Action-outcome contingencies as the engine of open-ended learning: computational models and developmental experiments

Gianluca Baldassarre [1], Francesco Mannella [1], Vieri G. Santucci [1], Eszter Somogyi [2], Lisa Jacquey [3], Mollie Hamilton [3], and J. Kevin O'Regan [3]

[1] Institute of Cognitive Sciences and Technologies, National Research Council, Rome, Italy

[2] Department of Psychology, University of Portsmouth, Portsmouth, U.K.

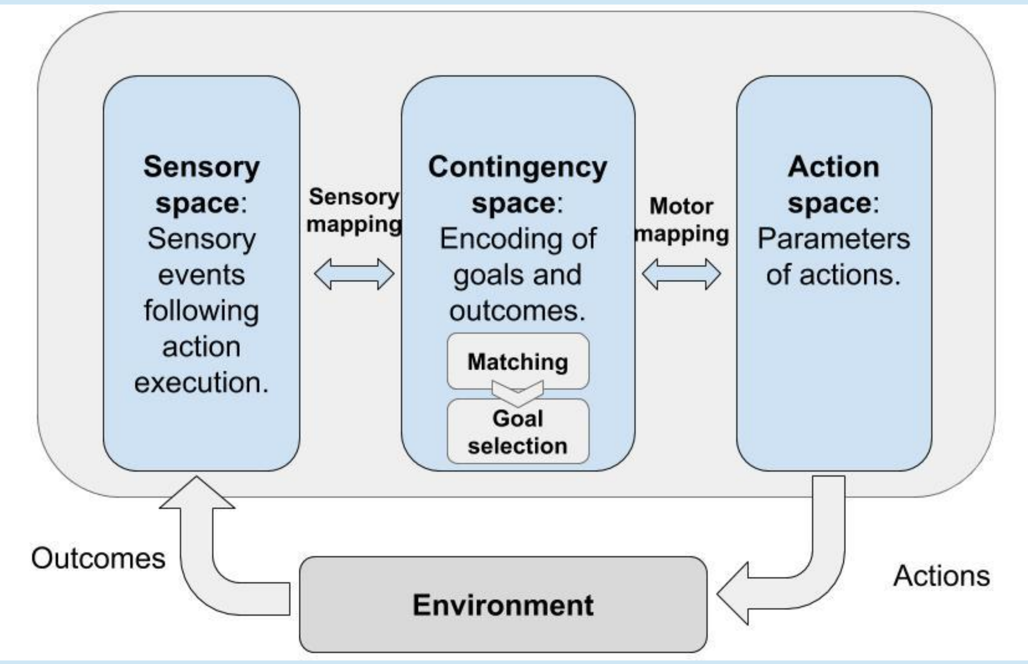
[3] Laboratoire Psychologie de la Perception, CNRS UMR 8242, Université Paris Descartes, Paris, France

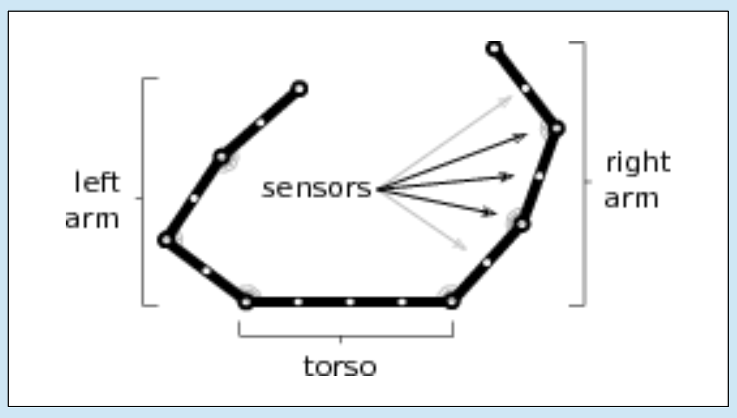
ICDL-EpiRob2018
Tokyo, Japan
16-20 September 2018

- **Research aim:** Understanding the development of sensorimotor body maps in humans and robots
- **Focus and objectives:** Open-ended learning allows humans and robots to autonomously acquire new skills that later allow them to achieve desirable effects in the environment (`goals'). Empirical evidence from developmental psychology suggests that action-outcome contingencies can drive open-ended learning. This research aims to develop a detailed theory and computational/empirical evidence on these processes.
- **Hypothesis:**
  - Detection of action-outcome contingencies has a pivotal role in building a map between one's actions and the related sensory events
  - Mapping both actions and outcomes into a common domain is needed to collect robust statistics of the interplay between sensory and motor domains
  - Action-outcome contingencies are reflected by the matching between the goal generating the action and the action outcome as internally represented in a common domain
  - Internal contingencies support goal generation and also guide both sensory and motor learning processes so that progressively they become coupled
- **Methodology:**
  A. **Specifying the hypothesis into a theoretical framework** highlighting the key processes needed to support contingency-based open-ended learning
  B. **Creating and testing** computational models operationalising the framework and able to produce predictions testable in empirical experiments
  C. **Designing and running** developmental psychology experiments to test the predictions of the models

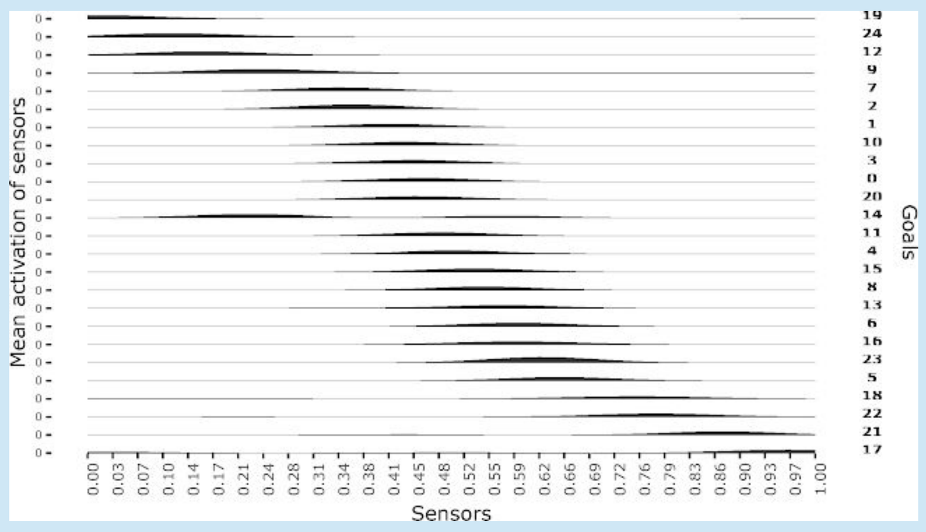
Framework, computational model, and test results

- **Goal selection:** Goals are generated with a probability distribution over the contingency space, based on statistics of the matching events
- **Motor mapping**: Learned mapping between the goals and the motor trajectories in the joint space (current model: echo-state network)
- **Perception:** Sensory detection of the action effects (outcomes)
- **Sensory mapping**: Learned mapping between the sensory space and the contingency space (current model: SOM - Self-Organizing Map).
- **Matching:** distance between the goal and the sensory event within the contingency space (current model: binary match/mismatch)

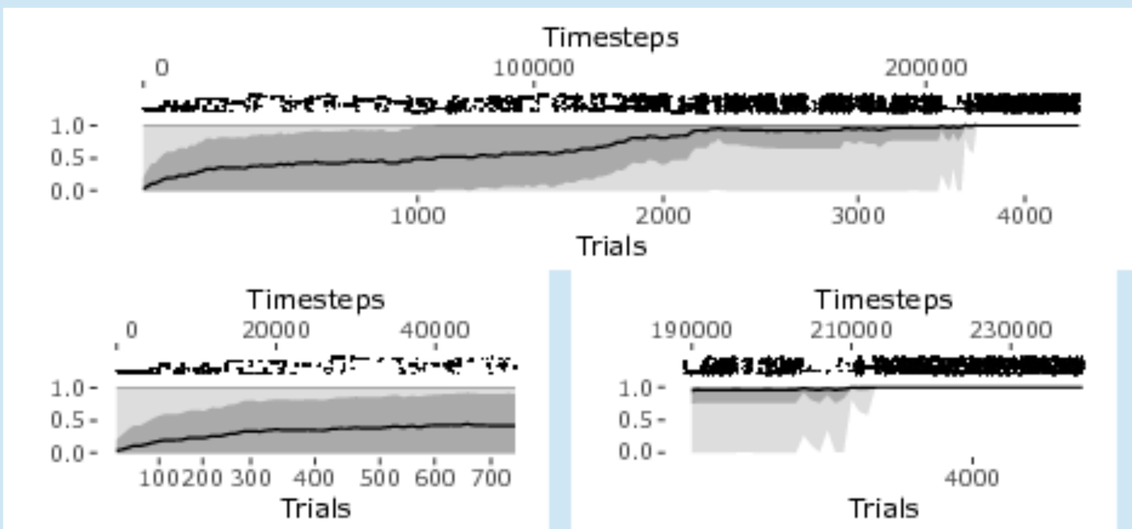




The simulated 2D kinematic body of the agent:
- 2 3DoF arms
- 30 touch sensors



Activation (y-axis) of the 30 touch sensors (x-axis) corresponding to the outcomes encoded by the 25 units of the SOM (y-axis rows)

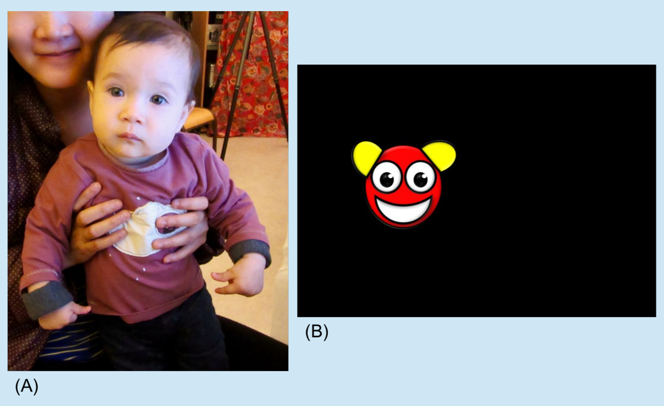


The competence over the 25 goals increases until equilibrium (100% probability of reaching an outcome that is linked to a selected goal). Raster plots on the top indicate the matching events during time. The black line indicates the mean probability of success over all 25 goals. Standard deviation (dark grey) and min-max boundaries (light grey) are also shown.

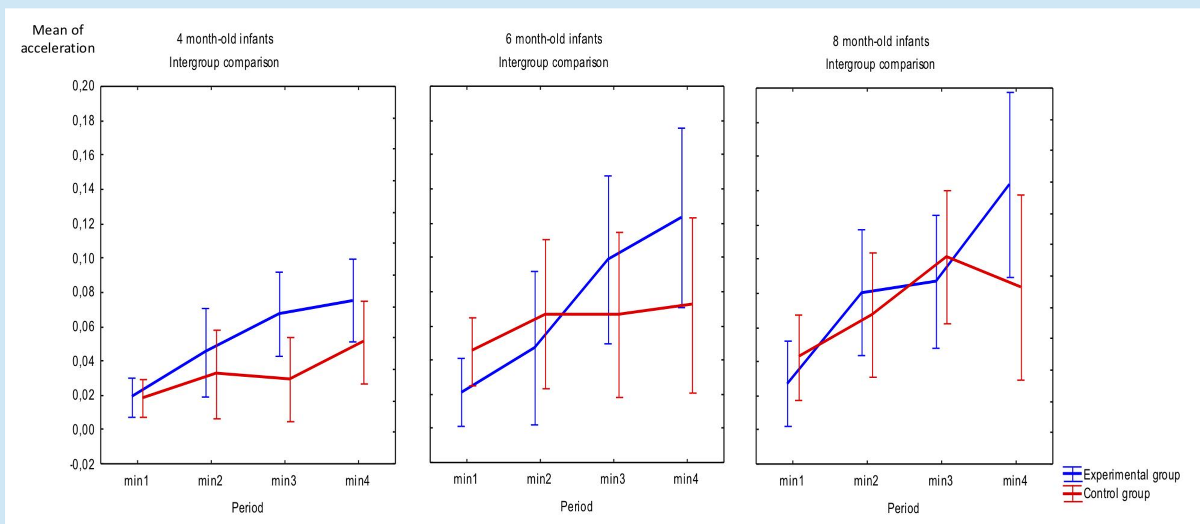
Psychology Experiments

The Contingencies experiment

- Experimental group: babies (aged 4, 6 and 8 months) were equipped with bluetooth-enabled bracelets on their wrists that generated a bell sound coupled with movement of a smiley face on the screen when the infant moved one of its arms.
- Control group: babies were given audio and visual stimulation equivalent to the Experimental group, but that was independent of their movements.



(A) An 8-month-old infant wearing a bracelet around each wrist. (B) Screenshot of the visual stimulus used.



Activity of infants' arms (measured in multiples of earth's acceleration *g* over the 4 minutes of the experiment, for the contingent and non-contingent groups at 4, 6 and 8 months of age. The error bars represent one standard error on either side of the mean. An ANOVA shows that the slopes of the blue (contingent) lines differ significantly from those of the red (non-contingent) lines for the 4 and 6 month old infants.

The "Buzzer" experiment

- *Tactile stimulation condition:* infants received a tactile stimulation session in which buzzers were attached for about 30 seconds to the infant's hands, feet, knees and abdomen, one body part at a time.
- *Control condition:* infants received identical sessions with the only difference that the experimenter did not actually attach the buzzers to their bodies, but only approached the infants with the buzzer.
- *Procedure*: weekly sessions from 4 to 7 months of age. Sessions took place during home visits.

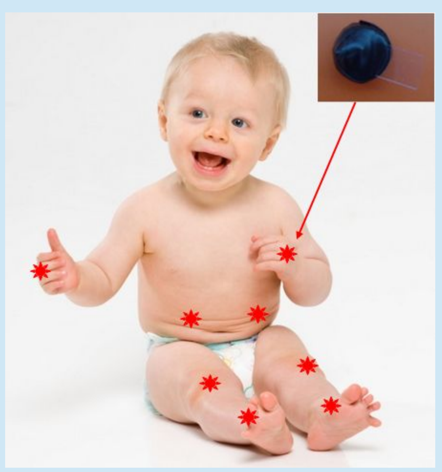
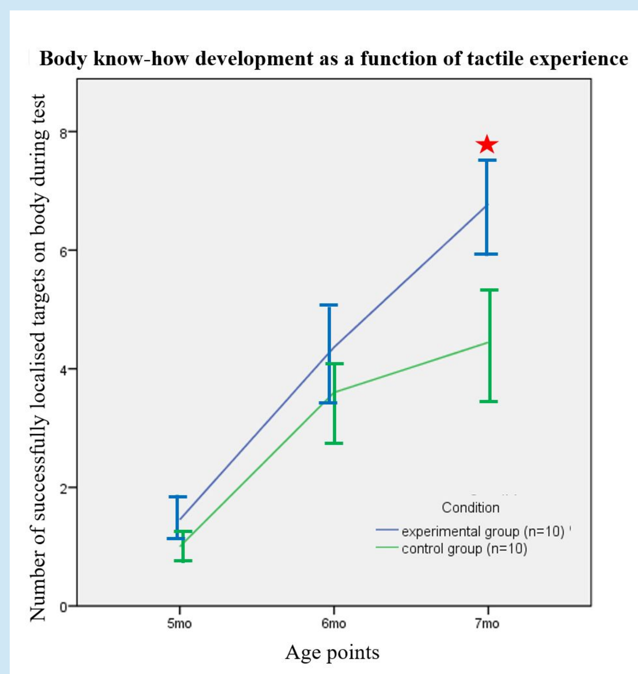


Illustration of the buzzer and the locations stimulated in the 'tactile stimulation' group.

Ability of infants to reach for buzzers for the experimental (who received weekly tactile stimulation with the buzzer) and control groups at 5, 6 and 7 months of age (n=10 in each group). The error bars represent one standard error on either side of the mean.



Conclusions

We presented a hypothesis on contingency-based mechanisms possibly underlying open-ended learning of multiple goals and actions. The hypothesis was implemented for the case of the sensorimotor development of the capacity to touch own body in infants. The theoretical framework and computational model give an operational explanation of the role of contingencies in driving sensorimotor development. The experiments on infants show, in accordance with the model, that contingencies indeed have a main role in the behaviour of 4-8 month infants and that the amount of sensory experience determines the level of precision in the acquisition of one's body map.

References

Santucci, V. G.; Baldassarre, G., Mirolli, M. (2016). GRAIL: a goal-discovering robotic architecture for intrinsically-motivated learning. *IEEE Transactions on Cognitive and Developmental Systems*, 8, 214-231.
Mannella, F., Santucci, V. G., Eszter, S., Jacquey, L., O'Regan, K. J., Baldassarre, G. (2018). Know your body through intrinsic goals. *Frontiers in neurorobotics*, 12(30), E1-17.
Watanabe, H., & Taga, G. (2006). General to specific development of movement patterns and memory for contingency between actions and events in young infants. *Infant Behavior and Development*, 29(3), 402-422.