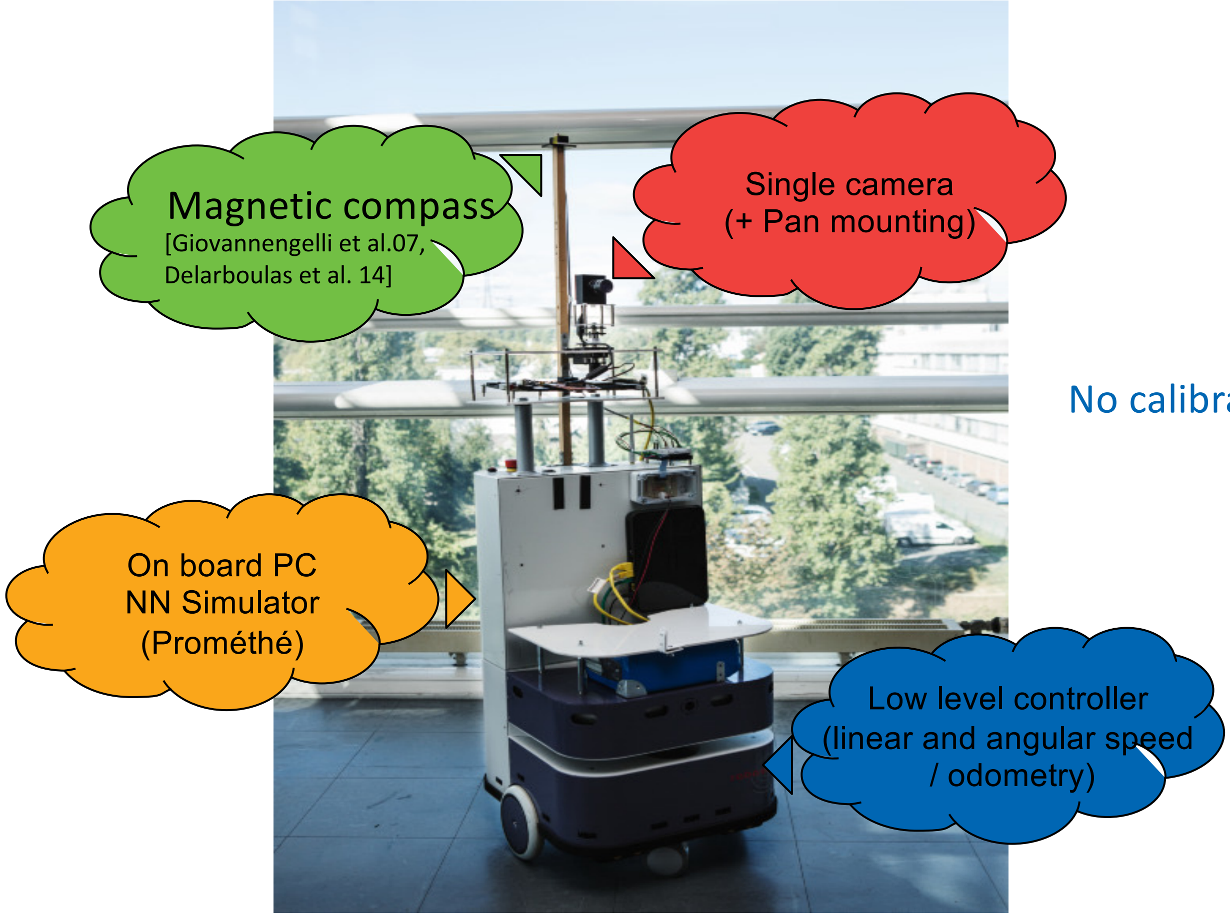
Une cellule de lieu dans l'hippocampe du rat
(Lab. B. Poucet – Marseille)

10 place cells (rat hippocampus CA1) recorded simultaneously over 50 minutes of foraging (Roddy Grieves)

Visual Place Recognition (VPR)

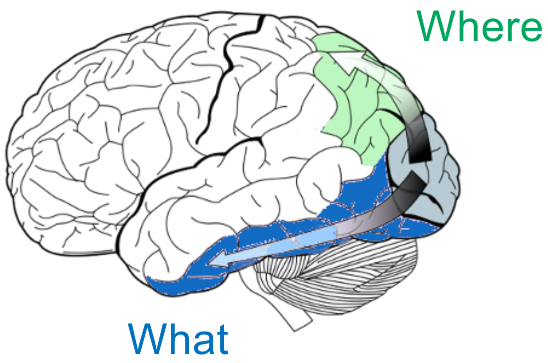


Robotic platform

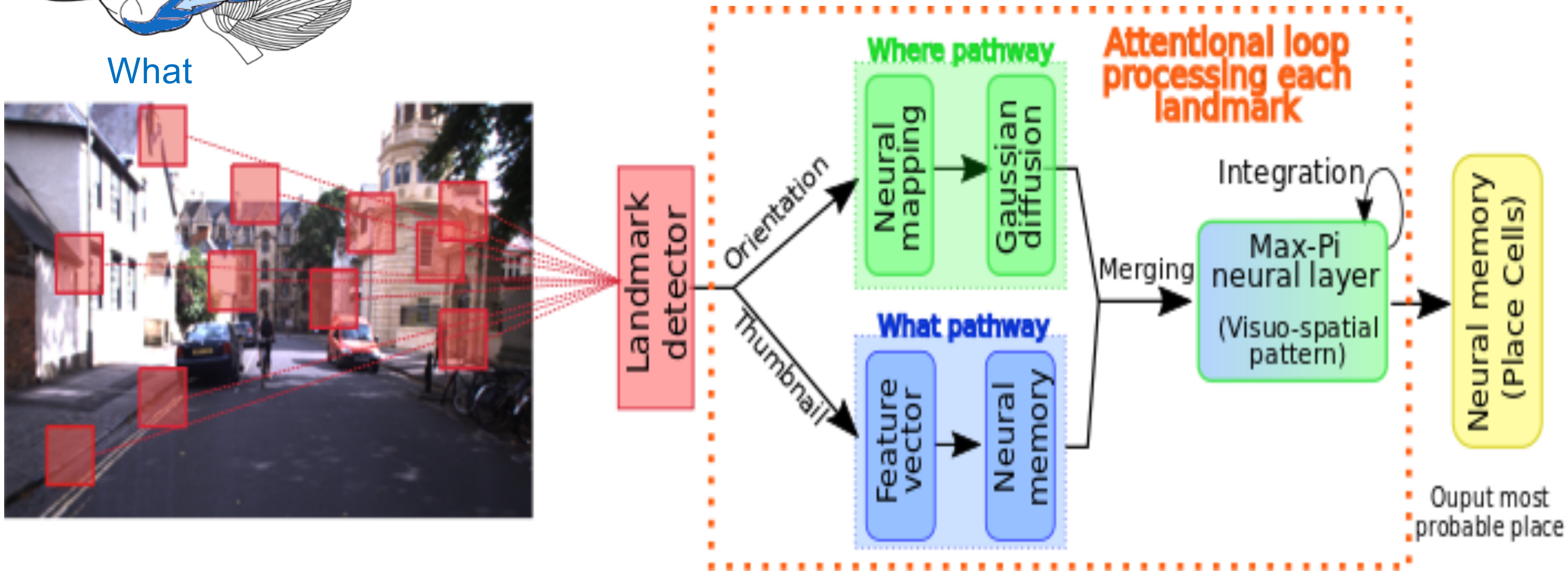


No calibration

Vision based model of hippocampal Place Cells

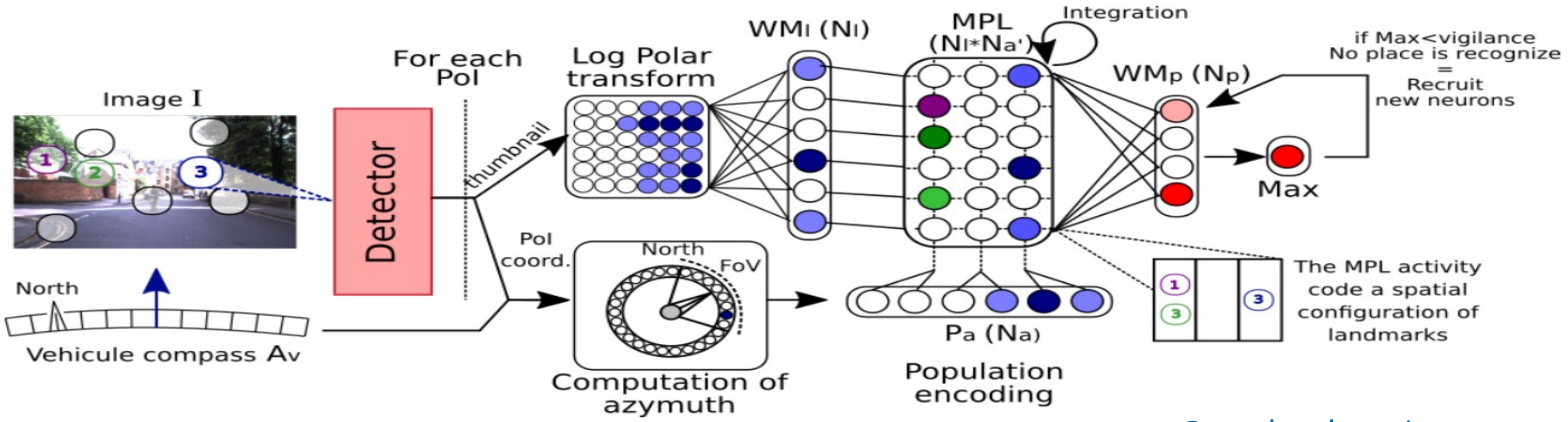


One-shot learning
No a priori information

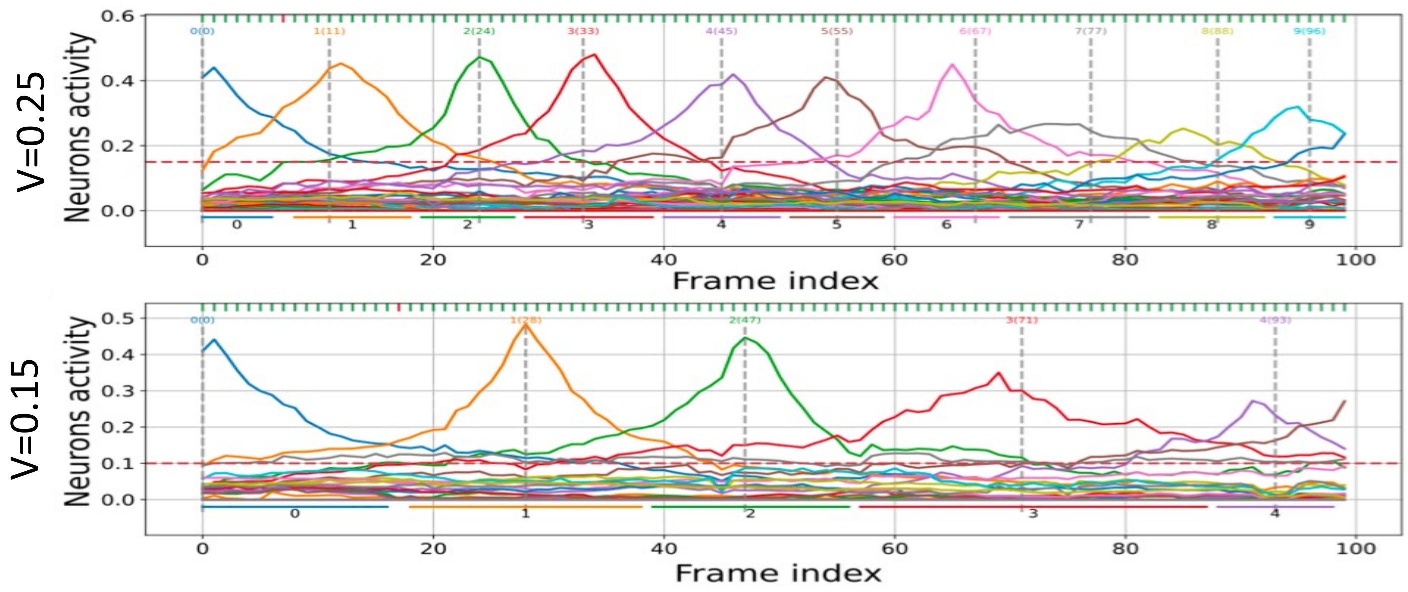


[Gaussier P.1995] [Jauffret et al. 2013] [Espada et al. 2018] [Colomler et al. 2021]

LPMP (log-polar Max-Pi) model



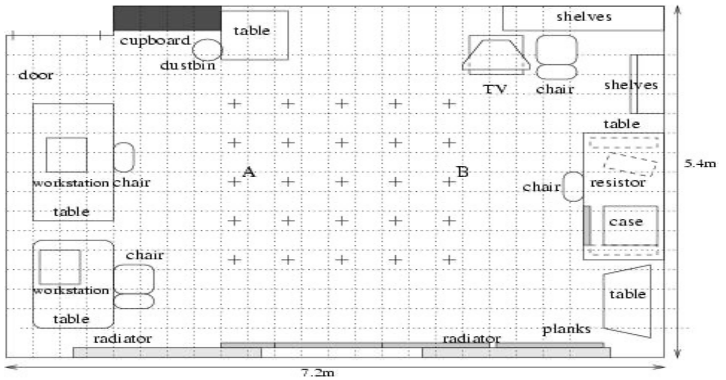
One-shot learning



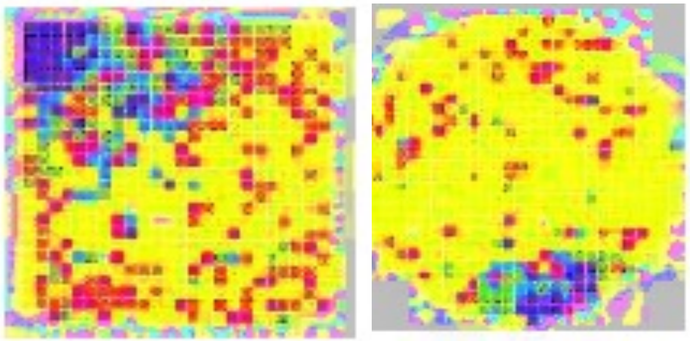
[Gaussier P.1995] [Jauffret et al. 2013] [Espada et al. 2018] [Colomer et al. 2021a]

Key results (1) : simulated PC

Experiment setup

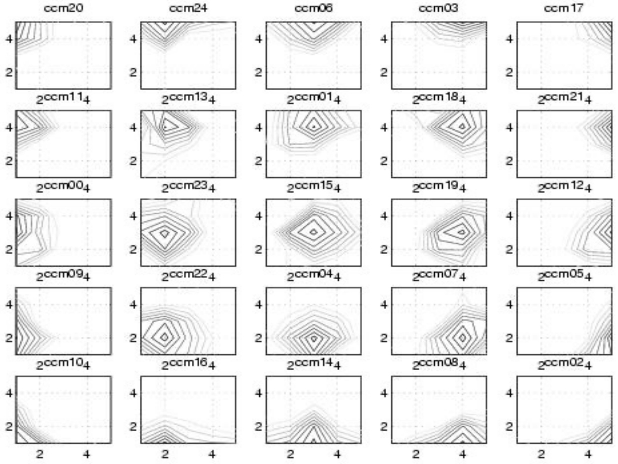


Rats place cells

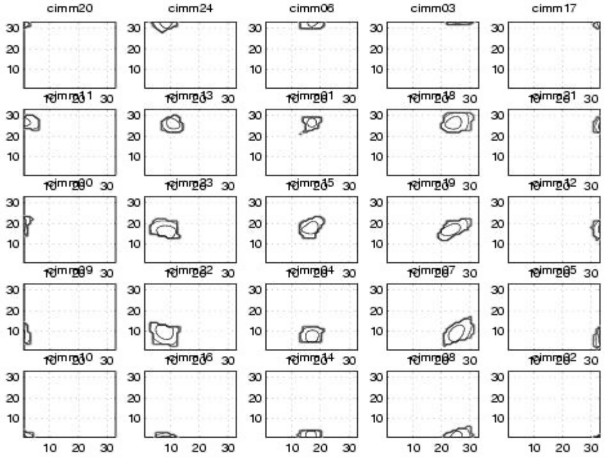


Simulated PC in robot:

Before competition



After competition :

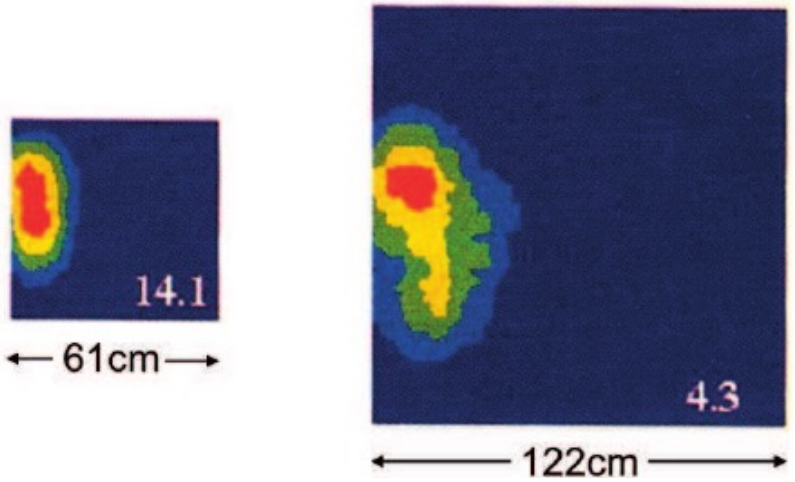


[Gaussier&Zrehen94, Gaussier&Joulain96]

Simulated visual place cells can exhibit similar activities than biological ones (in DG, in HS if followed by a WTA)

Key results (2) : adaptation of place field size

Rat

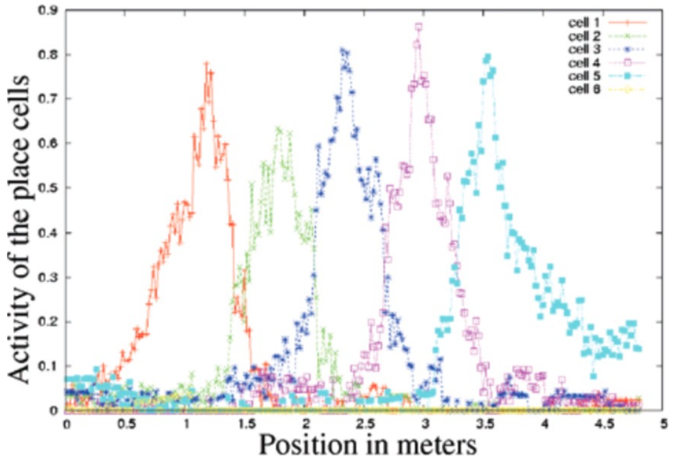


Individual place field increases in size when the environment dimensions are enlarged

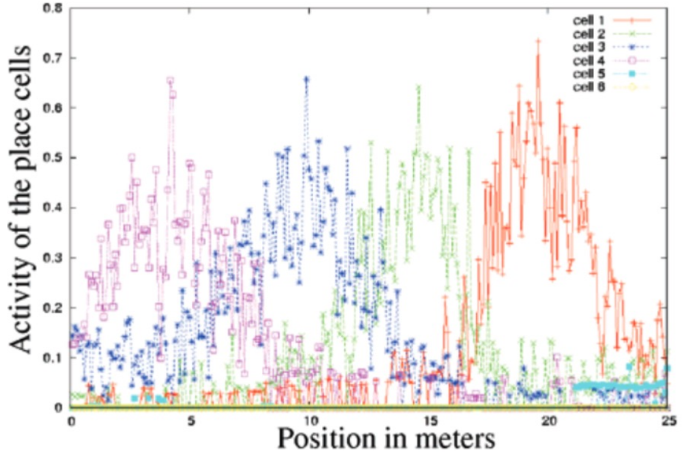
[Okeefe et al. 1996]

Robot

Indoor



Outdoor



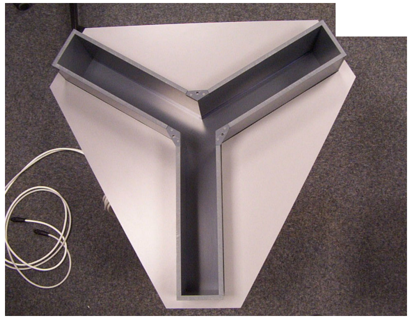
[Giovannangeli et al. 2006]

Place field size is controlled by the distance of visual landmarks

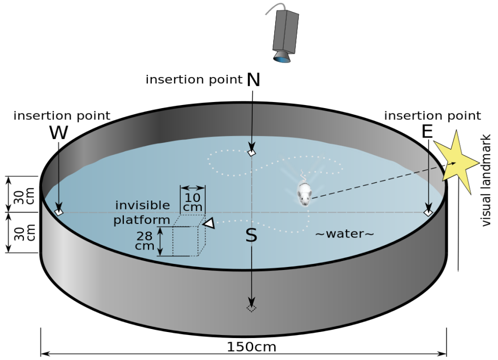
Study of spatial cognition in mammals

– **Laboratory**: 80 cm – 2/3 m diameter (small environments)

- Rodents (rats/mice)

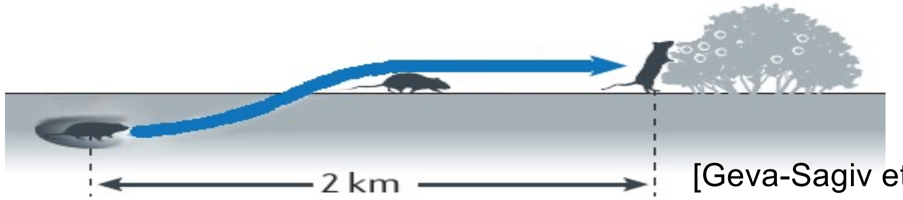


Y- Maze



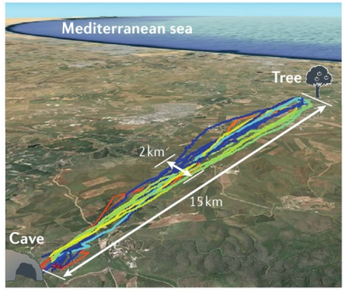
Morris water pool

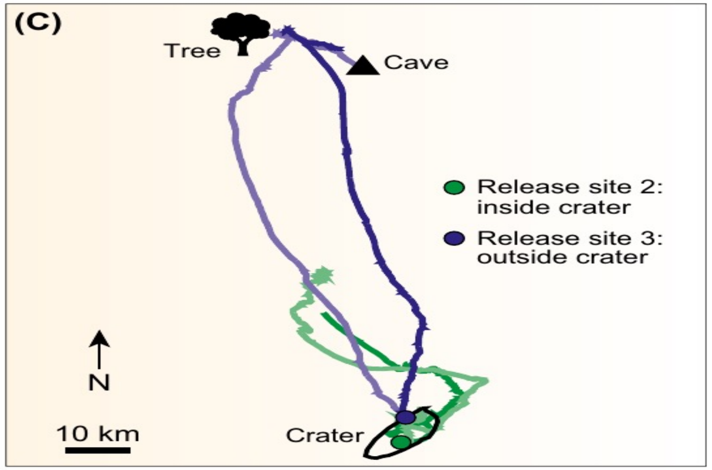
- Natural environments: trajectories from 600m to 2km



[Geva-Sagiv et. Al 2015]

- Fruit bats





Vehicle localization in large, complex and dynamic environments

KITTI odometry datasets

KITTI dataset	00	01	05	06	07	09
Nb of images	4541	1101	2761	1101	1101	1501
Type	urban	highway	suburban	suburban	urban	suburban
Length (m)	3721	2450	2203	1232	695	1701
Framerate (Hz)	10	10	10	10	10	10
Average speed (m/s)	7.90	21,54	7.61	10.80	6.09	10.33

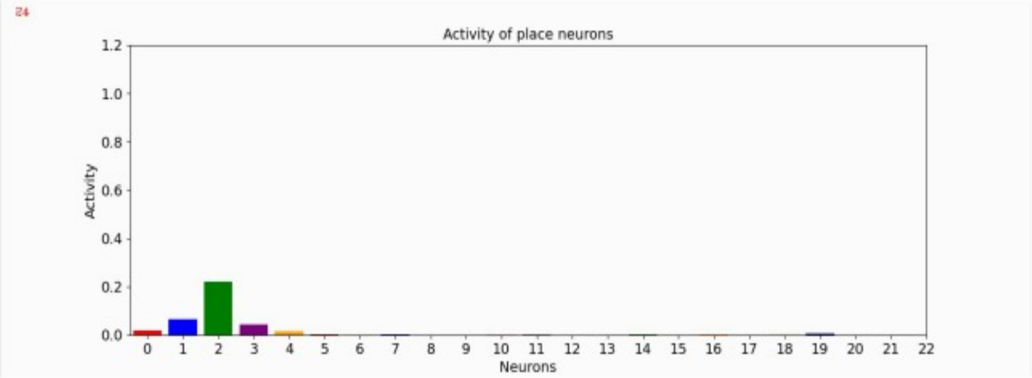
Vedecom datasets

Dataset	Satory tracks	Scenic highway
Nb of images	1366	2000
Type	rural	highway
Length (m)	4064	4082
Frame rate (Hz)	4	12
Average speed (m/s)	12.74	25.53

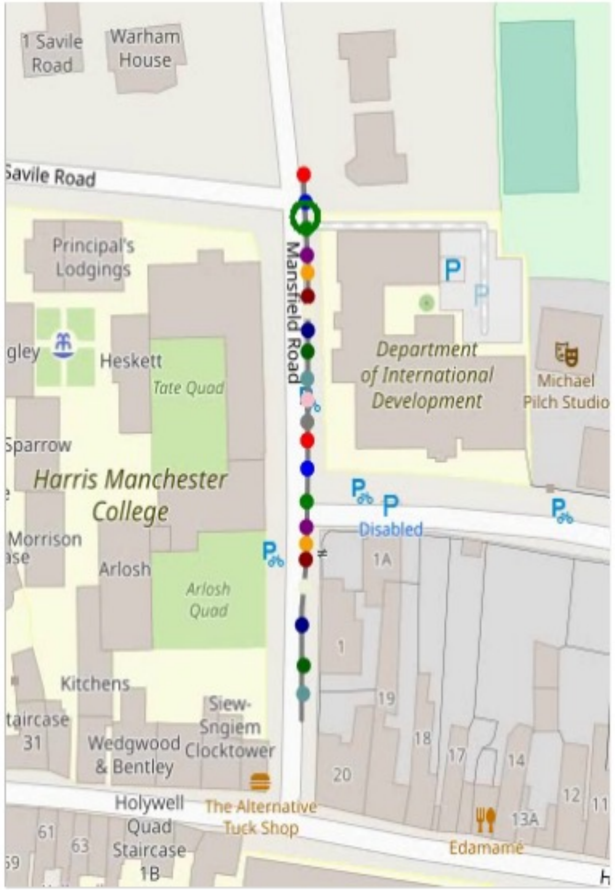
Oxford robucar datasets

Id	Env.	Images	Distance(m)	duration(s)	activity rate
S-1	Suburb	1930	632	125	4.5
S-2	Suburb	1401	625	89	6.8
S-3	Suburb	1159	624	74	7.0
S-4	Suburb	1572	626	101	7.1
C-1	City	1521	532	104	10.6
C-2	City	1904	569	124	10.9
C-3	City	2227	527	143	12.0
C-4	City	2134	585	140	13.5
R-1	Road	927	292	61	5.9
R-2	Road	828	289	54	6.2
R-3	Road	566	286	38	6.6
R-4	Road	595	287	37	8.6

Front view

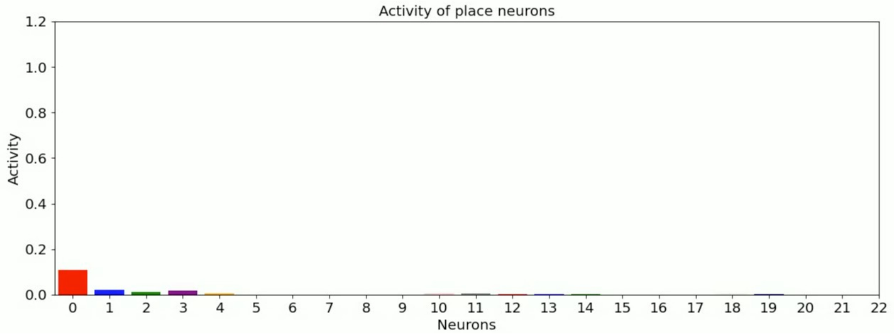


Place cells activity



Place cells maps

Front view

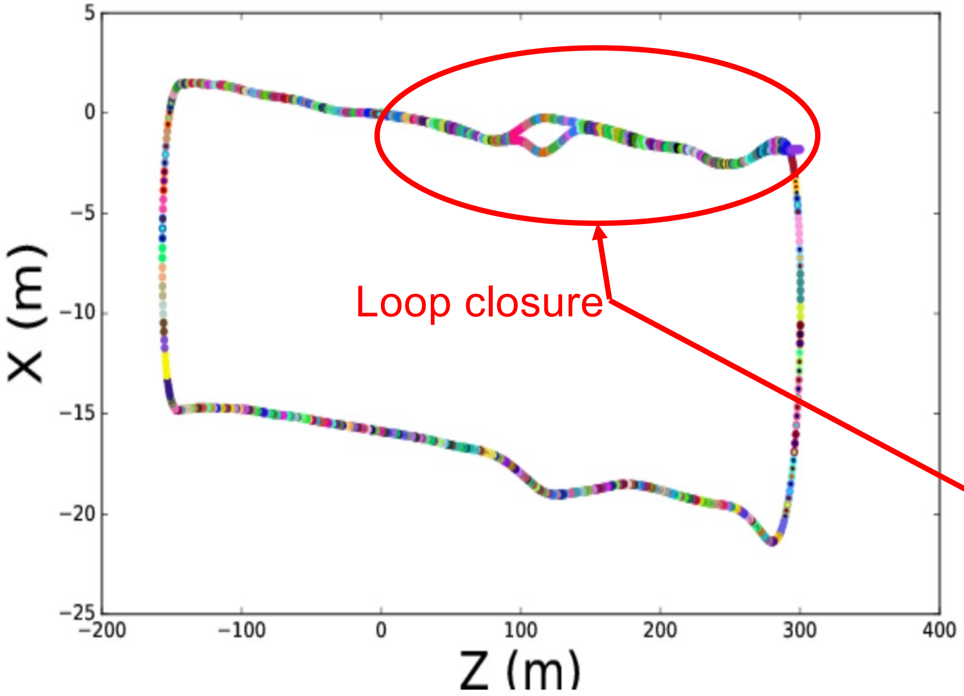


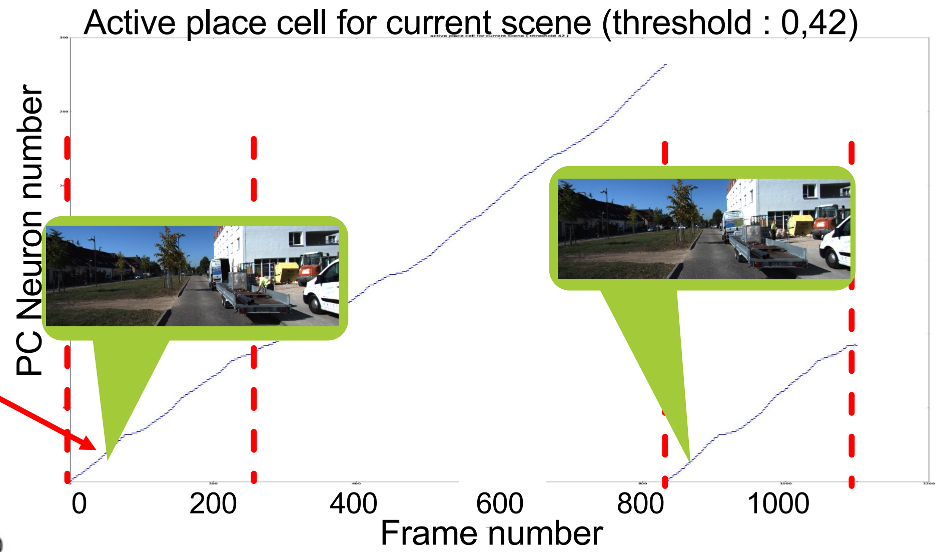
Place cells activity

Place cells maps

Key results (3): outdoor loop closure

Kitti 06 dataset



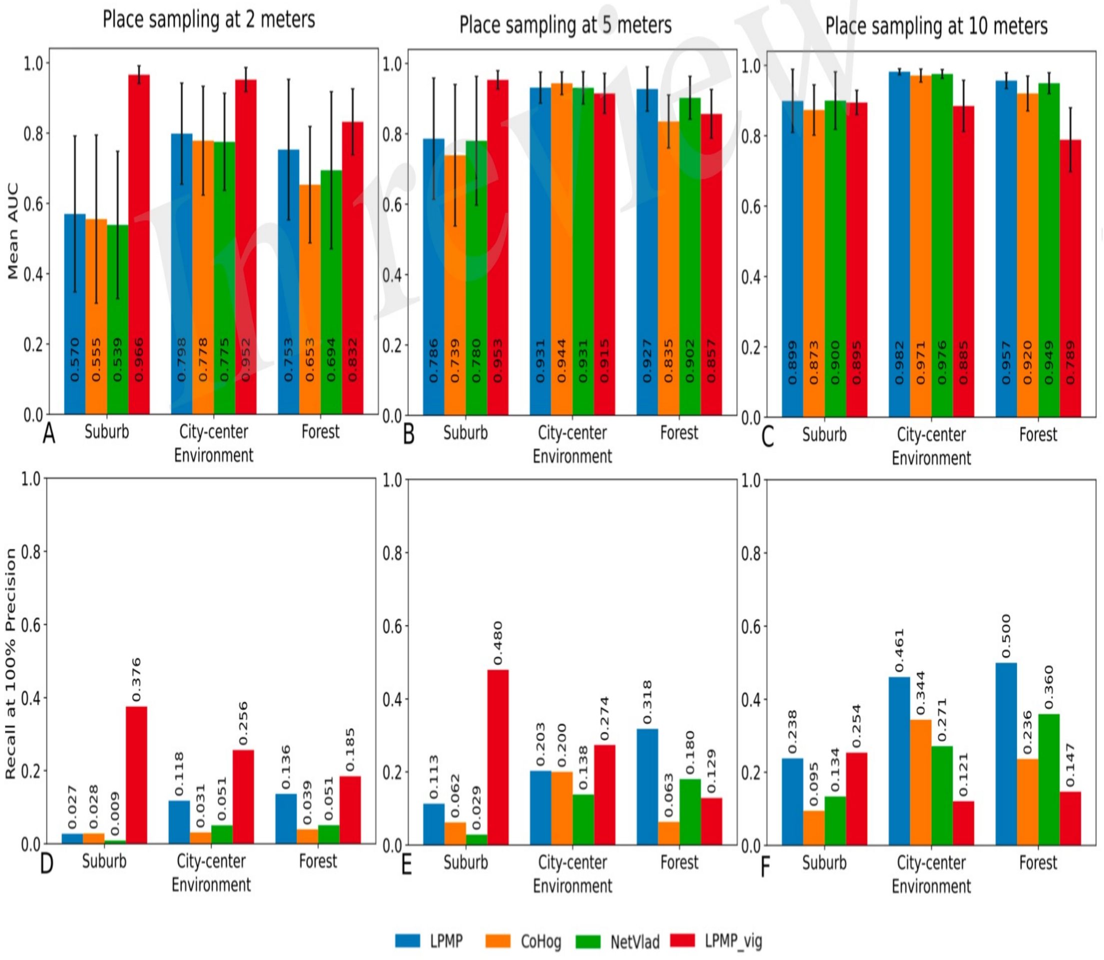


➡ Correctly performs loop closure

[Espada et al. 2018, 2019]

Key results (3): outdoor loop closure

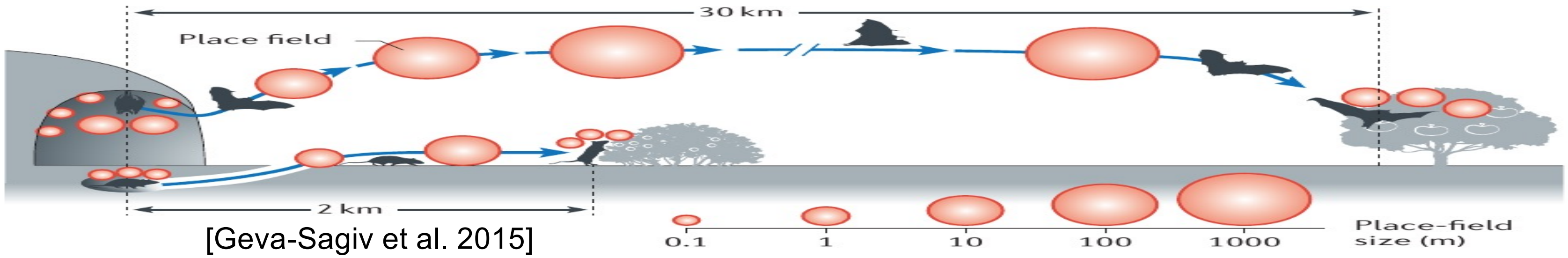
Test dataset illustrations: recorded trajectories; images from the dataset



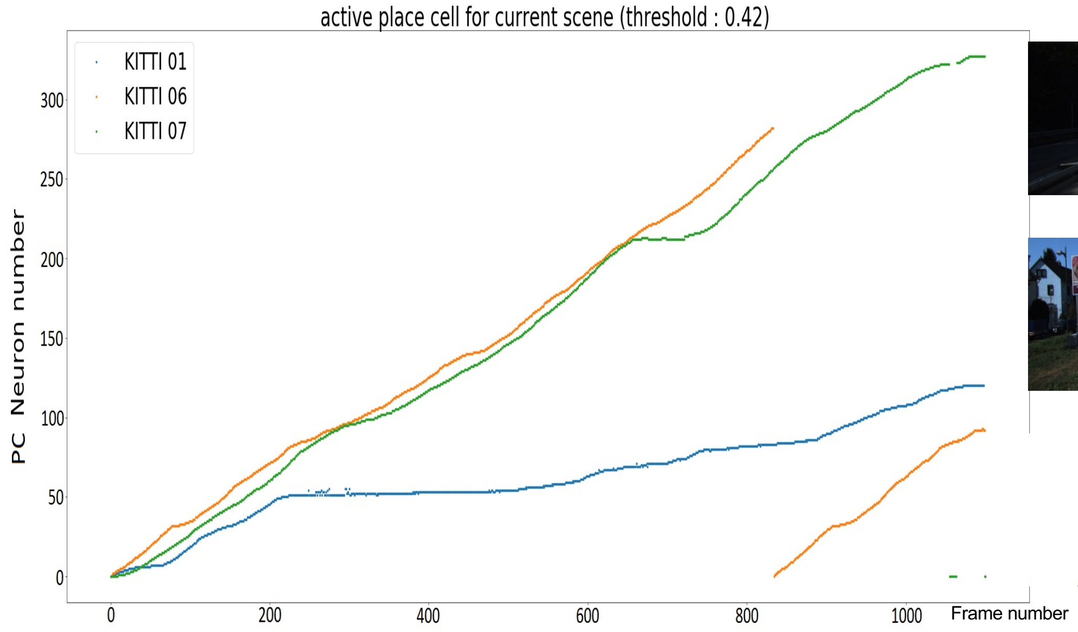
AUC (Area Under Curve) and recall obtained on the suburb sequence between LPMP, NetVlad (2018) and CoHog (2020)

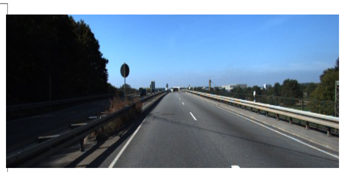
[Colomer et al. 2021a]

Key results (4): adaptative place field



[Geva-Sagiv et al. 2015]





KITTI 01

KITTI 06

KITTI 07

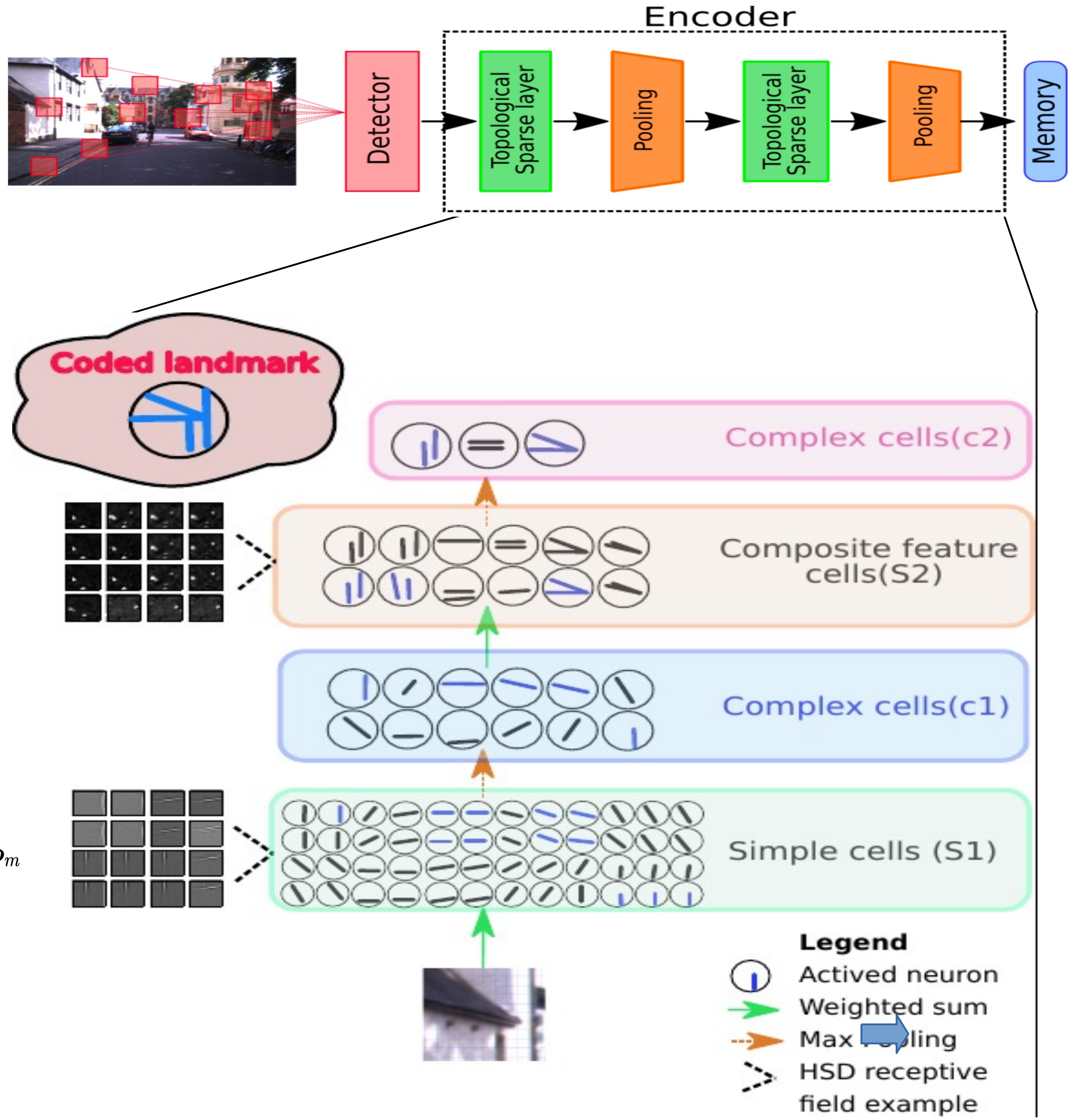
Place field size adapts to the environment.

[Espada et al. 2018, 2019]

Visual landmarks sparse coding

Sparse encoding of visual landmarks:
Hierarchical Sparse Dictionary (HSD)

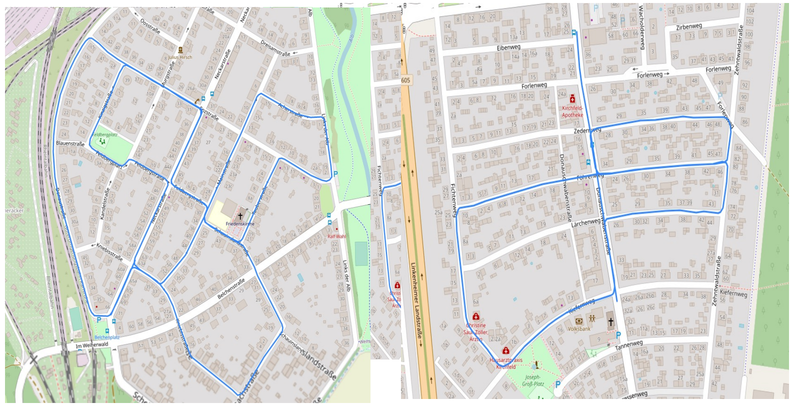
$$\min_{\boldsymbol{a}} \|\boldsymbol{a}\|_0 \quad \text{subject to} \quad \boldsymbol{s} = \sum_{m=1}^{M} a_m \boldsymbol{\phi}_m$$

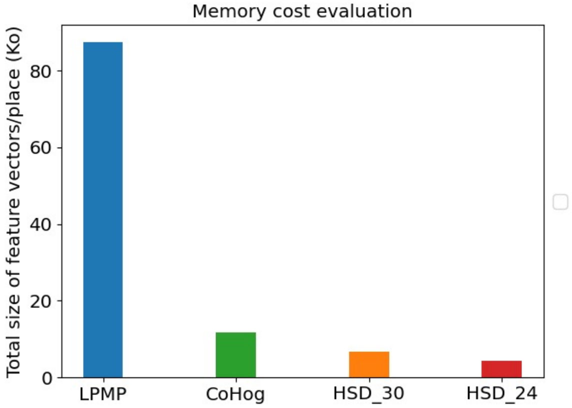


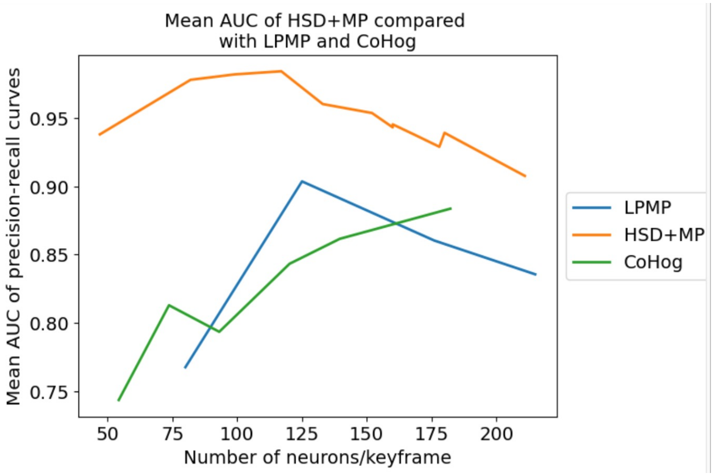
[Colomer et al. 21b]

Key results (5): toward scaling up LPMP

Name	K0-1	K2-1	K3-1
Dataset	KITTI 00	KITTI 05	KITTI 05
Size (learn;test)	(540;440)	(106;91)	(230;265)
Index learn	392-932	10-116	550-780
Index test	3399-3839	2420-2511	1289-1554
Distance	378m	96m	199m
Type	Street	City	Suburb



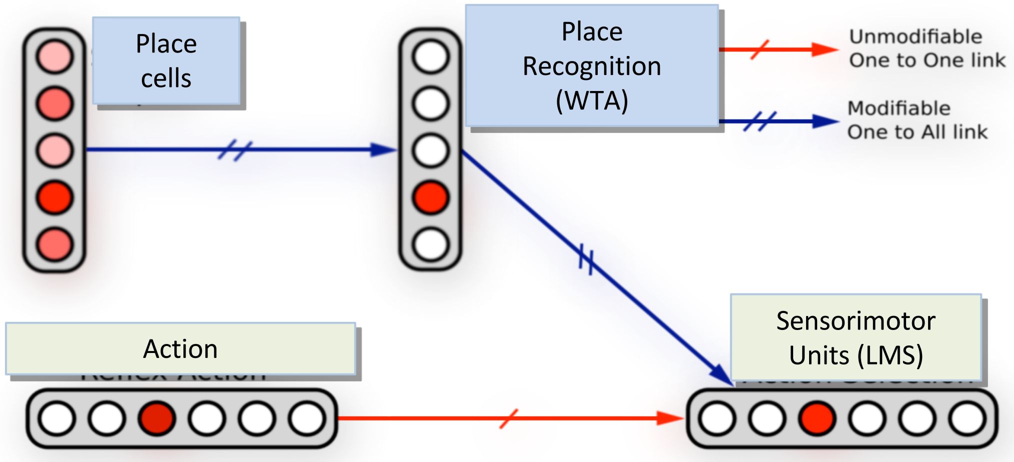




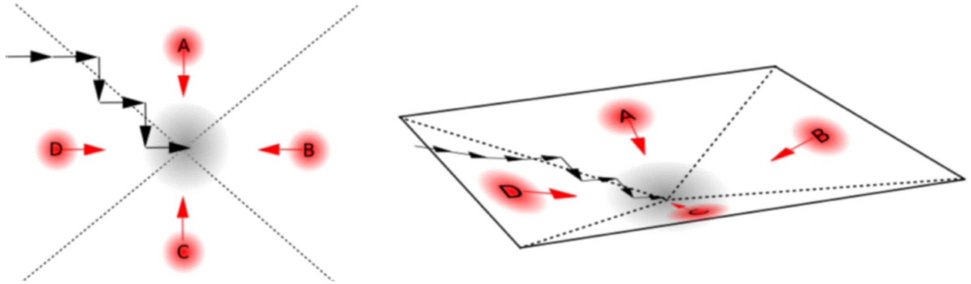
Increased accuracy and lower memory footprint

Sensorimotor learning : place/action

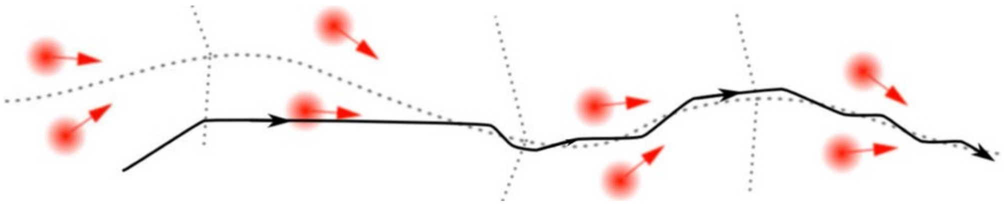
PerAc
[Gaussier et al. 95, Giovannangelli et al. 06, Cuperlier et al. 07, Jauffret et al. 15]



Return to a goal place (homing):



Path following (proscriptive learning):



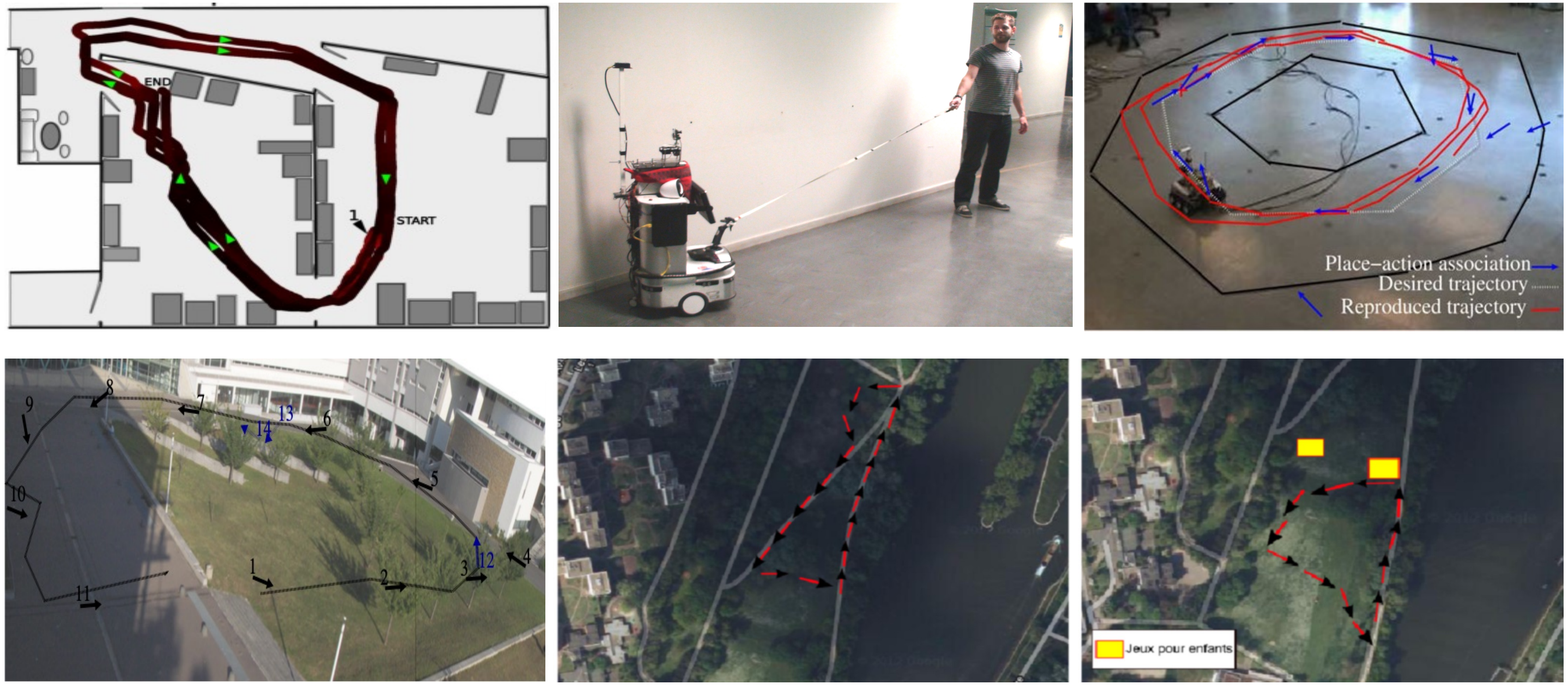
A real robot performing robust path following by the learning of multimodal sensorimotor associations

Adrien Jauffret
Nicolas Cuperlier
Philippe Gaussier

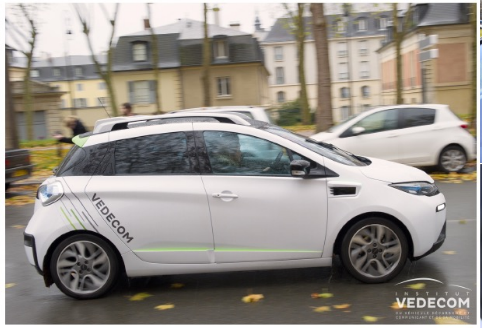
Nuit des chercheurs
Ecole polytechnique de Palaiseau

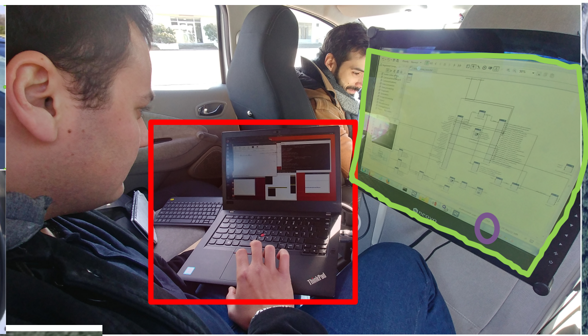
ETIS Laboratory, CNRS UMR 8051
Cergy-Pontoise University

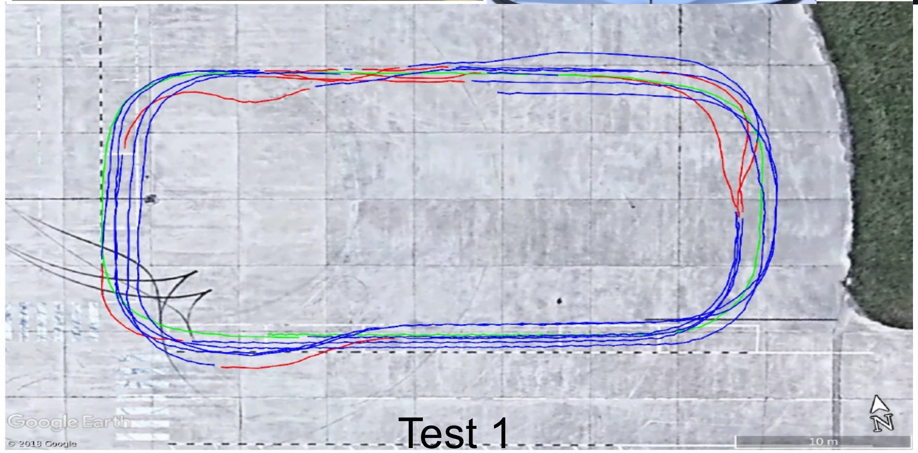
Key results (6): Path learning: indoor / outdoor (off-road)

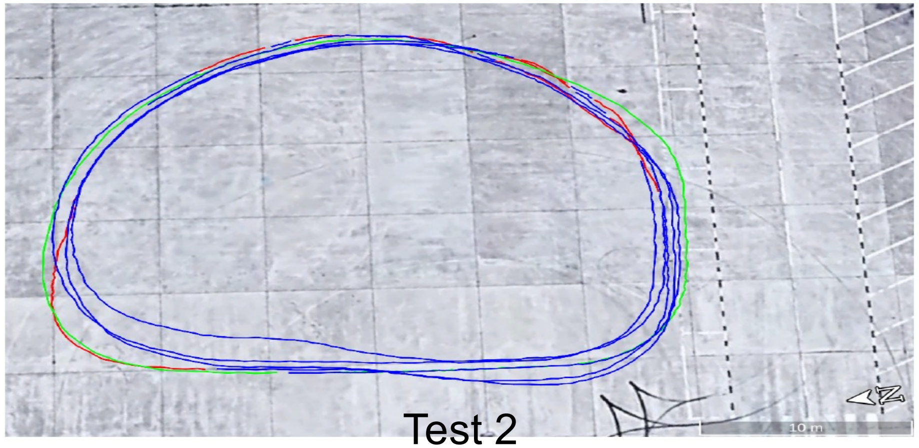


Key results (6): Sensorimotor navigation with a self-driving car









	Test 1	Test 2
Path length	105.35 m	86.06 m
Mean positioning error (Std)	0.71 (0.53)	0.63 (0.51)
Number of trajectory corrections	11	9

3 interactive teaching laps are enough to learn to reproduce a loop-shaped trajectory

Embedded system solutions

Work done with the Cell team of ETIS

Smart Camera

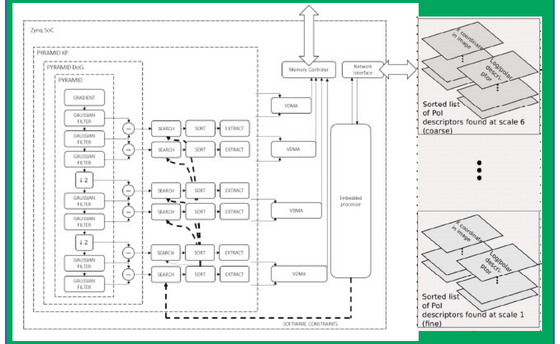
2013

2018

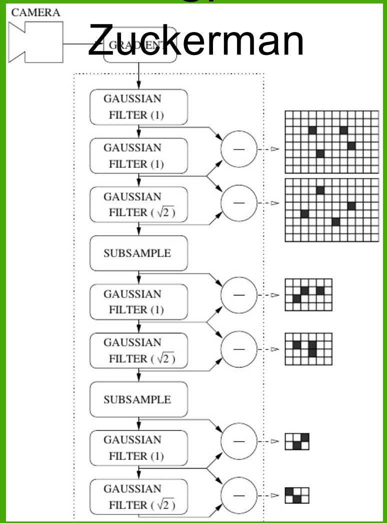
Full neural system

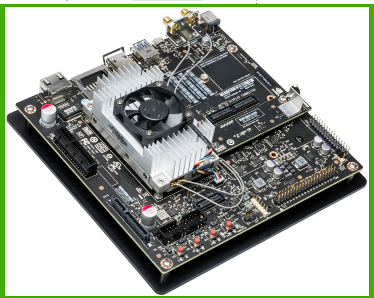
2019

RobotSoC
FPGA Zynq 7020
B. Miramond et al. (Fiack et al. 2013)

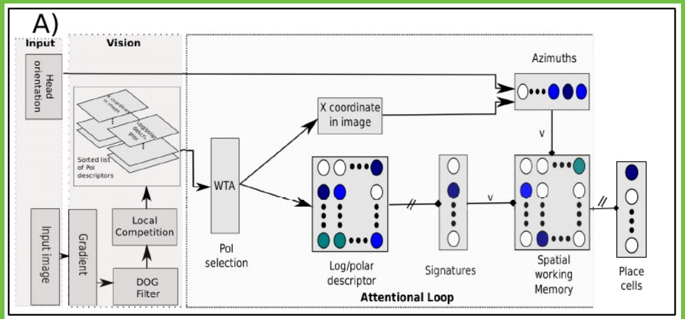


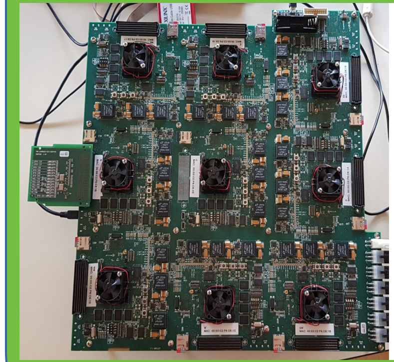
Jetson TX2
(GPU)
S.
Zuckerman

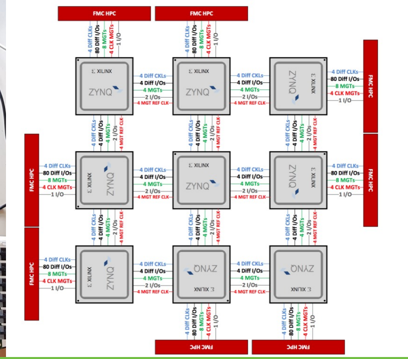




WIZARDE :
Heterogeneous Multi-FPGA Systems (T. Elouaret et al. 2019)

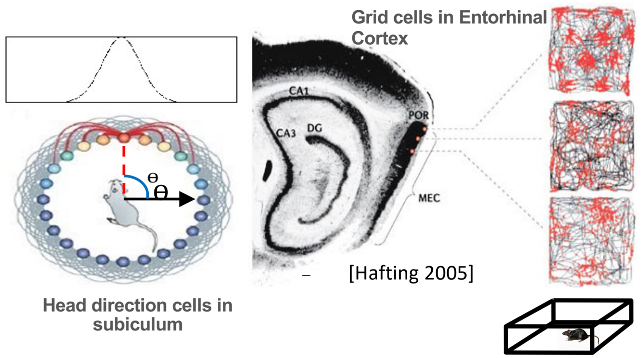






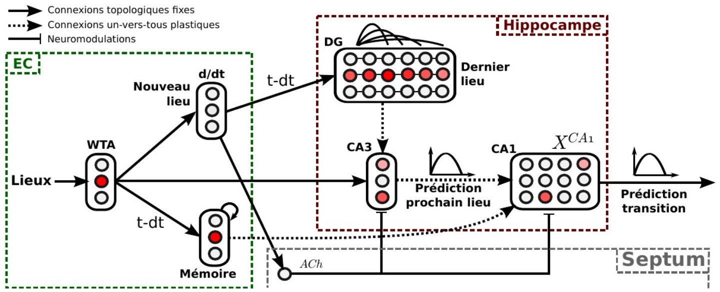
Current and future challenges

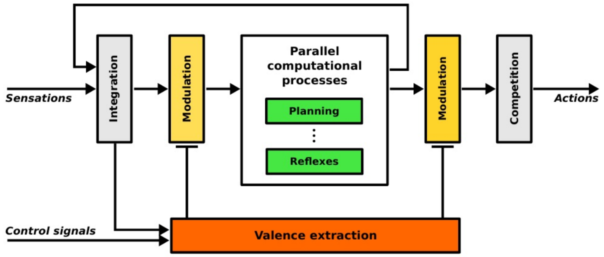
- **Computational neurosciences:**
  - Taking into account more brain structures (Entorhinal Cortex, Subiculum, Retrosplenial Cortex, ...)
  - with other cell types (grid cells, head direction cells, border cells, ...)
  - and their interactions ...



- **Neural control architecture for robot navigation :**
  - toward long term and large distance
    - deal with highly dynamic environments (day/night, weather, seasons)
    - Improve sensorimotor prediction and learning

→ Sparse coding, contextual neuro-modulation, population decoding of PC, transition cells, …





People involved

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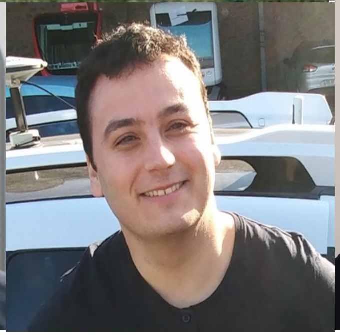
Philippe Gaussier (ETIS)

Olivier Romain (ETIS)



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