A close-up, slightly blurred image of the iCub robot's face, showing its large, white, circular eyes and a small, pinkish mouth. The background is a soft, out-of-focus grey.

# EXPANDING **SENSORIMOTOR** CAPABILITIES OF **HUMANOID** ROBOTS THROUGH MULTISENSORY **INTEGRATION** :

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## **PeriPersonal Space** on the **iCub**

**Alessandro Roncone**, iCub Facility

Matej Hoffmann, Ugo Pattacini, Giorgio Metta, Luciano Fadiga

# The importance of PERIPERSONAL SPACE in humans .

*"THE SPACE AROUND US"* [Rizzolatti et al.,1997]

It is the **SPACE SURROUNDING OUR BODIES**

It acts as an **INTERFACE** between the body and the external world

**MULTIMODAL REPRESENTATION** of space

[vision, tactile, proprioception, auditory, motor system]

# The importance of PERIPERSONAL SPACE in humans .

## NEUROPHYSIOLOGY

- Bottom-up approach
- Focus on **PROPRIOCEPTION**  
and its role in the **CONTROL OF**  
**MOVEMENT**

PPS

## PSYCHOLOGY

- Top-down approach
- Focus on the **MULTISENSO-**  
**RY** aspect

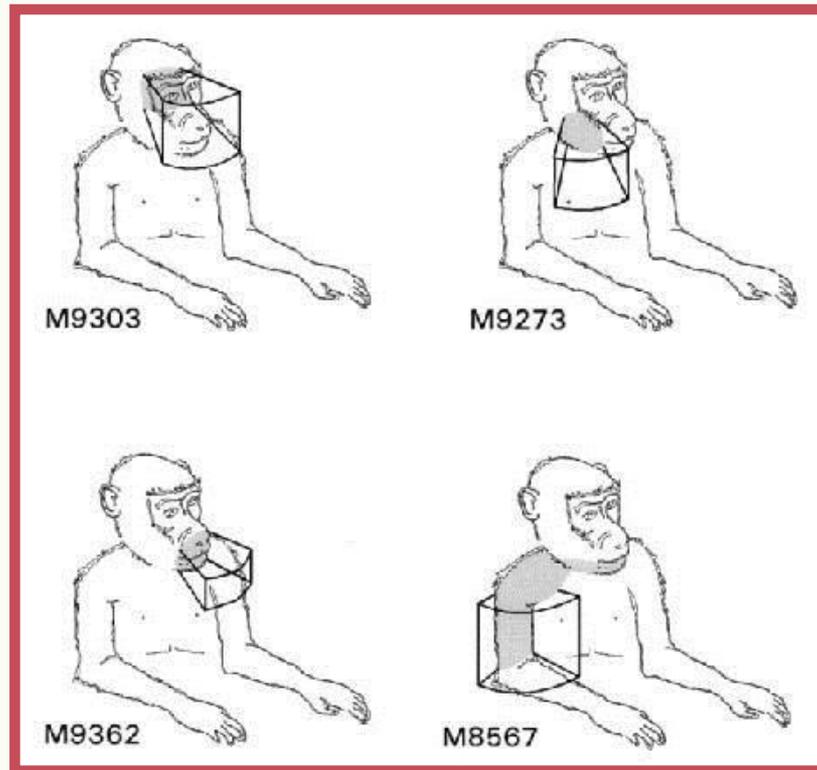
# The importance of PERIPERSONAL SPACE in humans .

**DIFFERENT REFERENCE FRAMES** for different modalities  
(and goals)

Figure removed due to copyright restrictions. Please see the video.

# The importance of PERIPERSONAL SPACE in humans .

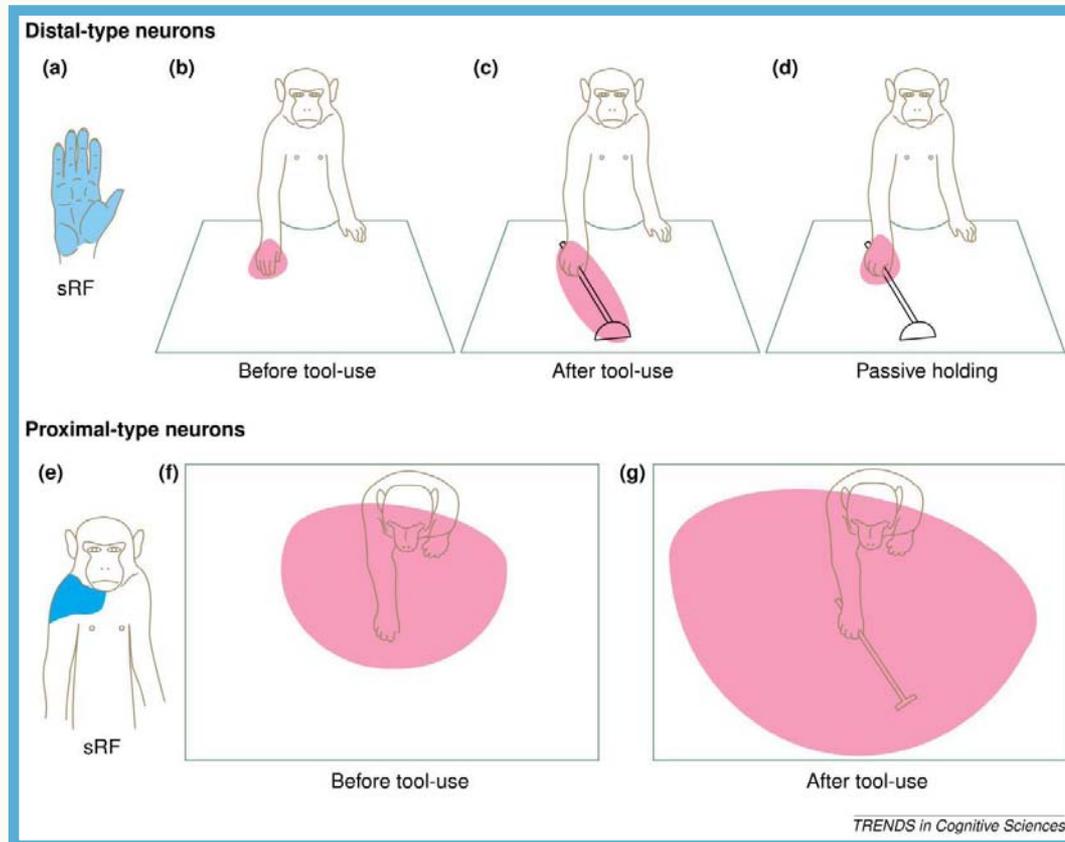
**MULTISENSORY INTEGRATION** to form a coherent view of the body and the space surrounding it [Fogassi et al. 1996]



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Source: Fogassi, Leonardo, Vittorio Gallese, Luciano Fadiga, Guiseppe Luppino, Massimo Matelli, and Giacomo Rizzolatti. "Coding of peripersonal space in inferior premotor cortex (area F4)." Journal of neurophysiology 76, no. 1 (1996): 141-157.

# The importance of PERIPERSONAL SPACE in humans .

## Intrinsic **PLASTIC BEHAVIOR** [Iriki et al. 2004]



Courtesy of Elsevier, Inc., <https://www.sciencedirect.com>. Used with permission. Source: Maravita, Angelo, and Atsushi Iriki. "Tools for the body (schema)." Trends in cognitive sciences 8, no. 2 (2004): 79-86.

# PERIPERSONAL SPACE in robotics .

## MODELS

- [Antonelli et al. 2012]
- [Hikita et al. 2009]
- [Fuke et al. 2009]

PPS

## IMPLEMENTATIONS

- [Mittendorfer et al. 2015]

# Outline .

Learning visuo-tactile associations on the iCub

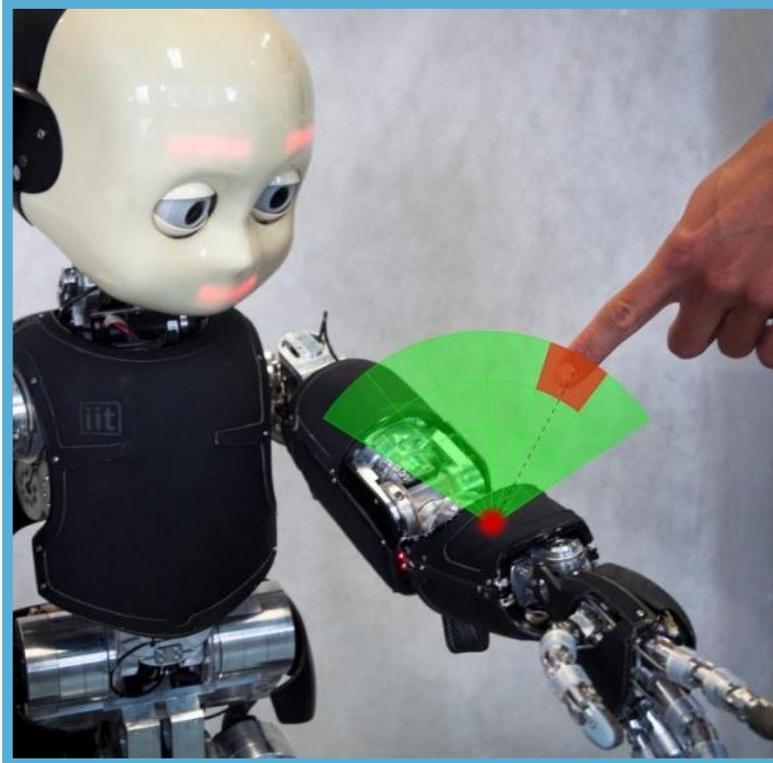
Application[s]: Margin of Safety and Catching with Any Body Part

Discussion



# PERIPERSONAL SPACE on the iCub

# Representation of space around the body .



**DISTRIBUTED REPRESENTATION**  
of the nearby space

Each taxel possess a

**SPATIAL RECEPTIVE FIELD**

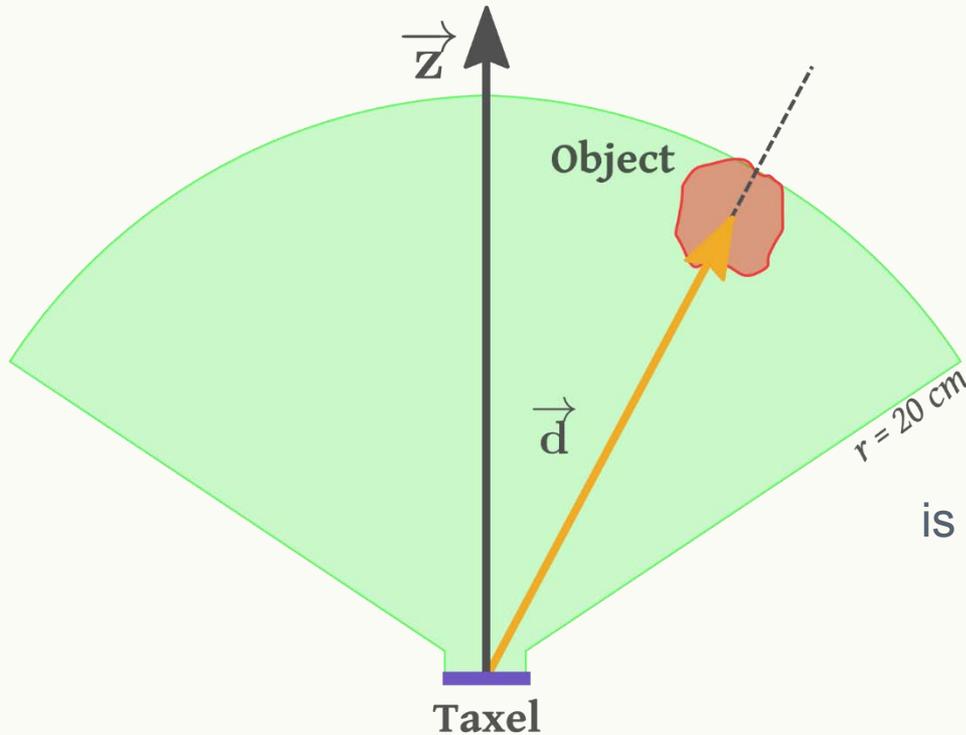
growing out from it

each taxel learns a

**PROBABILITY** of **BEING TOUCHED**

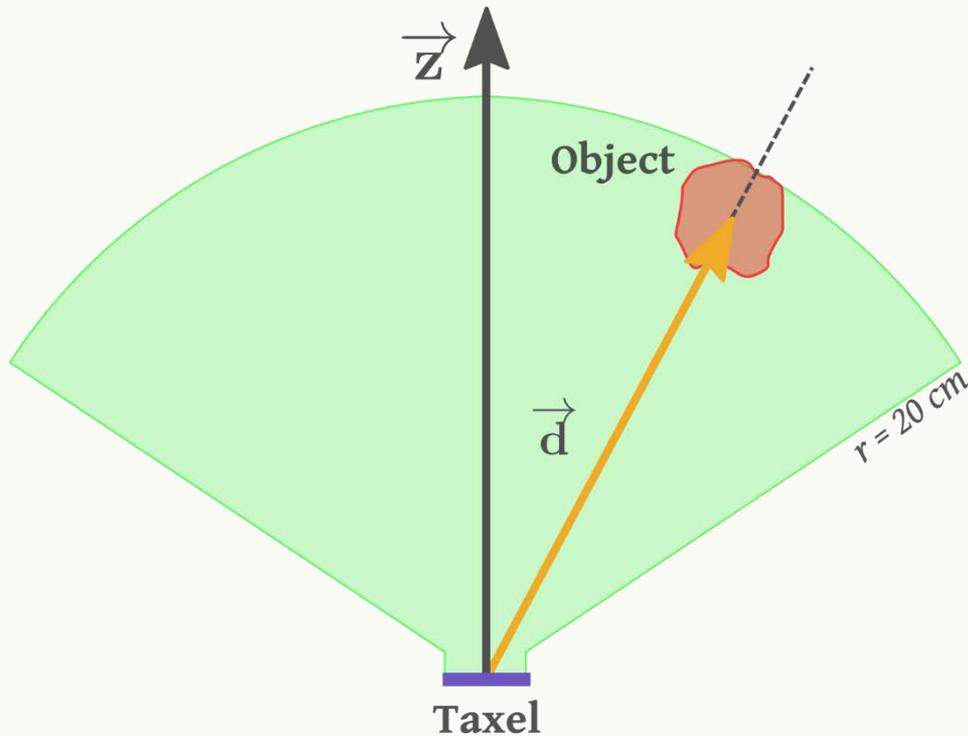
Courtesy of Alessandro Roncone and Matej Hoffman. Used with permission.  
Source: Roncone, Alessandro, Matej Hoffmann, Ugo Pattacini, and Giorgio Metta. "Learning peripersonal space representation through artificial skin for avoidance and reaching with whole body surface." In Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on, pp. 3366-3373. IEEE, 2015.

# Representation of space around the body .



For any input event,  
its **DISTANCE** wrt the taxel  
is recorded in a **3 seconds** buffer

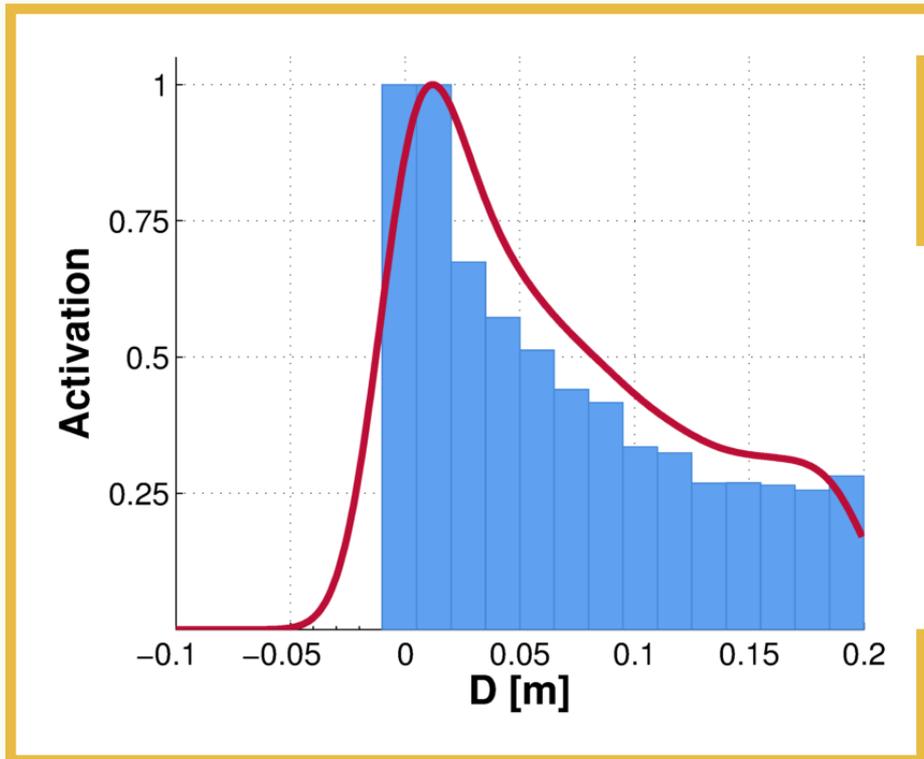
# Representation of space around the body .



Distance [D]

$$D = \text{sgn}(\vec{d} \cdot \vec{z}) \|\vec{d}\|$$

# Representation of space around the body .



$$P(D) \approx f(D) = \frac{n_{positive}(D_i)}{n_{positive}(D_i) + n_{negative}(D_i)}$$

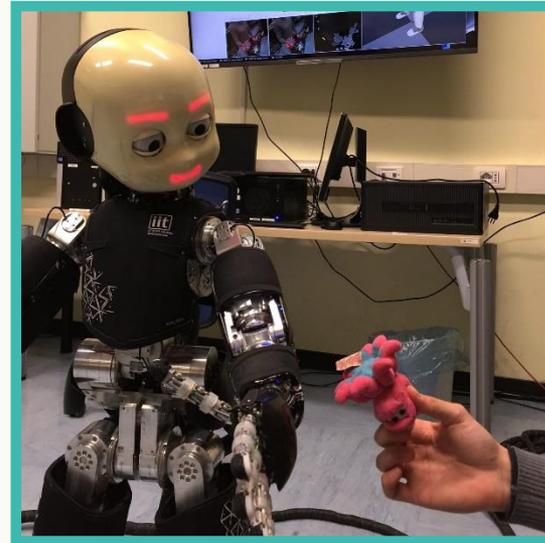
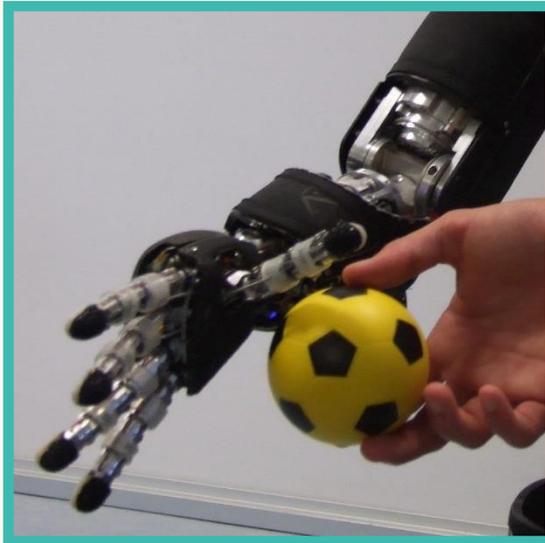
$$p(\mathbf{x}) = \frac{1}{n} \sum_{i=1}^n \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(\mathbf{x}_i - \mathbf{x})^2}{2\sigma^2}\right)$$

Courtesy of Alessandro Roncone and Matej Hoffman. Used with permission.  
Source: Roncone, Alessandro, Matej Hoffmann, Ugo Pattacini, and Giorgio Metta. "Learning peripersonal space representation through artificial skin for avoidance and reaching with whole body surface." In Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on, pp. 3366-3373. IEEE, 2015.

# Experiments .

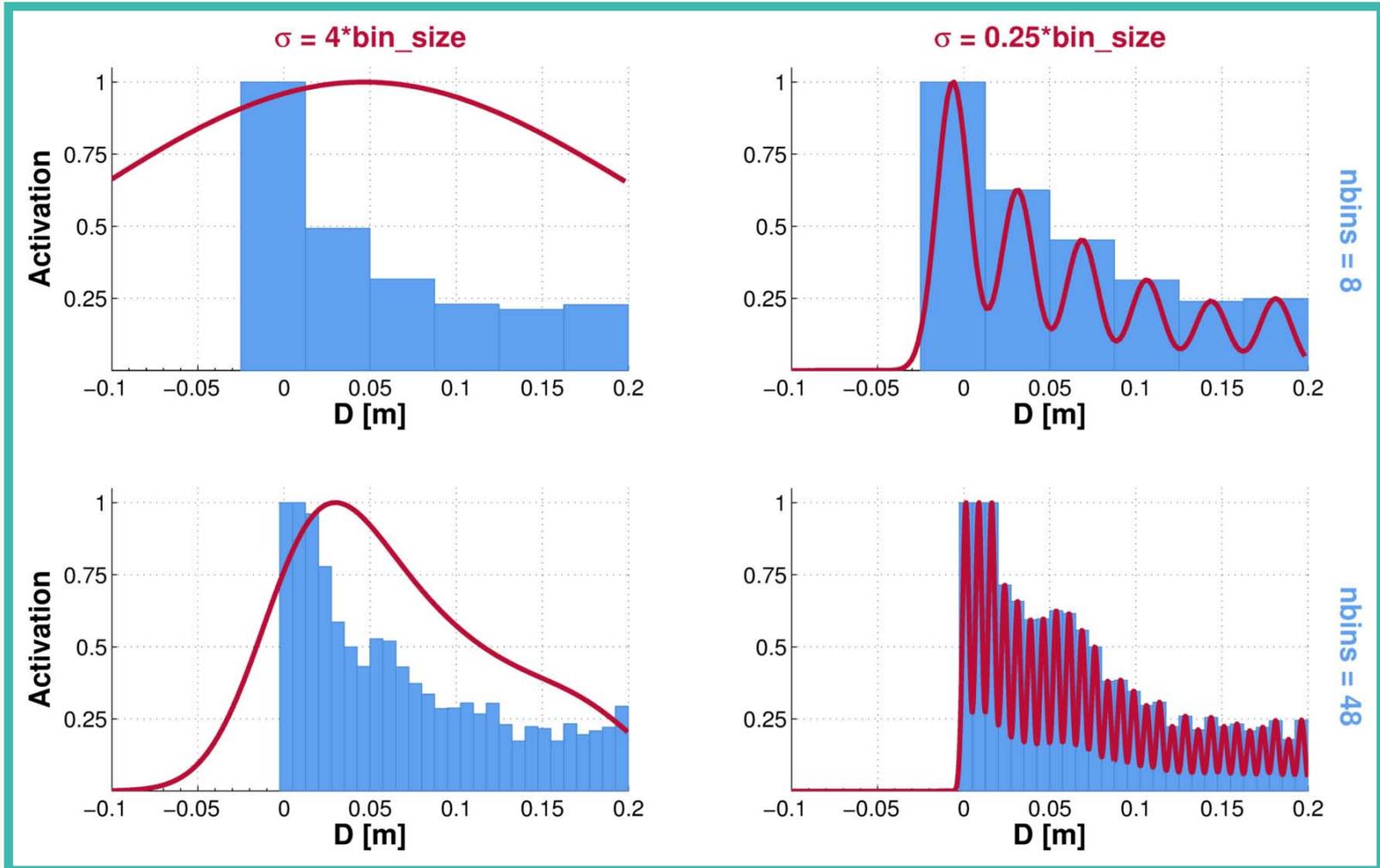
A MONTE CARLO SIMULATION :  
single taxel model

B TACTILE - VISUAL LEARNING :  
external objects detected through 3D optical flow



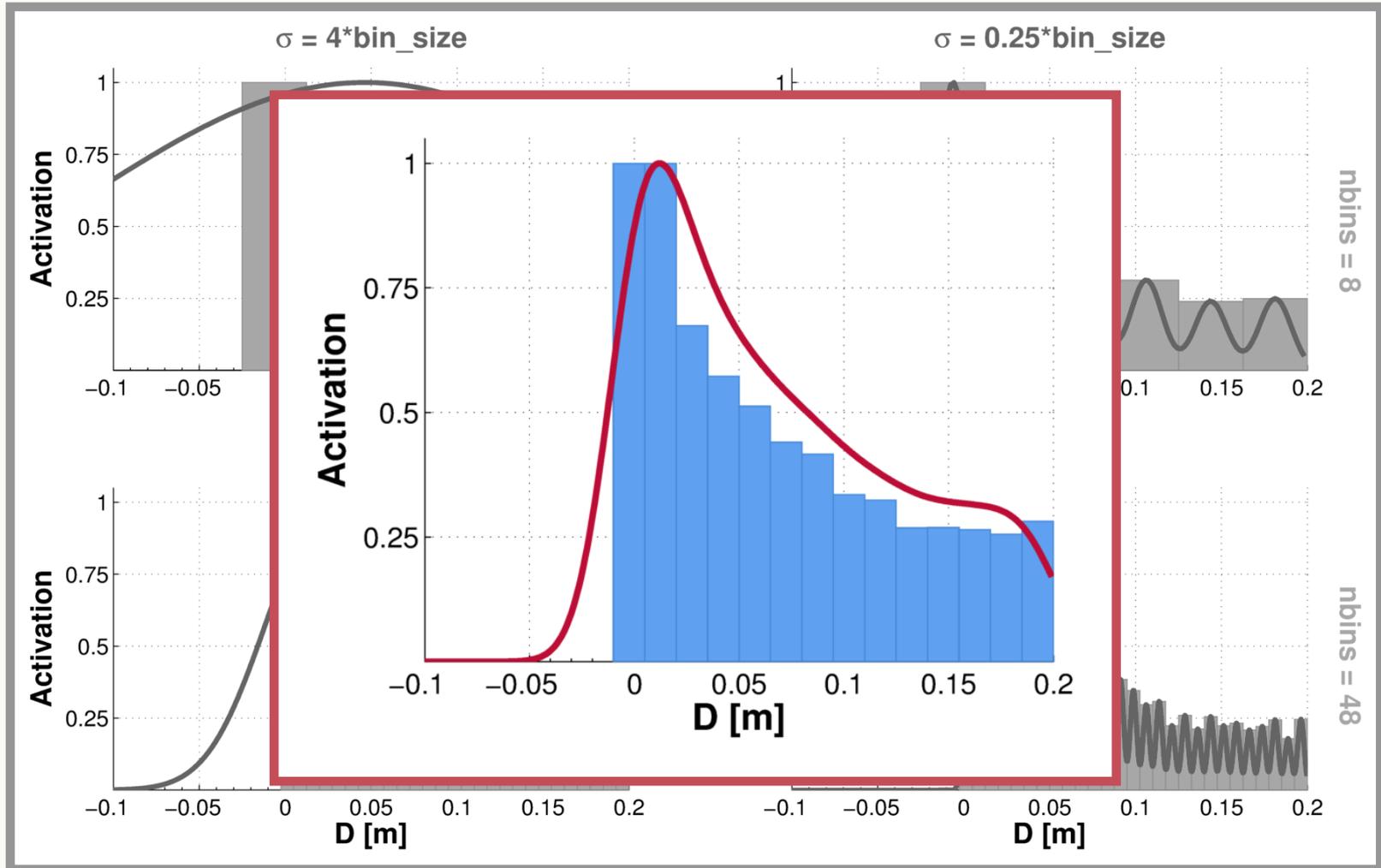
Courtesy of Alessandro Roncone and Matej Hoffman. Used with permission.  
Source: Roncone, Alessandro, Matej Hoffmann, Ugo Pattacini, and Giorgio Metta. "Learning peripersonal space representation through artificial skin for avoidance and reaching with whole body surface." In Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on, pp. 3366-3373. IEEE, 2015.

# Exp A - Single Taxel Model - Tuning of the parameters .



Courtesy of Alessandro Roncone and Matej Hoffman. Used with permission.  
Source: Roncone, Alessandro, Matej Hoffmann, Ugo Pattacini, and Giorgio Metta. "Learning peripersonal space representation through artificial skin for avoidance and reaching with whole body surface." In Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on, pp. 3366-3373. IEEE, 2015.

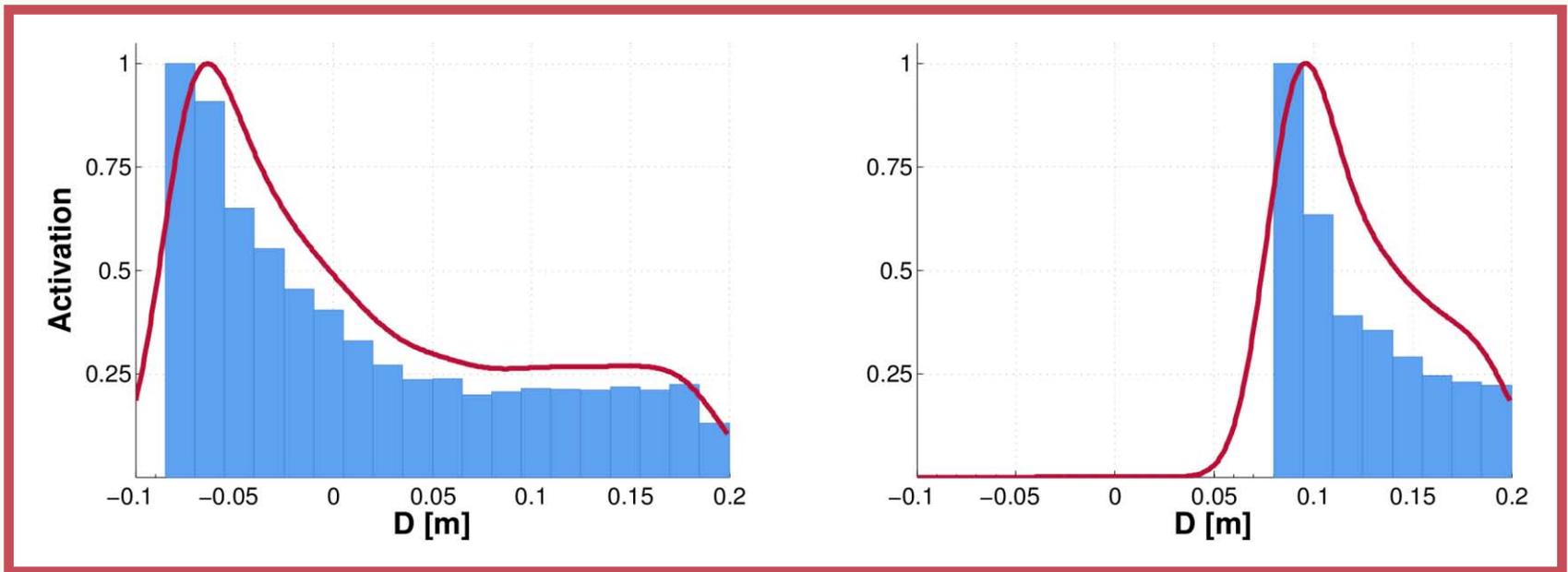
# Exp A - Single Taxel Model - Tuning of the parameters .



Courtesy of Alessandro Roncone and Matej Hoffman. Used with permission.  
Source: Roncone, Alessandro, Matej Hoffmann, Ugo Pattacini, and Giorgio Metta.  
"Learning peripersonal space representation through artificial skin for avoidance and reaching with whole body surface." In Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on, pp. 3366-3373. IEEE, 2015.

# Exp A - Single Taxel Model - Validation of the Model .

- On the real robot, object positions are subject to systematic errors / offsets
- The errors propagate up to the taxel, but the representation is able to account for them and compensate accordingly



Negative Offset

Positive Offset

Courtesy of Alessandro Roncone and Matej Hoffman. Used with permission.

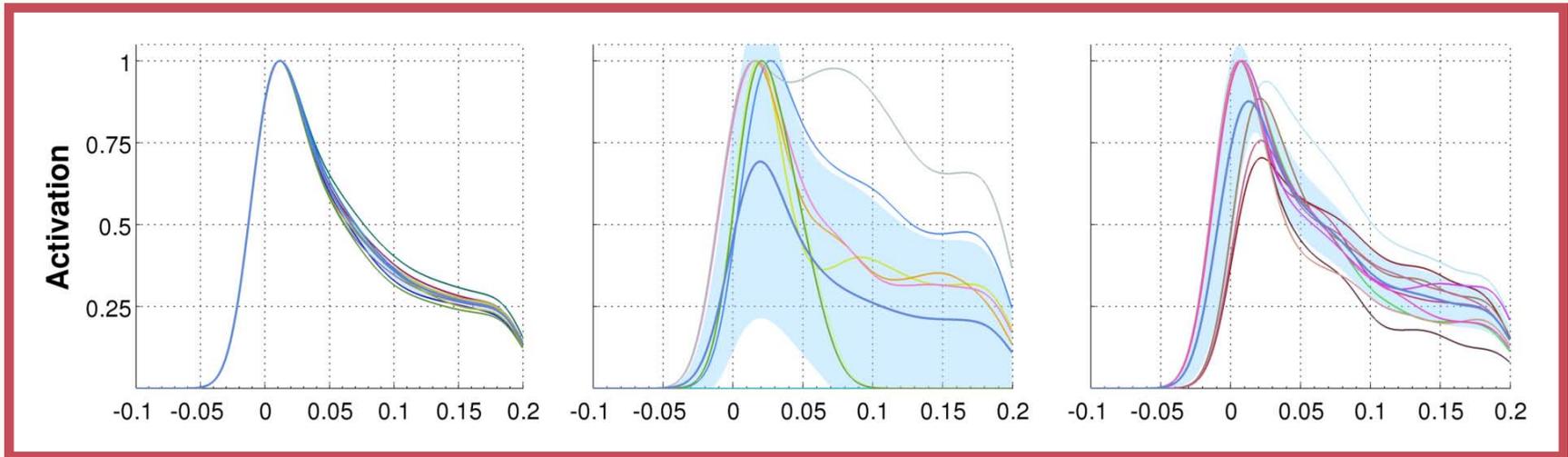
Source: Roncone, Alessandro, Matej Hoffmann, Ugo Pattacini, and Giorgio Metta. "Learning peripersonal space representation through artificial skin for avoidance and reaching with whole body surface." In Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on, pp. 3366-3373. IEEE, 2015.

# Exp A - Single Taxel Model - Validation of the Model .

**1000** events/trial,  
no noise

**10** events/trial,  
no noise

**100** events/trial,  
noise in the measurements

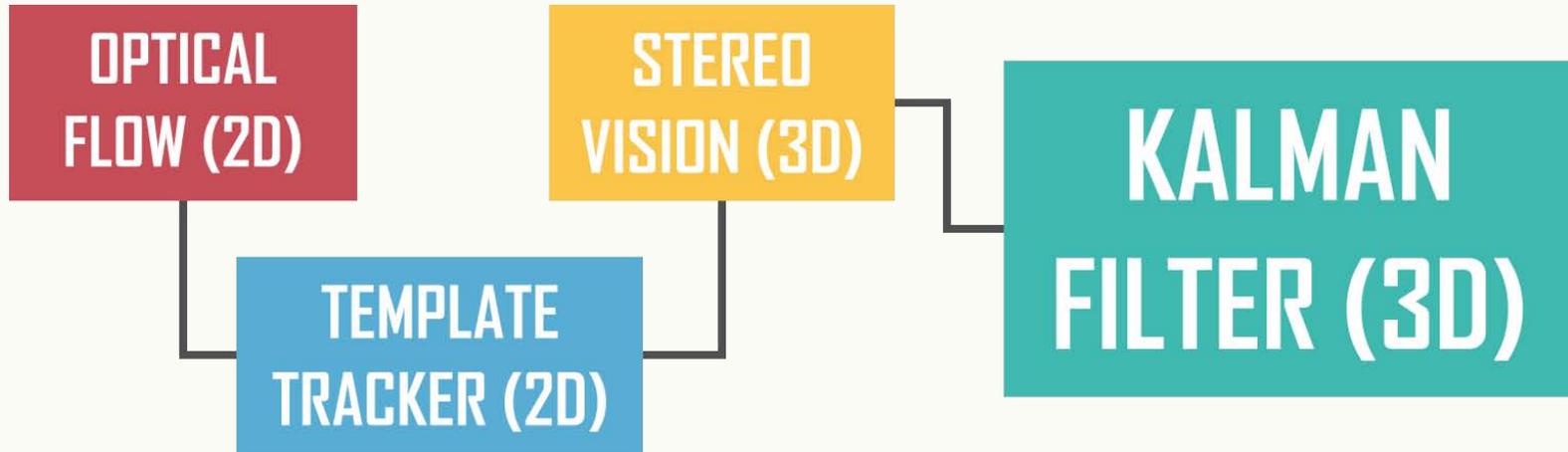


Courtesy of Alessandro Roncone and Matej Hoffman. Used with permission.

Source: Roncone, Alessandro, Matej Hoffmann, Ugo Pattacini, and Giorgio Metta. "Learning peripersonal space representation through artificial skin for avoidance and reaching with whole body surface." In Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on, pp. 3366-3373. IEEE, 2015.

- Convergence of the model during **long-term learning**
- **"One-shot" learning** is still meaningful (albeit noisy)
- With sufficient training, the representation converges even in **noisy** environments

# Exp B - 3D Tracking of arbitrary objects .



## 2D Optical Flow

[Ciliberto et al. 2011]

## 3D Stereo Vision

[Fanello et al. 2014]

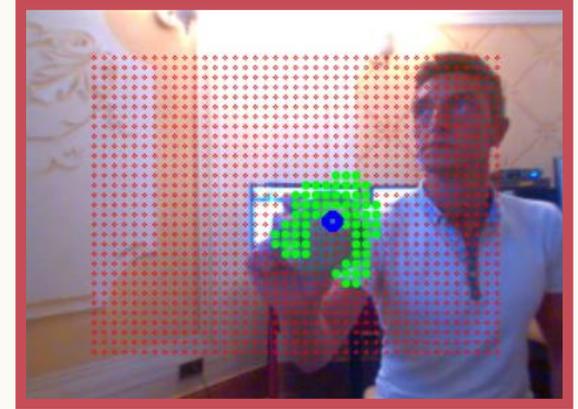
## 2D Particle Filter

[Tikhanoff et al. 2013]

## Kalman Filter

for robust 3D tracking

# Exp B - 3D Tracking of arbitrary objects .



Courtesy of Alessandro Roncone and Matej Hoffman. Used with permission.  
Source: Roncone, Alessandro, Matej Hoffmann, Ugo Pattacini, and Giorgio Metta. "Learning peripersonal space representation through artificial skin for avoidance and reaching with whole body surface." In Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on, pp. 3366-3373. IEEE, 2015.

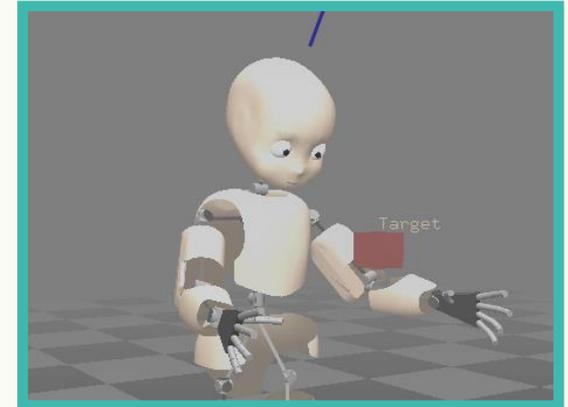
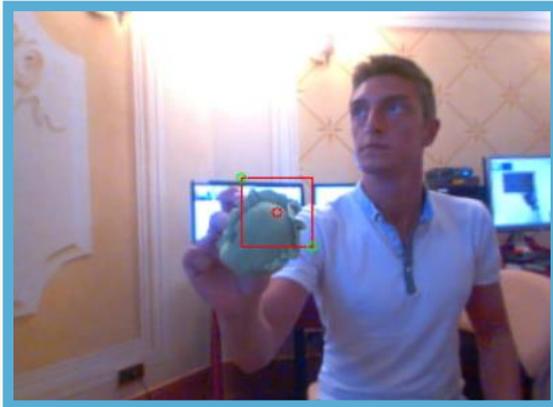
**OPTICAL  
FLOW (2D)**

**STEREO  
VISION (3D)**

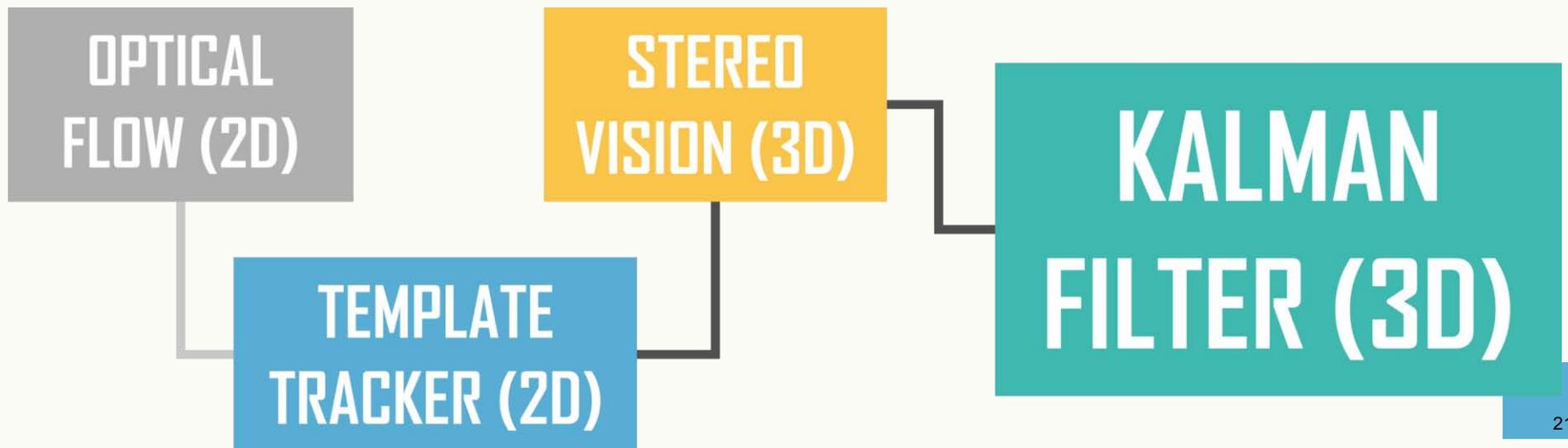
**TEMPLATE  
TRACKER (2D)**

**KALMAN  
FILTER (3D)**

# Exp B - 3D Tracking of arbitrary objects .



Courtesy of Alessandro Roncone and Matej Hoffman. Used with permission.  
Source: Roncone, Alessandro, Matej Hoffman, Ugo Pattacini, and Giorgio Metta. "Learning peripersonal space representation through artificial skin for avoidance and reaching with whole body surface." In Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on, pp. 3366-3373. IEEE, 2015.

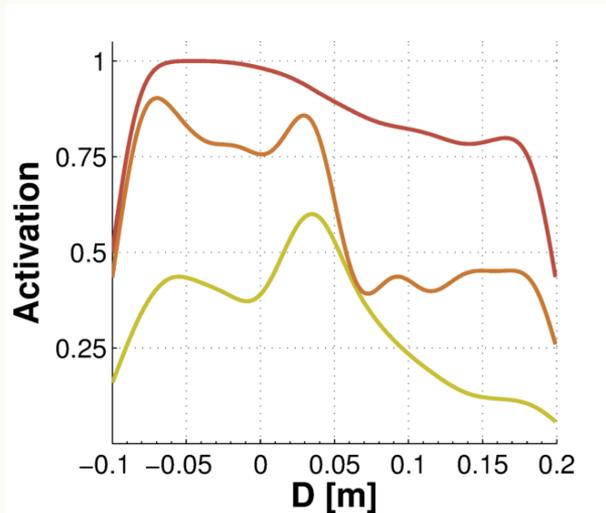




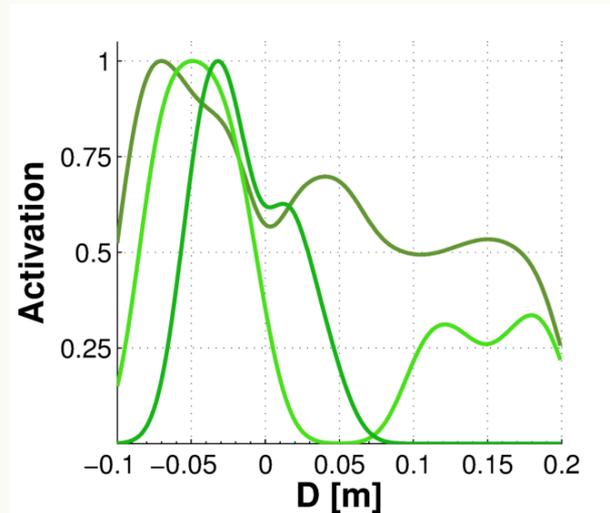
# Video Time .

# Exp B - Tactile-Visual learning [ext. objects] .

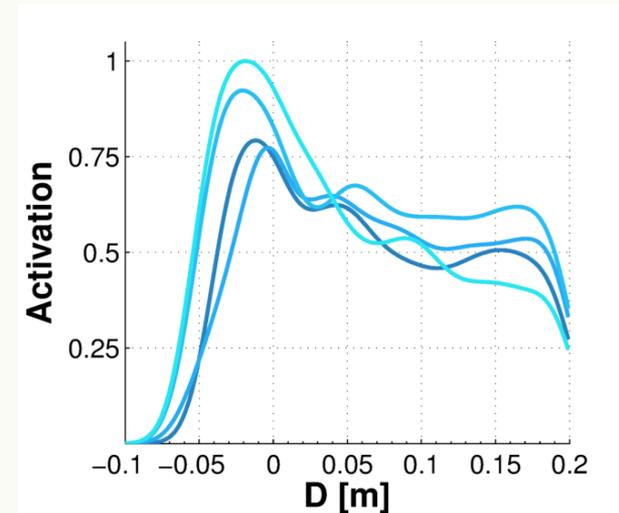
## Left Forearm [int]



## Left Forearm [ext]



## Right Hand



Courtesy of Alessandro Roncone and Matej Hoffman. Used with permission.

Source: Roncone, Alessandro, Matej Hoffmann, Ugo Pattacini, and Giorgio Metta. "Learning peripersonal space representation through artificial skin for avoidance and reaching with whole body surface." In Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on, pp. 3366-3373. IEEE, 2015.

**126** iterations

**864** samples

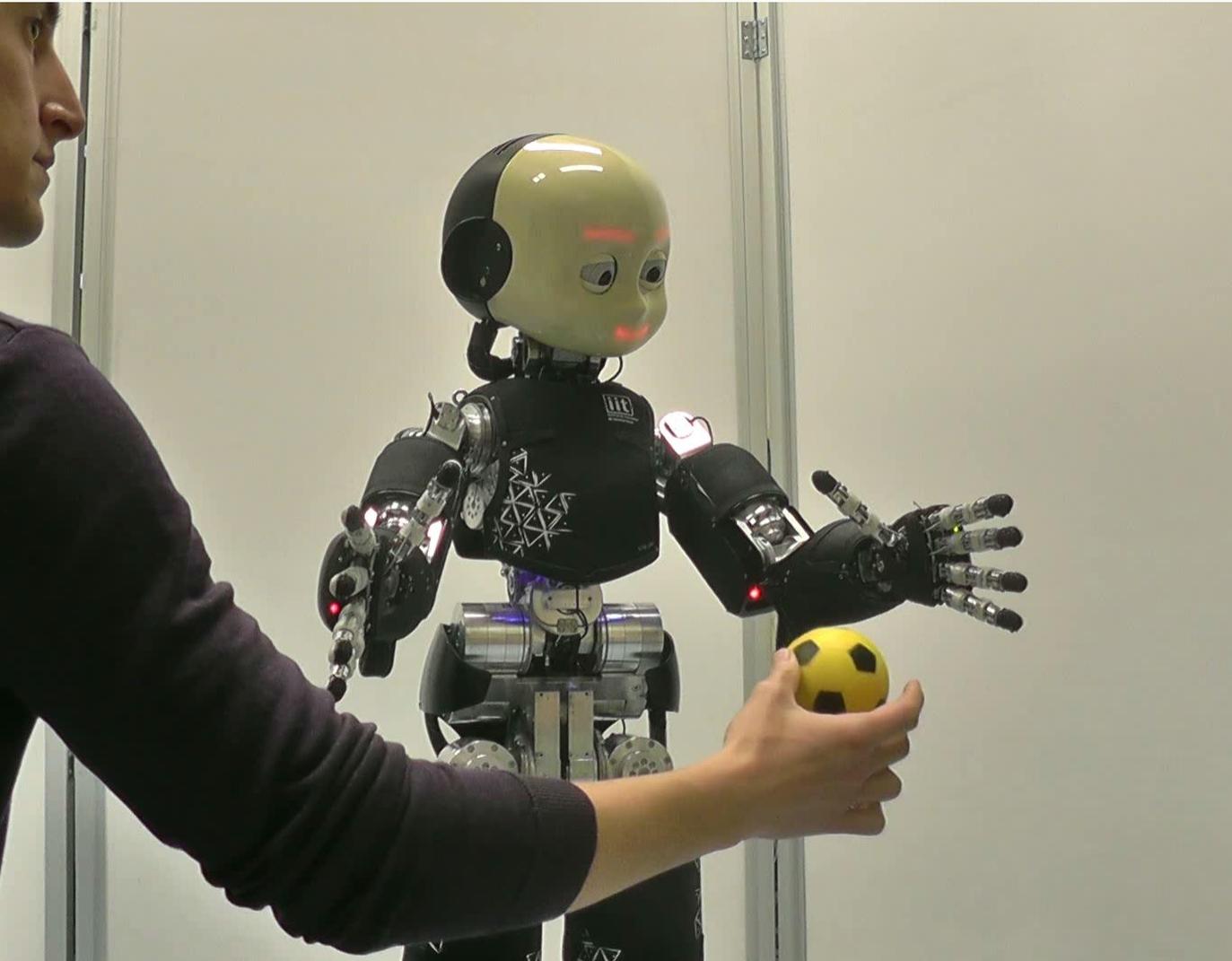
**76** iterations

**246** samples

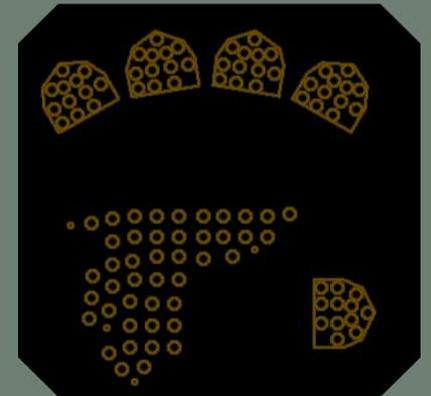
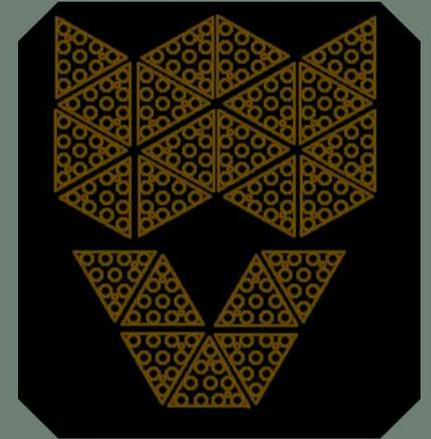
**138** iterations

**1916** samples

# Video Time .



## Left Forearm



## Right Hand

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**Applications of the visuo-tactile  
associations: AVOIDANCE and  
CATCHING with any body part**

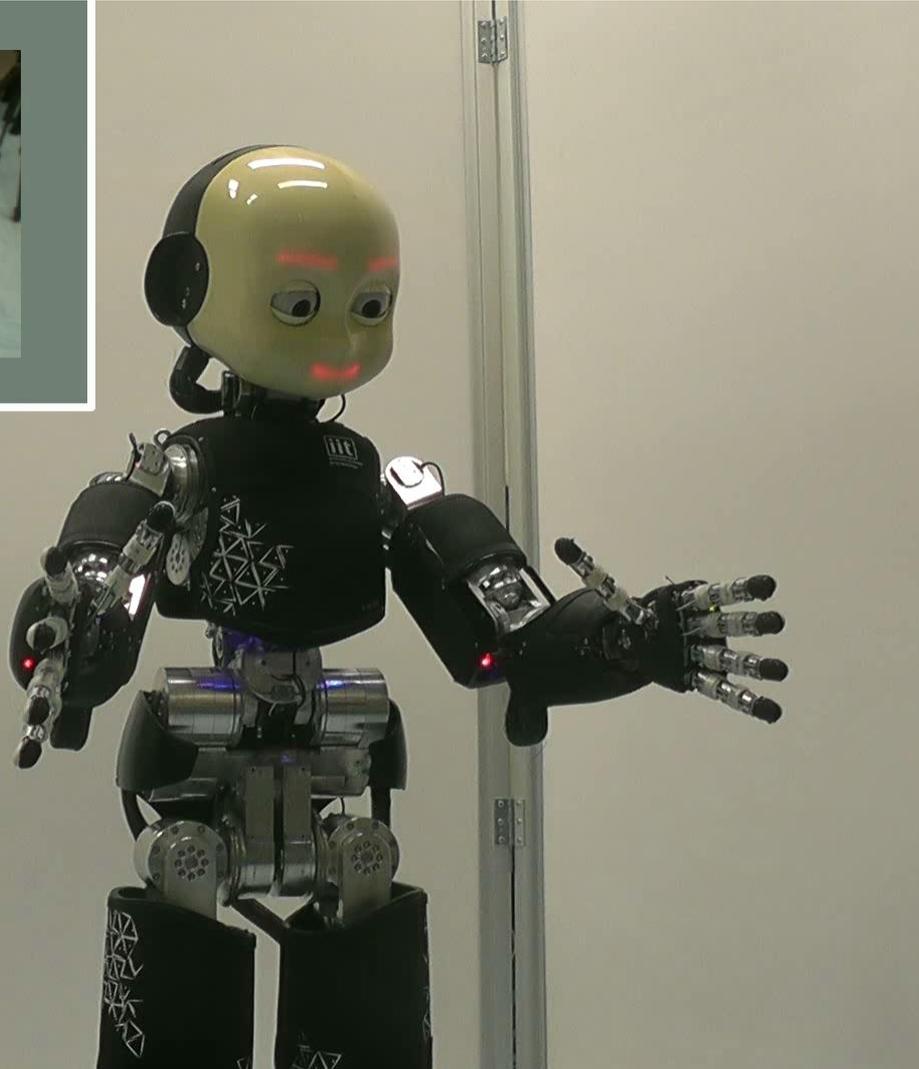
# Avoidance and Catching Controller .

## **Distributed control**

(i.e. avoidance and catching with any body part)

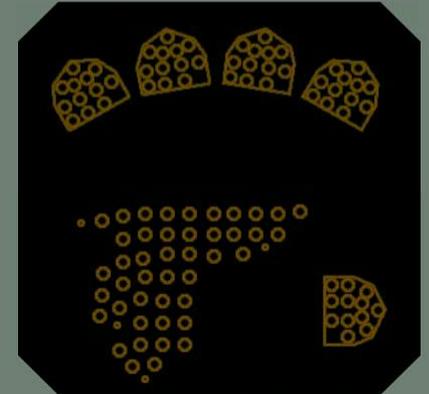
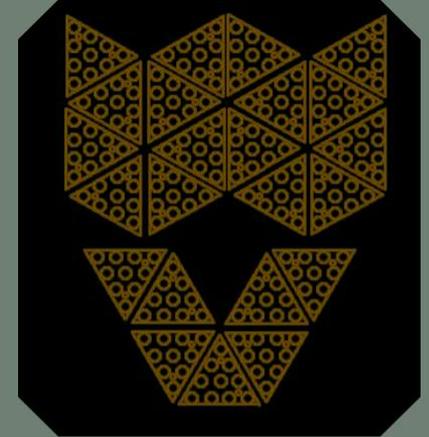
**Sensory based** guidance of the motor actions by means of the visuo-tactile associations

# Video Time - AVOIDANCE .



Avoidance

Left Forearm



Right Hand

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# Avoidance and Catching Controller .

## Distributed control

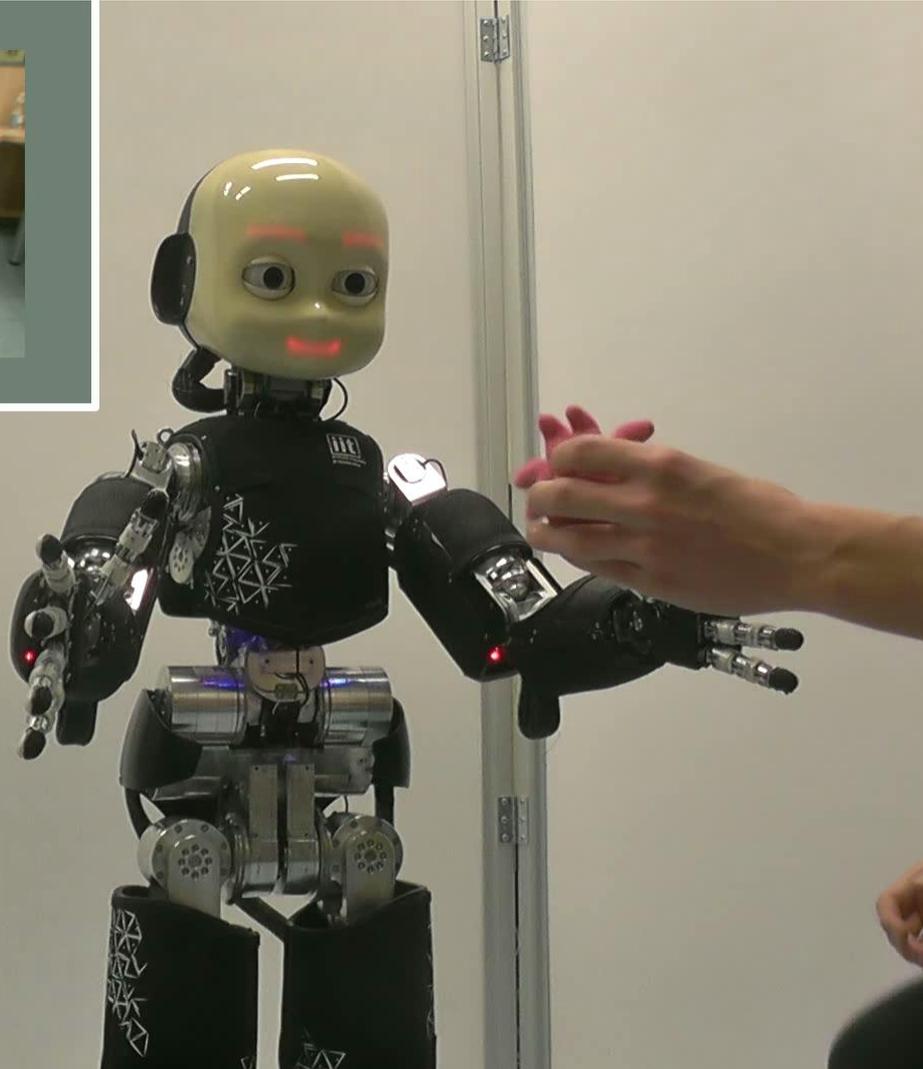
(i.e. avoidance and catching with any body part)

**Sensory based** guidance of

the motor actions by means of the visuo-tactile associations

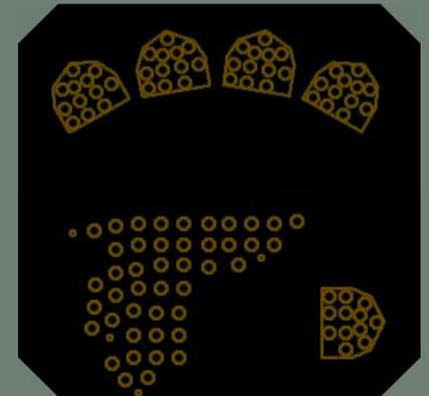
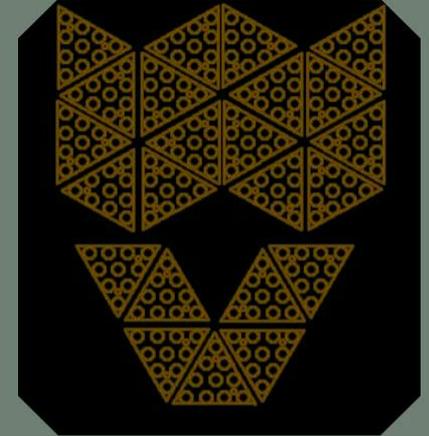
$$\mathbf{P}(t) = \frac{1}{k} \sum_{i=1}^k [\mathbf{a}_i(t) \cdot \mathbf{p}_i(t)]$$
$$\mathbf{N}(t) = \frac{1}{k} \sum_{i=1}^k [\mathbf{a}_i(t) \cdot \mathbf{n}_i(t)]$$

# Video Time - CATCHING .



Reaching

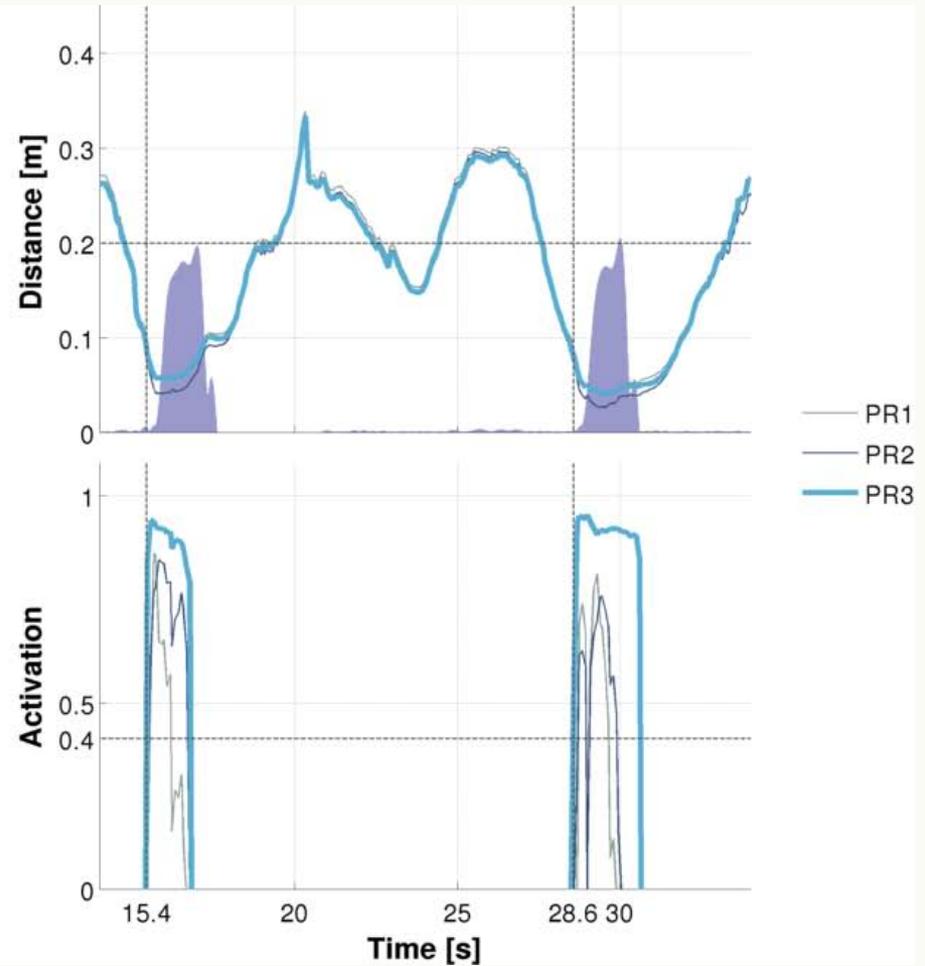
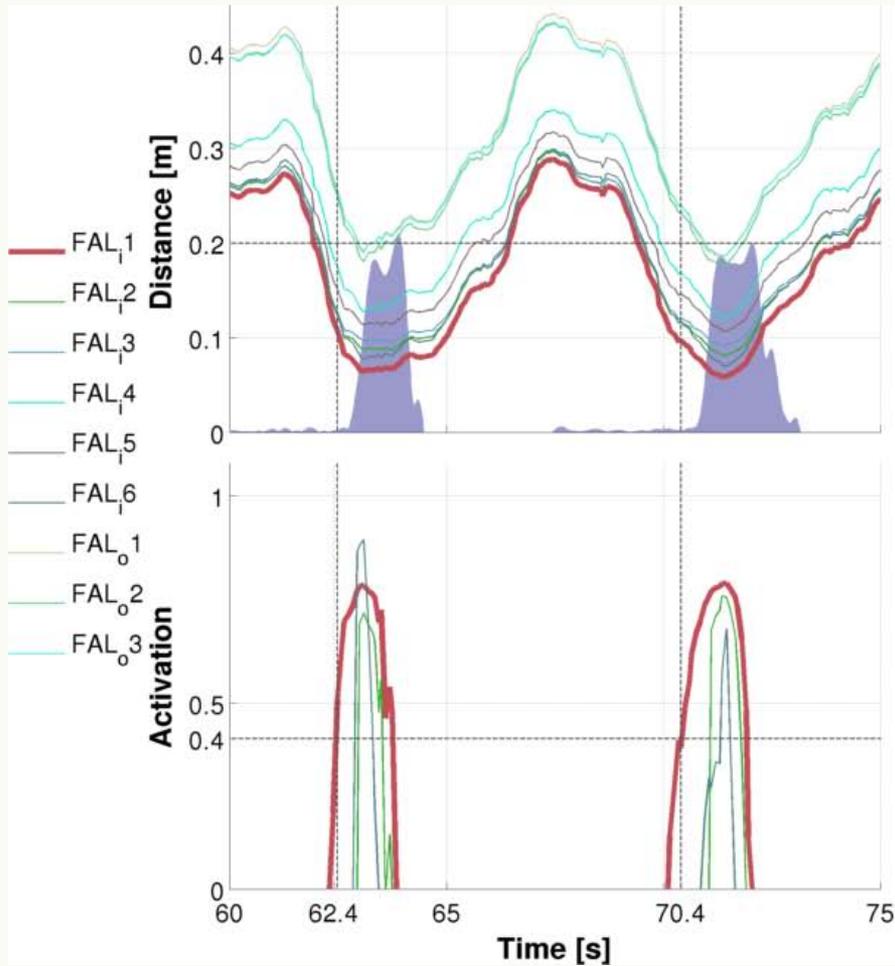
Left Forearm



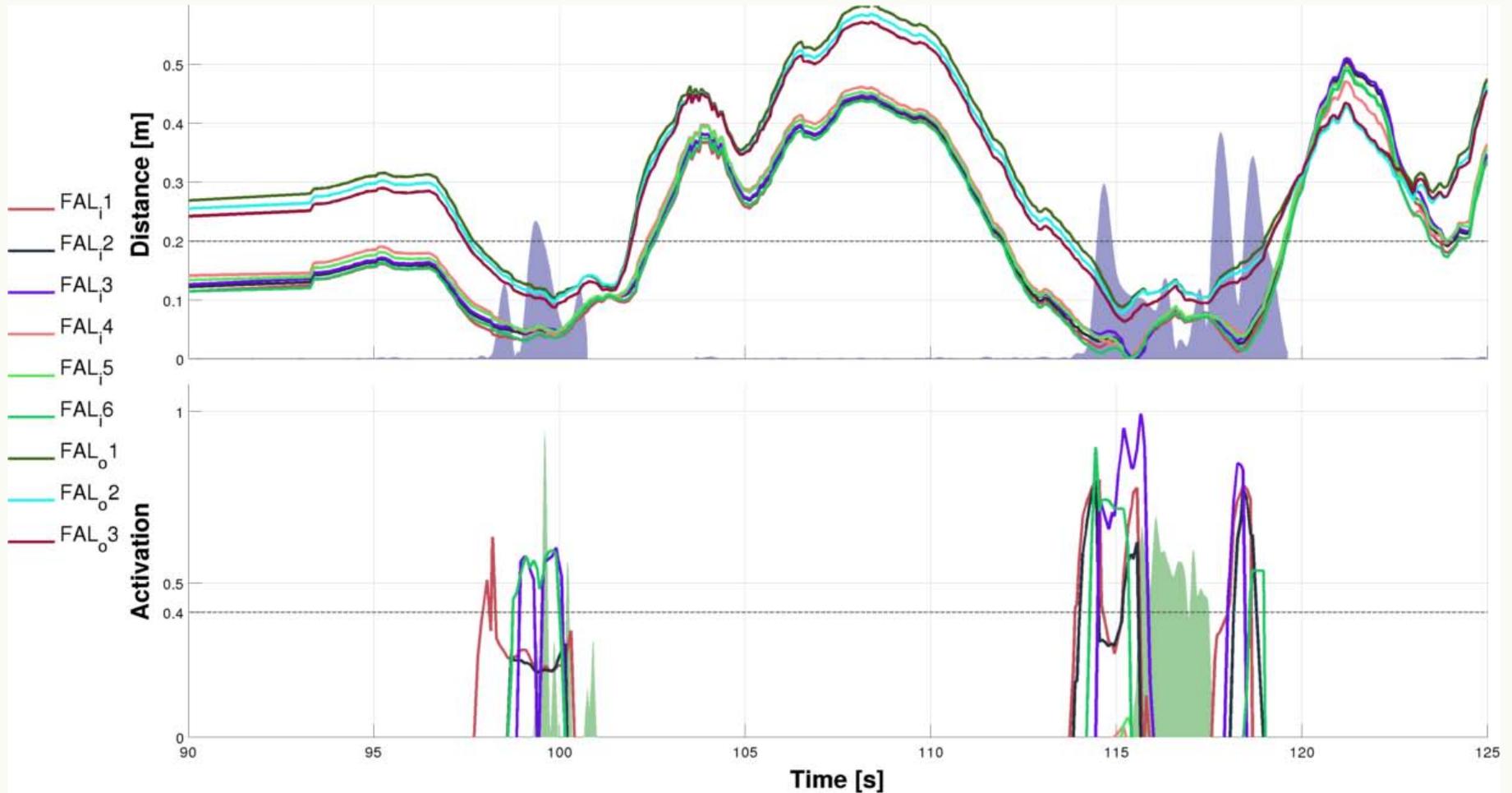
Right Hand

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# Avoidance Experiments



# Catching Experiments





# Conclusions

# Contribution and Discussion .

Distributed representation of the space around the body able to learn tactile visual associations and prior-to-contact activations

Learning is fast, proceeds in parallel for the whole body, and is incremental

Learning is adapted from experience, thus automatically compensating for errors in the model

A close-up photograph of a robot's face, likely a humanoid robot. The face is light-colored and has two large, prominent eyes with black pupils and white sclera. The robot's expression is neutral. The background is a plain, light color.

**THANK YOU !**

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Tomaso Poggio and Gabriel Kreiman

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