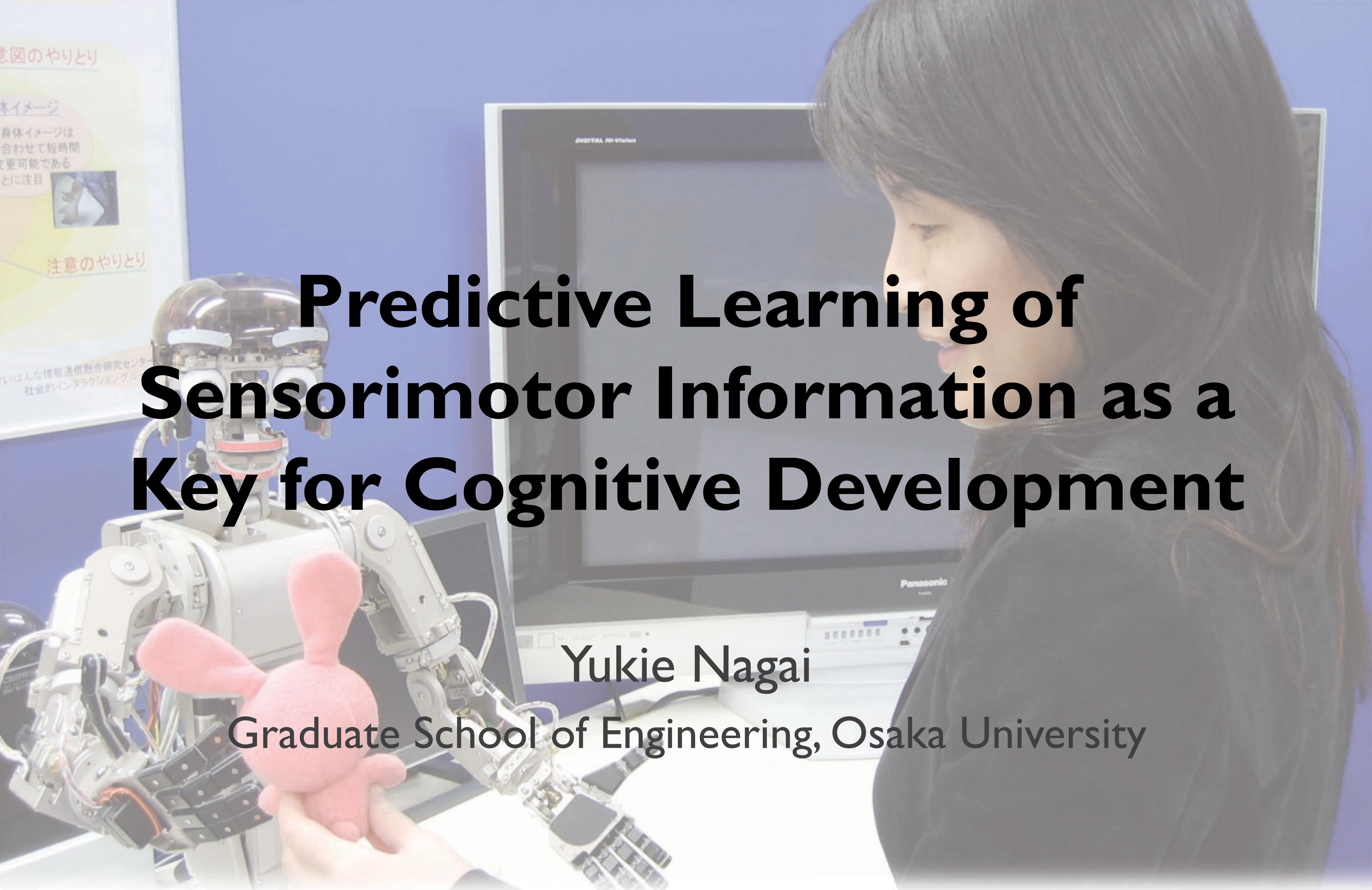


Predictive Learning of Sensorimotor Information as a Key for Cognitive Development

Yukie Nagai
Graduate School of Engineering, Osaka University

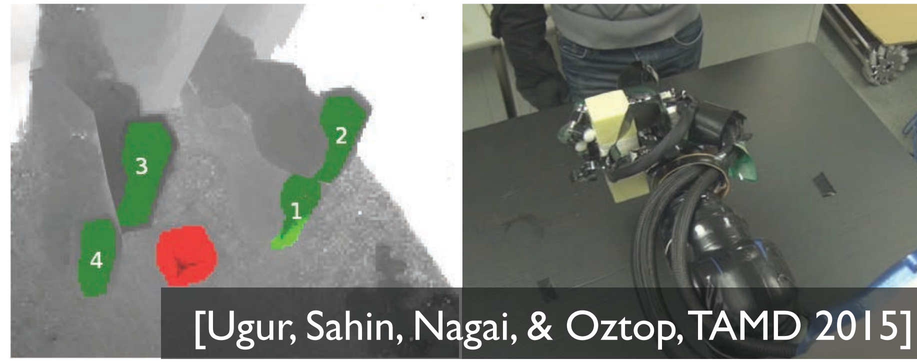
Cognitive
Neuroscience
Robotics

Humanoids 2015 WS on Towards Intelligent Social Robots – Current Advances in Cognitive Robotics
Seoul, Korea, November 3, 2015

Cognitive Development in Human Infants

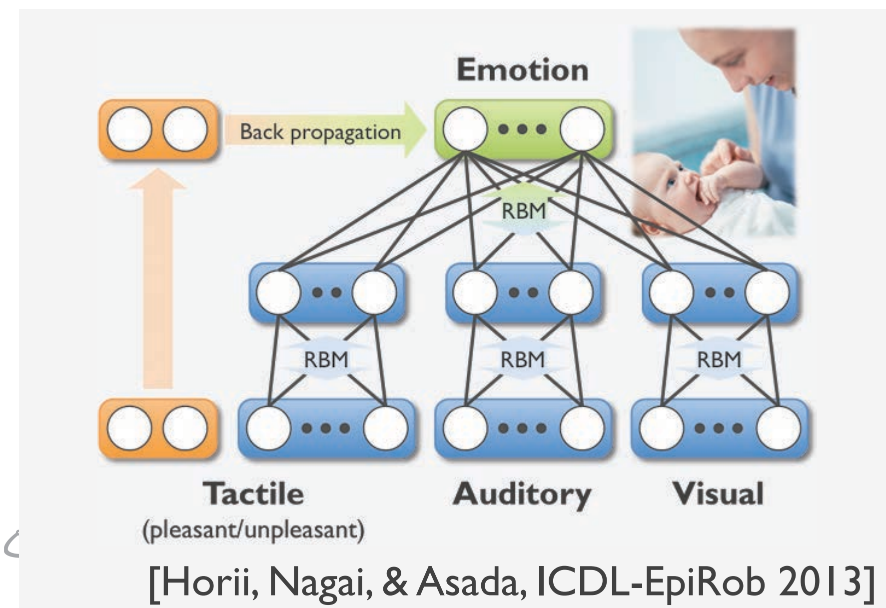
Cognitive Development in Robots

[Nagai, Kawai, & Asada, ICDL-EpiRob 2011;
Kawai, Nagai, & Asada, IROS 2012]

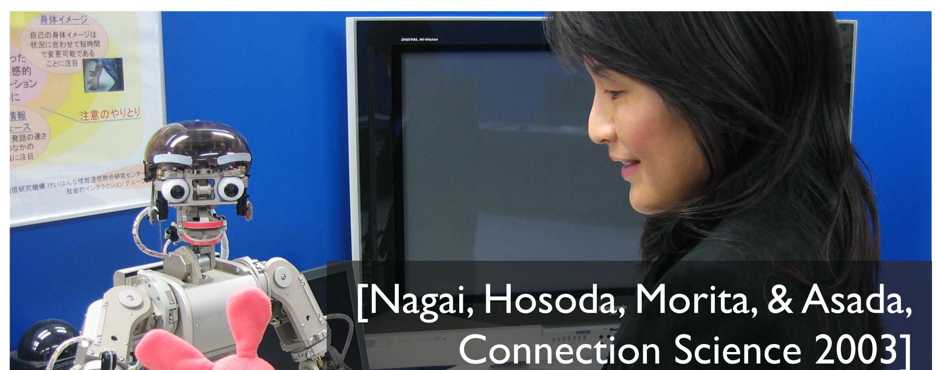


[Ugur, Sahin, Nagai, & Oztop, TAMD 2015]

[Nagai, Nakatani, & Asada, EpiRob 2010]

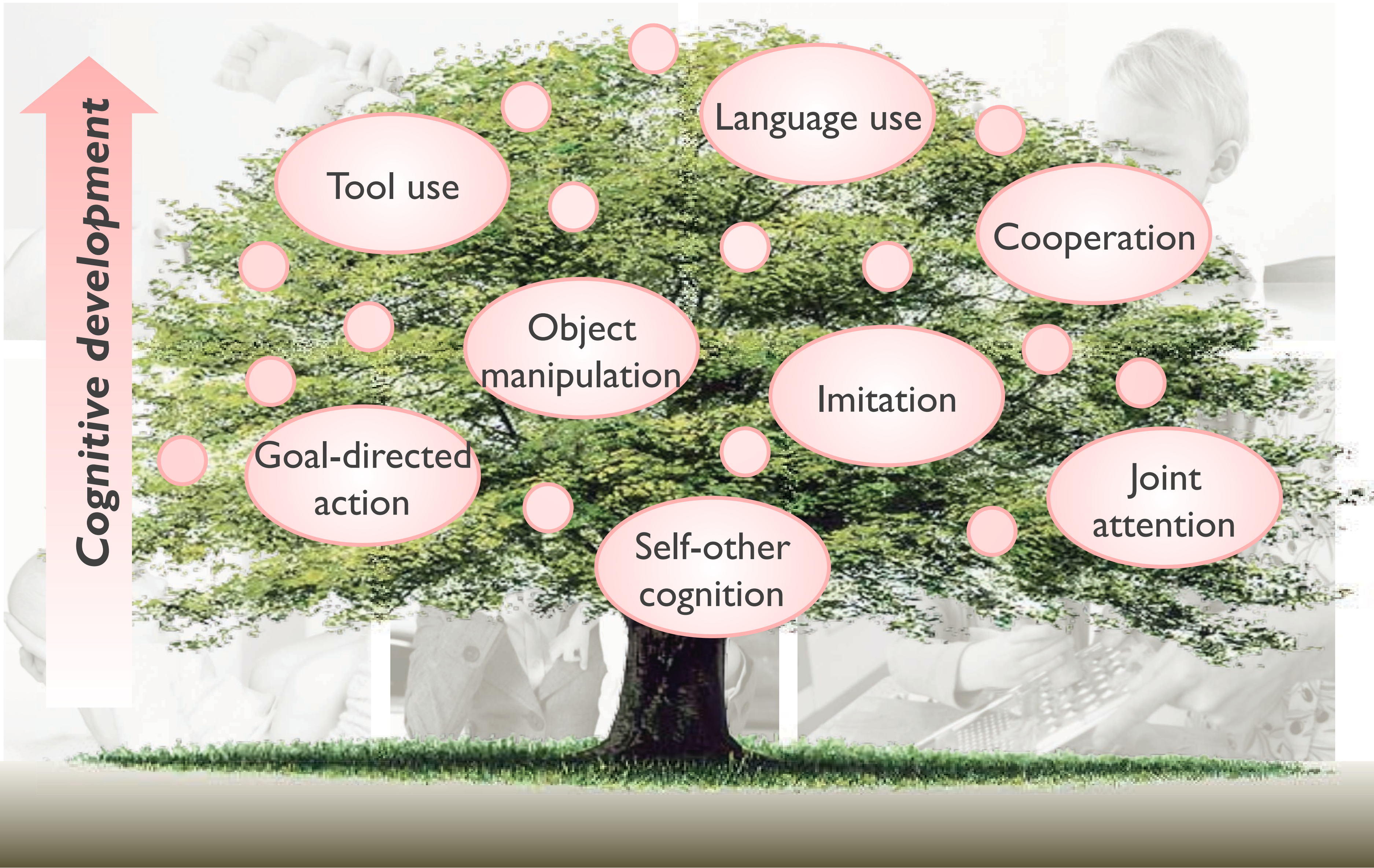


[Horii, Nagai, & Asada, ICDL-EpiRob 2013]



[Nagai, Hosoda, Morita, & Asada,
Connection Science 2003]

Development as a Continuous Process



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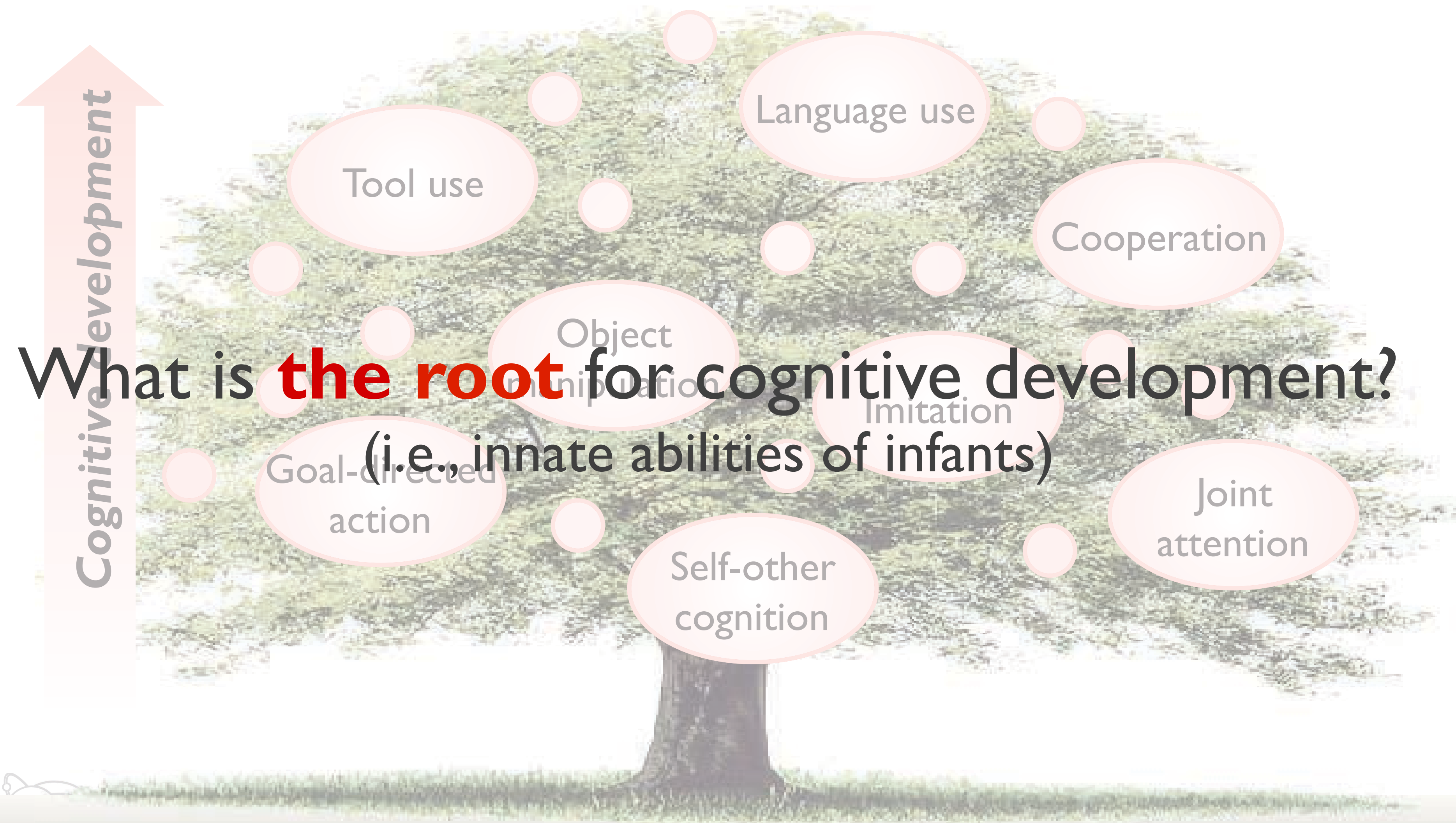
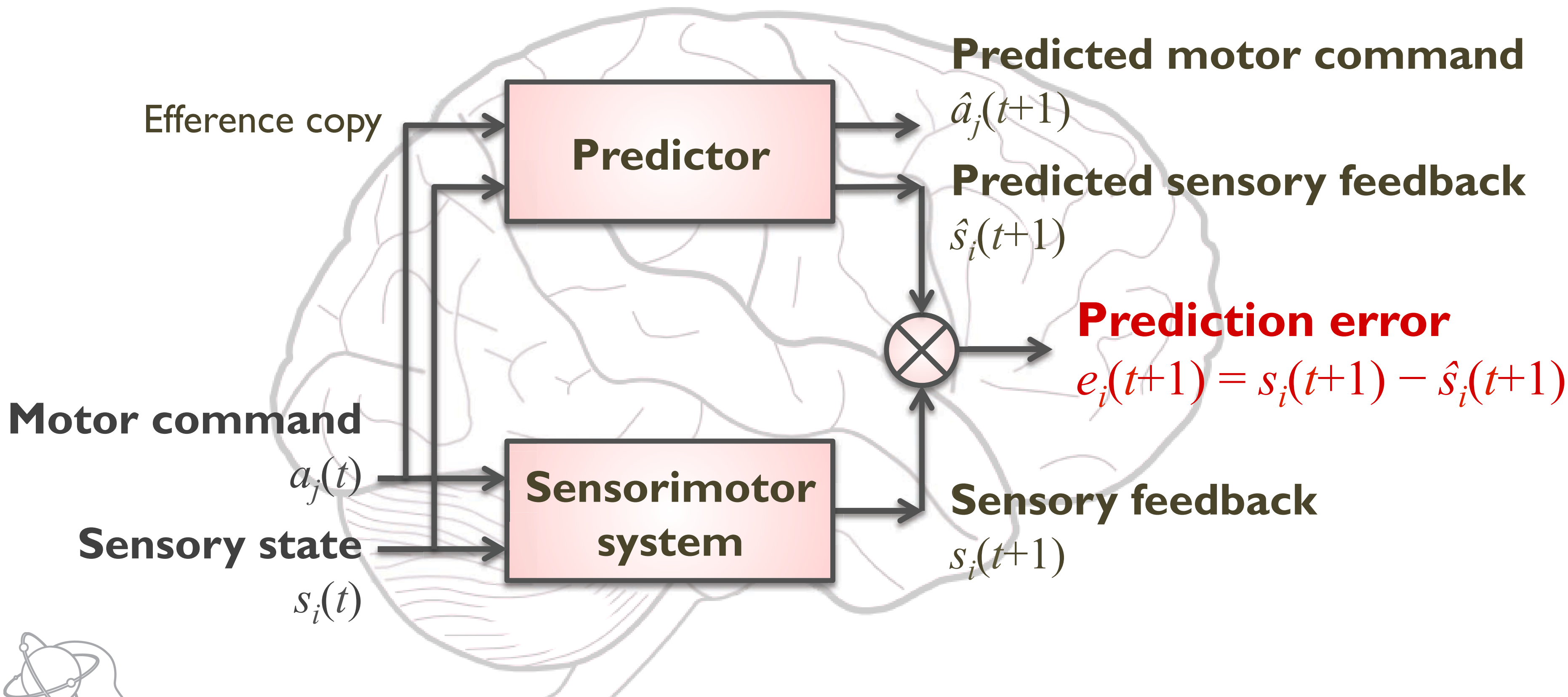


What is **the root** for cognitive development?

(i.e., innate abilities of infants)

Our Theory [Nagai & Asada, 2015]

Predictive learning of sensorimotor information (i.e., minimizing prediction error $e_i(t+1)$) leads to cognitive development.



(Modified from [Blakemore et al., 1999])

Our Theory [Nagai & Asada, 2015]

Predictive learning of sensorimotor information (i.e., minimizing prediction error $e_i(t+1)$) leads to cognitive development.

(1) *Update the predictor* through sensorimotor experiences

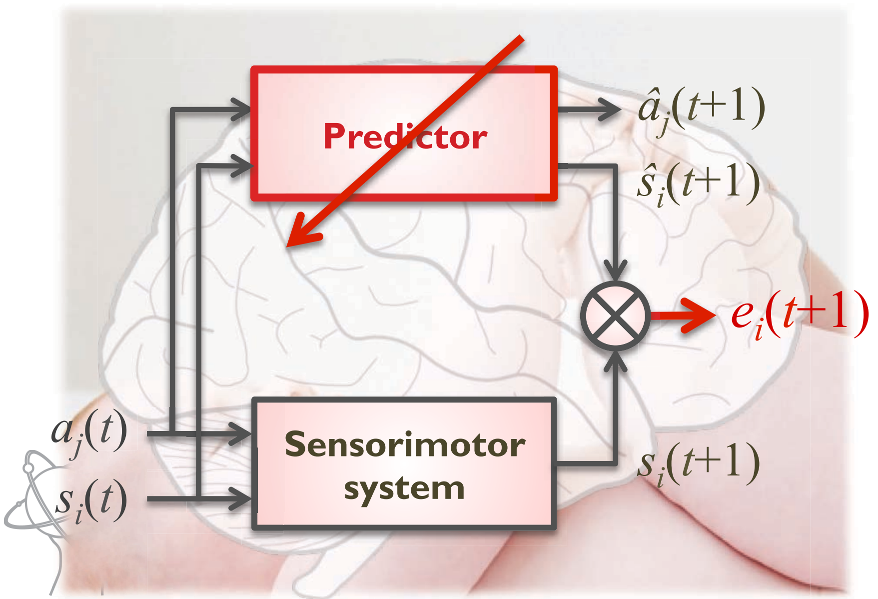
→ Self-other cognition

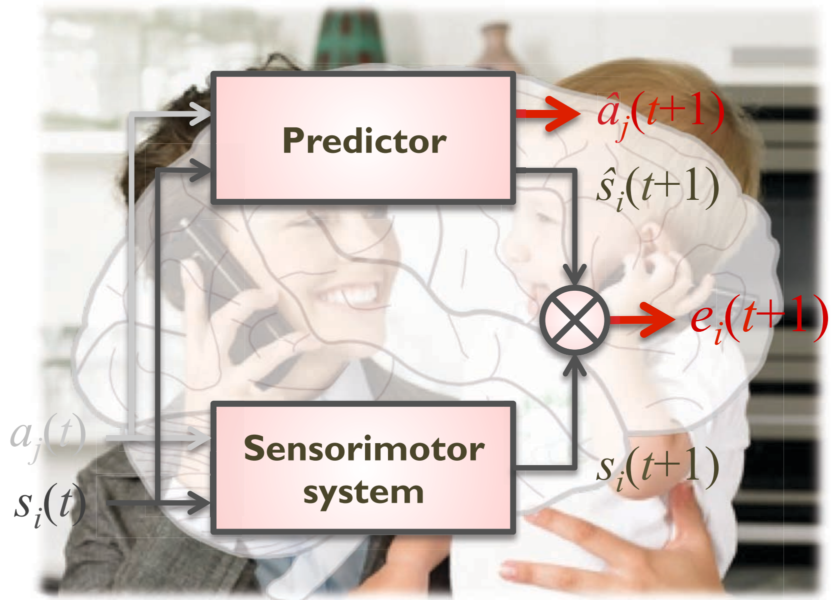
→ Goal-directed action, etc.

(2) *Execute a predicted action* in response to others' action

→ Imitation

→ Prosocial behavior, etc.





Increasing Interest in Predictive Learning

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B

Phil. Trans. R. Soc. B (2009) **364**, 1211–1221
doi:10.1098/rstb.2008.0300

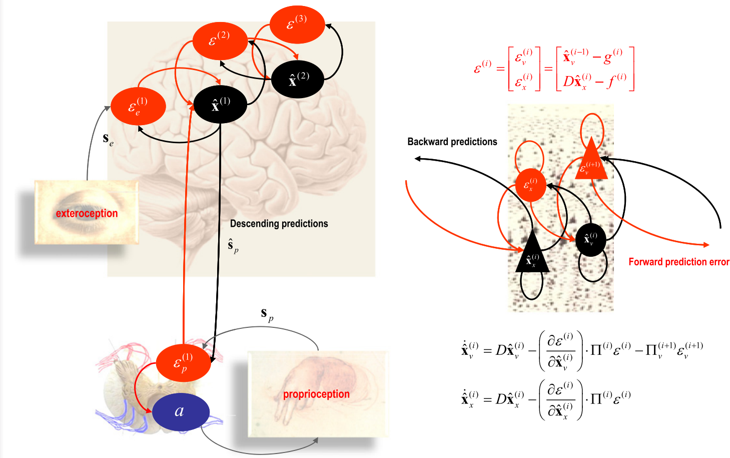
Predictive coding under the free-energy principle

Karl Friston* and **Stefan Kiebel**

The Wellcome Trust Centre of Neuroimaging, Institute of Neurology, University College London, Queen Square, London WC1N 3BG, UK

This paper considers prediction and perceptual categorization as an inference problem that is solved by the brain. We assume that the brain models the world as a hierarchy or cascade of dynamical systems that encode causal structure in the sensorium. Perception is equated with the optimization or inversion of these internal models, to explain sensory data. Given a model of how sensory data are generated, we can invoke a generic approach to model inversion, based on a free energy bound on the model's evidence. The ensuing free-energy formulation furnishes equations that prescribe the process of recognition, i.e. the dynamics of neuronal activity that represent the causes of sensory input. Here, we focus on a very general model, whose hierarchical and dynamical structure enables simulated brains to recognize and predict trajectories or sequences of sensory states. We first review hierarchical dynamical models and their inversion. We then show that the brain has the necessary infrastructure to implement this inversion and illustrate this point using synthetic birds that can recognize and categorize birdsongs.

Keywords: generative models; predictive coding; hierarchical; birdsong



Nature Reviews Neuroscience | AOP, published online 13 January 2010; doi:10.1038/nrn2787

REVIEWS

The free-energy principle: a unified brain theory?

Karl Friston

Abstract | A free-energy principle has been proposed recently that accounts for action, perception and learning. This Review looks at some key brain theories in the biological (for example, neural Darwinism) and physical (for example, information theory and optimal control theory) sciences from the free-energy perspective. Crucially, one key theme runs through each of these theories — optimization. Furthermore, if we look closely at what is optimized, the same quantity keeps emerging, namely value (expected reward, expected utility) or its complement, surprise (prediction error, expected cost). This is the quantity that is optimized under the free-energy principle, which suggests that several global brain theories might be unified within a free-energy framework.

Cogn Process (2007) 8:159–166
DOI 10.1007/s10339-007-0170-2

REVIEW

Predictive coding: an account of the mirror neuron system

James M. Kilner · Karl J. Friston · Chris D. Frith

Received: 21 February 2007 / Revised: 19 March 2007 / Accepted: 21 March 2007 / Published online: 12 April 2007

Abstract Is it possible to understand the intentions of other people by simply observing their actions? Many believe that this ability is made possible by the brain's mirror neuron system through its direct link between action and observation. However, precisely how intentions can be inferred through action observation has provoked much debate. Here we suggest that the function of the mirror system can be understood within a predictive coding framework that appeals to the statistical approach known as empirical Bayes. Within this scheme the most likely cause of an observed action can be inferred by minimizing the prediction error at all levels of the cortical hierarchy that

used to execute that same action (Jeannerod 1994; Prinz 1997). Interest in this idea has grown recently, in part due to the neurophysiological discovery of ''mirror'' neurons. Mirror neurons discharge not only during action execution but also during action observation, which has led many to suggest that these neurons are the substrate for action understanding.

Mirror-neurons were first discovered in the premotor area, F5, of the macaque monkey (Di Pellegrino et al. 1992; Gallese et al. 1996; Rizzolatti et al. 2001; Umilta et al. 2001) and have been identified subsequently in an area of inferior parietal lobule, area PF (Gallese et al. 2002;

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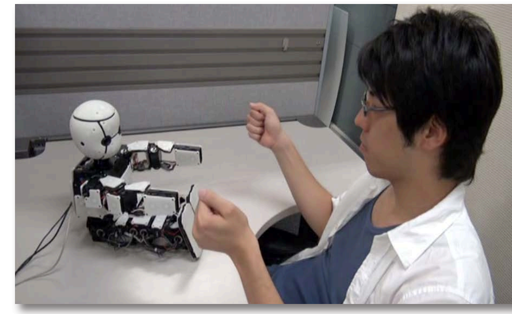

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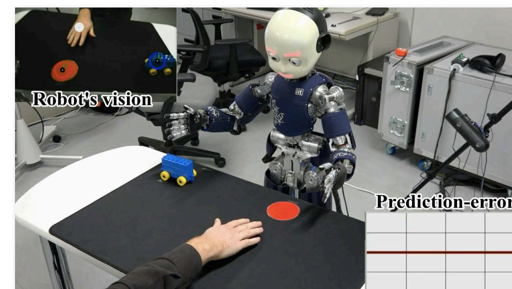

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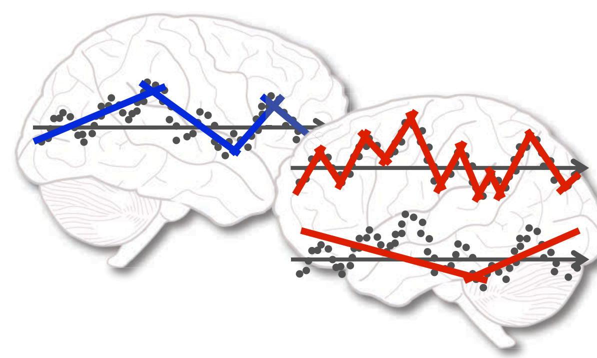


Young Infants Cannot Recognize Self in Mirror

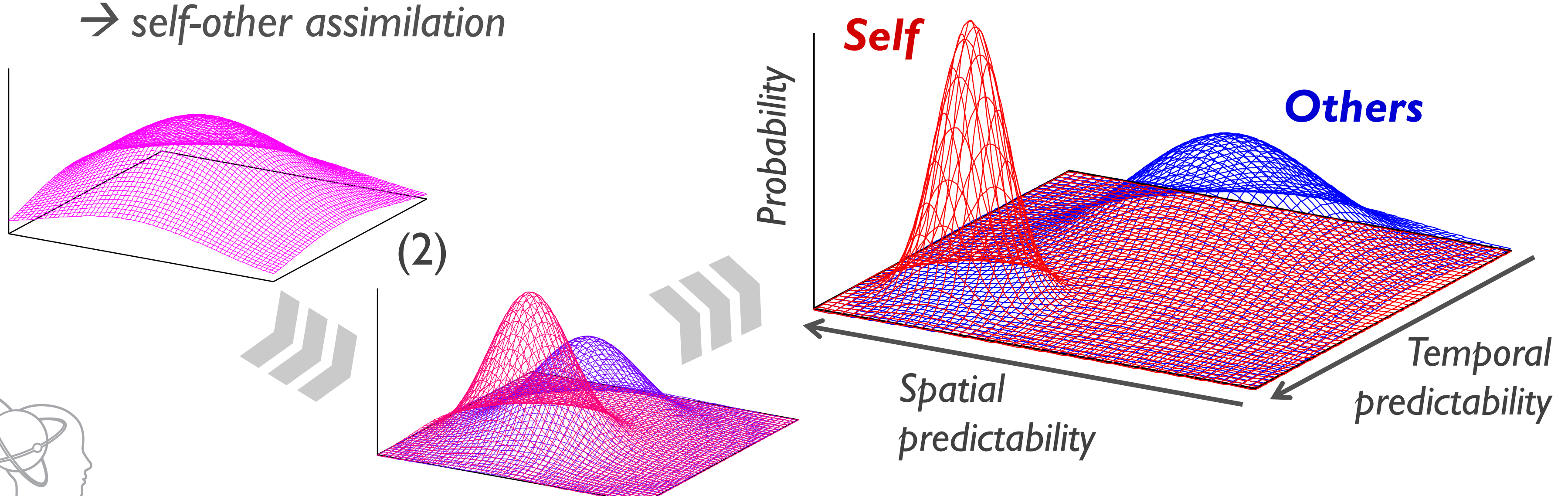
(Adapted from "The Baby Human 2" Discovery Channel)

Self-Other Cognition Based on Predictive Learning

- **Spatiotemporal predictability of sensorimotor information** discriminates the self from others.
  - Self = *higher* predictability, others = *lower* predictability
  - Perceptual and motor development leads to the emergence of *mirror neuron systems*.

(1) Immature perception & action
→ *self-other assimilation*

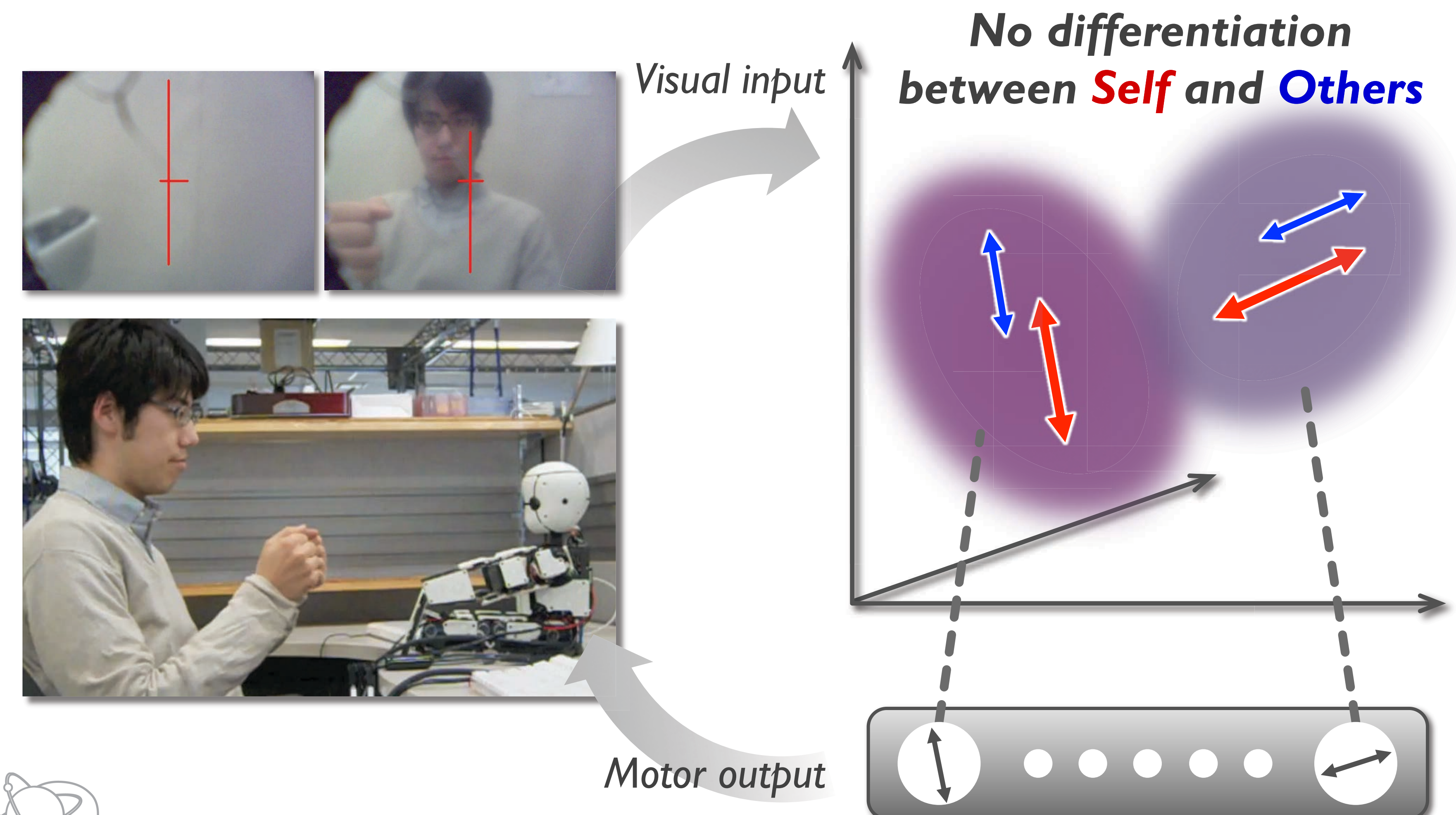
(3) Matured perception
→ *self-other correspondence*



[Nagai et al., ICDL-EpiRob 2011; Kawai et al., IROS 2012]

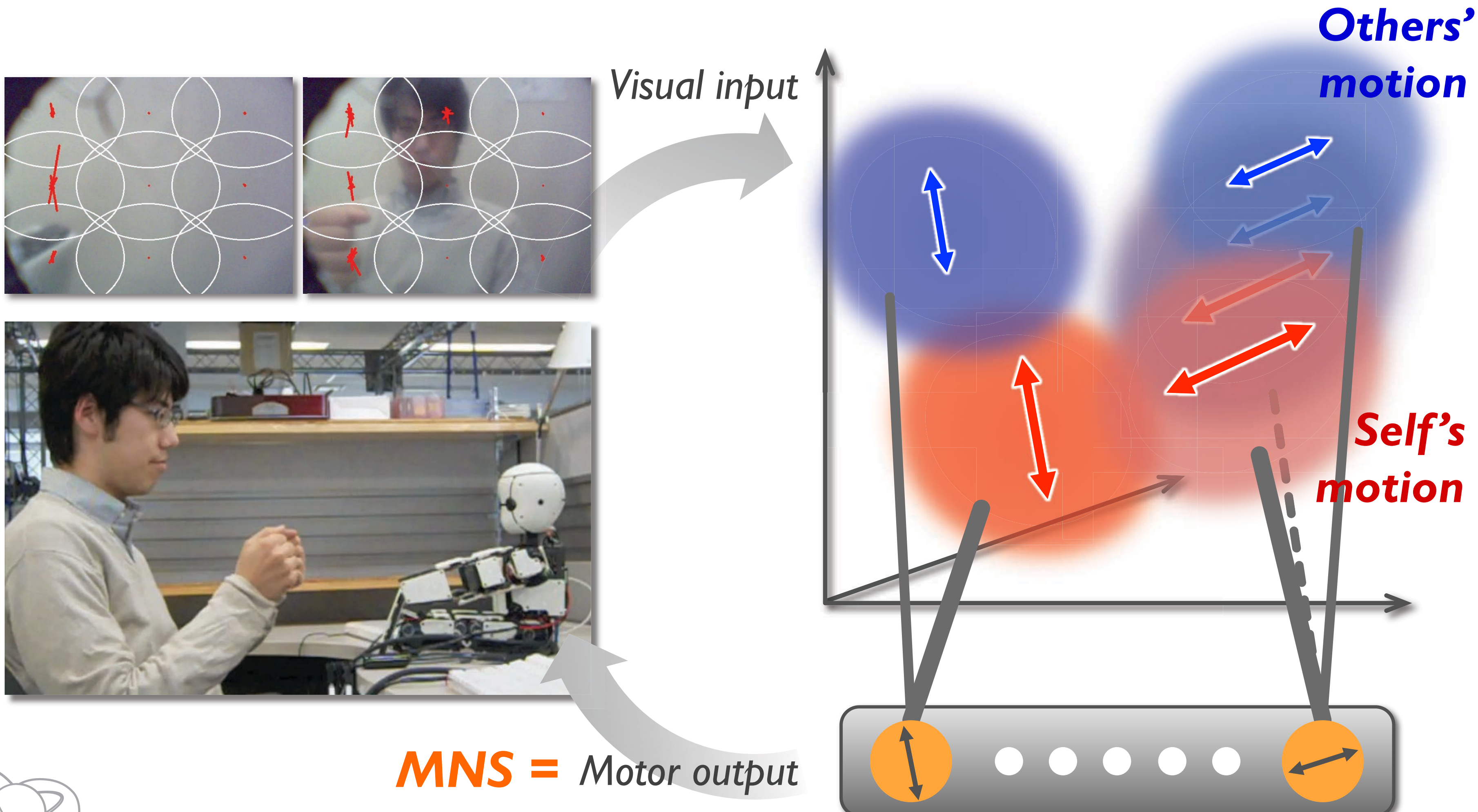
Computational Model for Self-Other Cognition

– *Early* Stage of Development –



[Nagai et al., ICDL-EpiRob 2011; Kawai et al., IROS 2012]

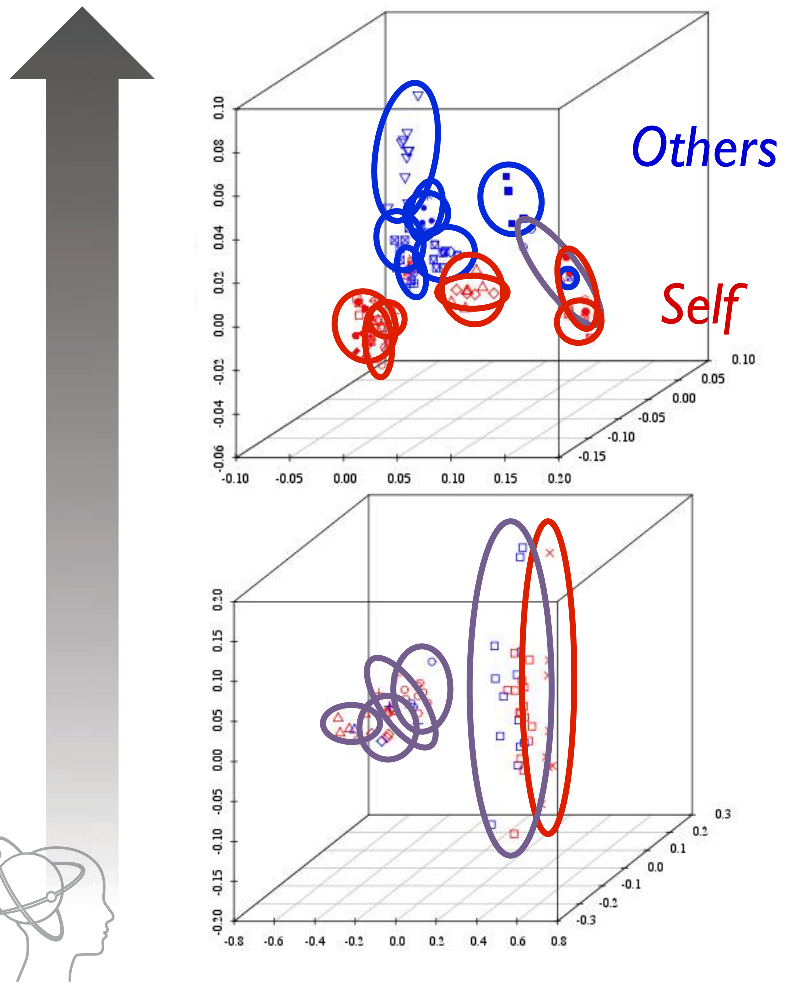
Computational Model for Self-Other Cognition
– *Later* Stage of Development –

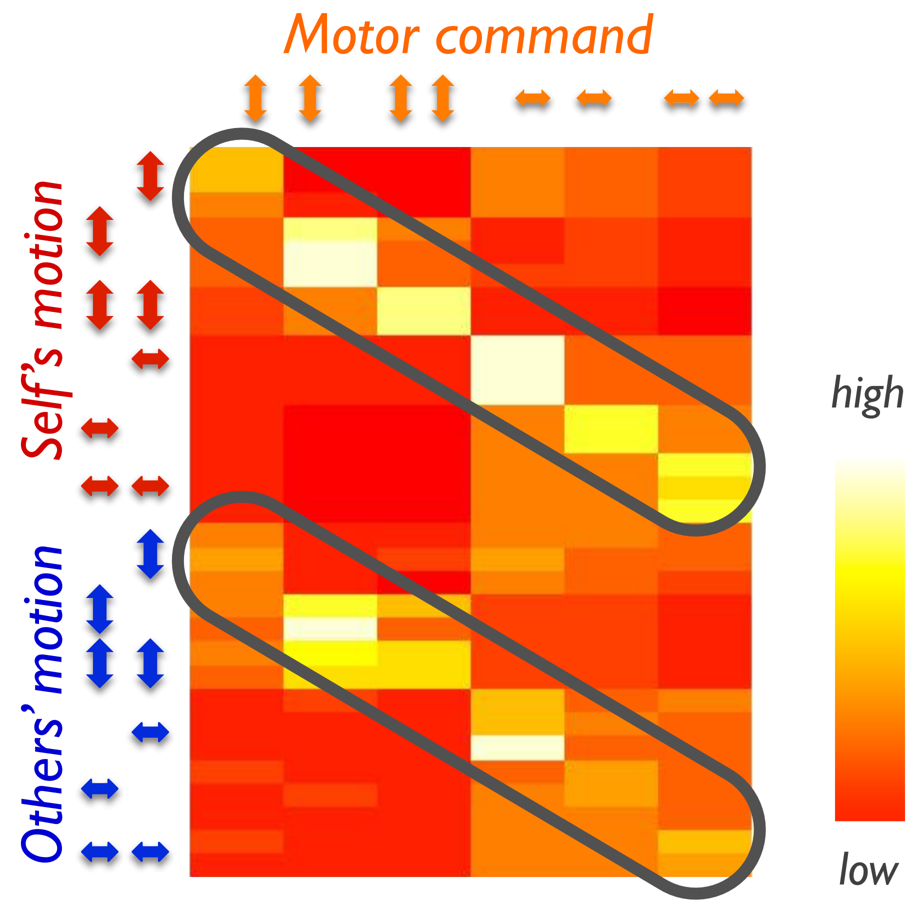


[Nagai et al., ICDL-EpiRob 2011; Kawai et al., IROS 2012]

Result 1: Self-Other Differentiation and MNS

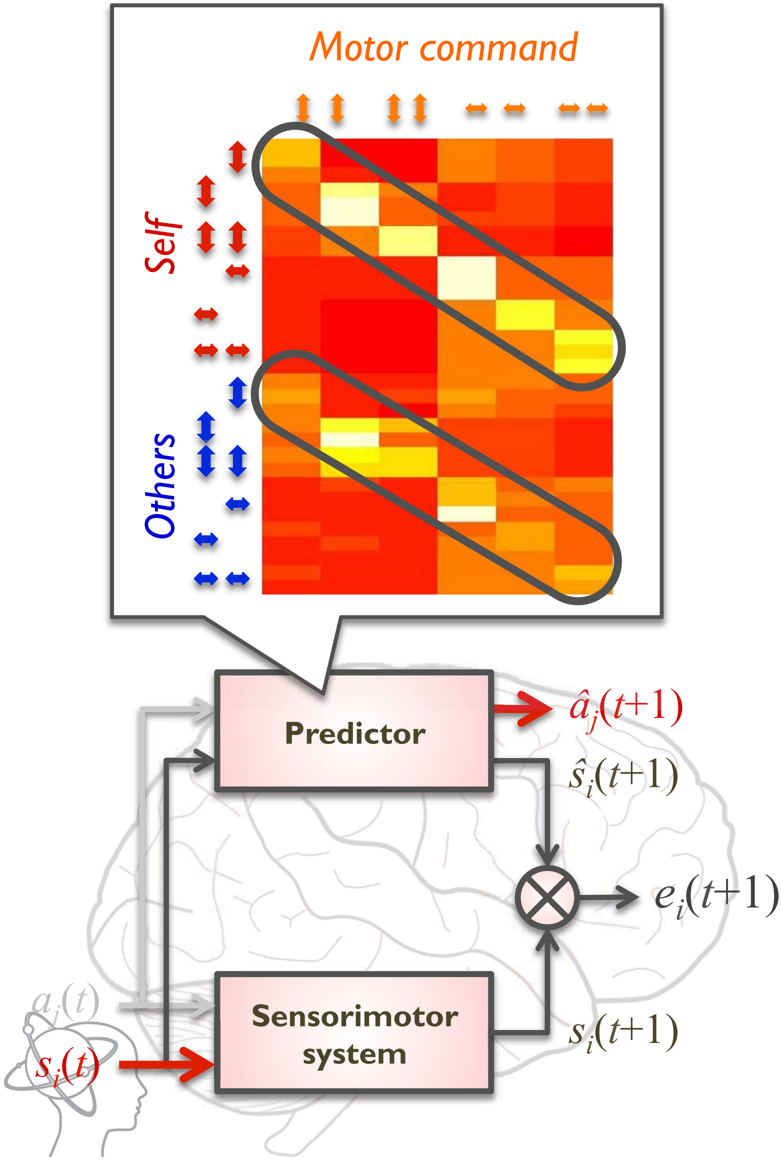
- Self-other differentiation in visual space
- MNS acquired in sensorimotor mapping

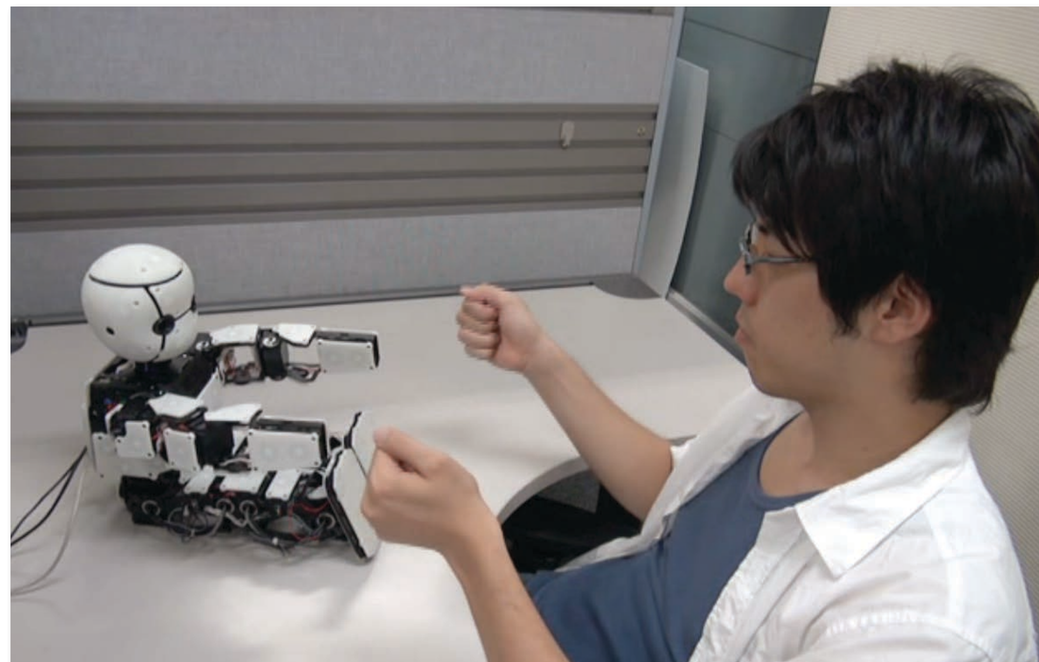




[Nagai et al., ICDL-EpiRob 2011; Kawai et al., IROS 2012]

Result 2: Imitation Using Acquired MNS





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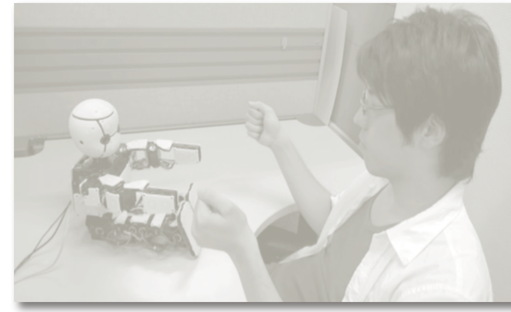

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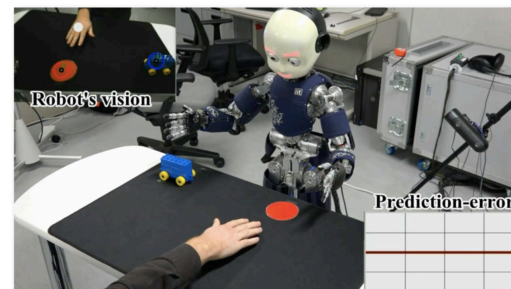

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   [Qin, Nagai, Kumagaya, Ayaya, & Asada, ICDL-EpiRob 2014]

Infants Help Others Even Without Reward

[Warneken & Tomasello, 2006]

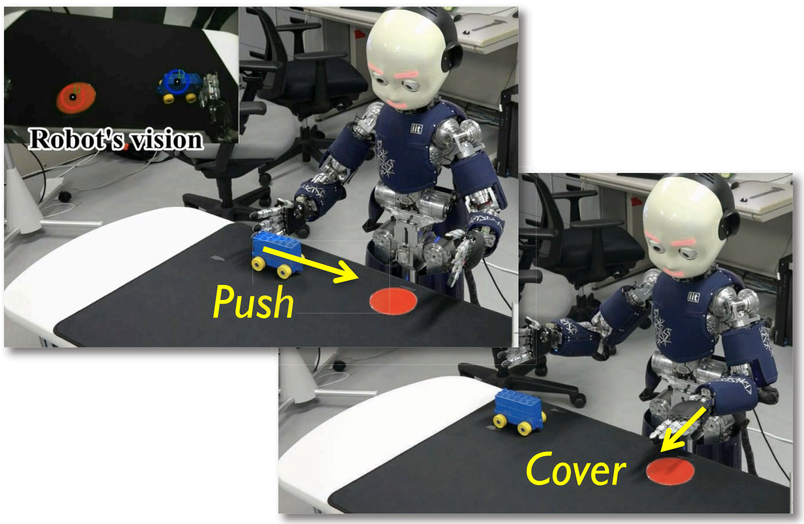
Two Theories for Prosocial Behaviors

[Paulus, 2014]

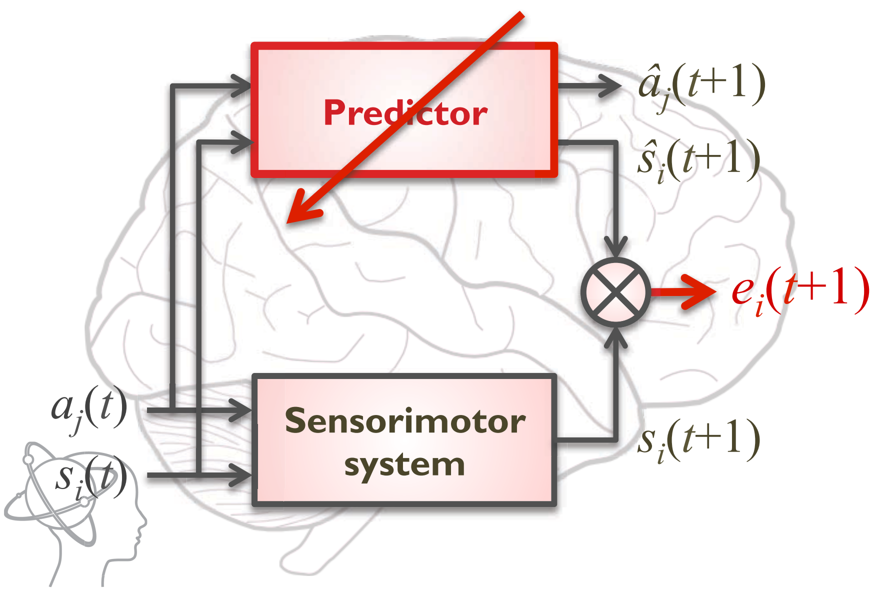
[Warneken & Tomasello, 2006]

- **Emotion-sharing theory**
  - Understand other person as an *intentional agent* [Batson, 1991]
  - Be motivated to help other based on *empathic concern for other's needs* [Davidov et al., 2013]
  - Self-other differentiation
- **Goal-alignment theory**
  - Understand *other's goal*, but not his/her intention [Barresi & Moore, 1996]
  - *Take over other's goal* as if it were infant's own
  - *No* self-other discrimination

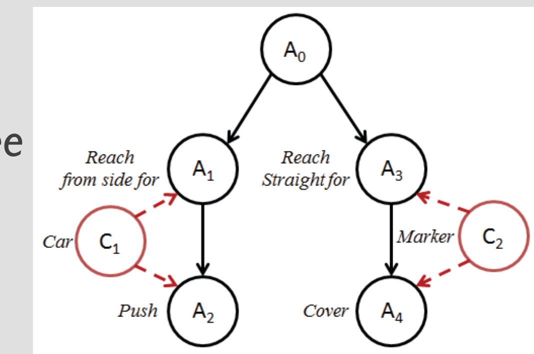
Prosocial Behavior Based on Minimization of Prediction Error



1. Update the predictor by minimizing a prediction error $e_i(t+1)$ through the robot's own experiences



Predictor: probabilistic state–action tree



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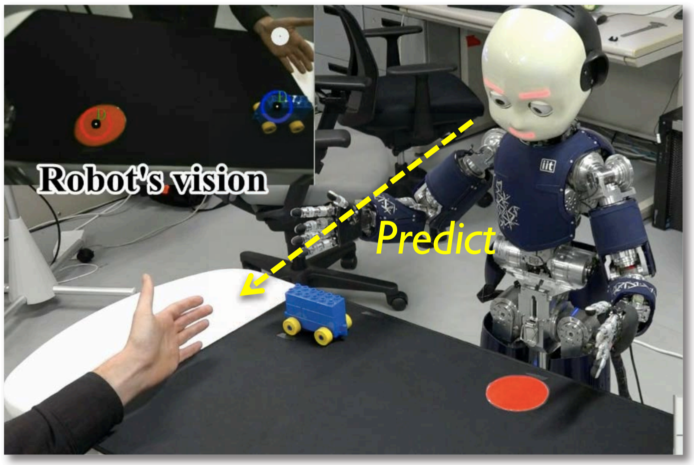
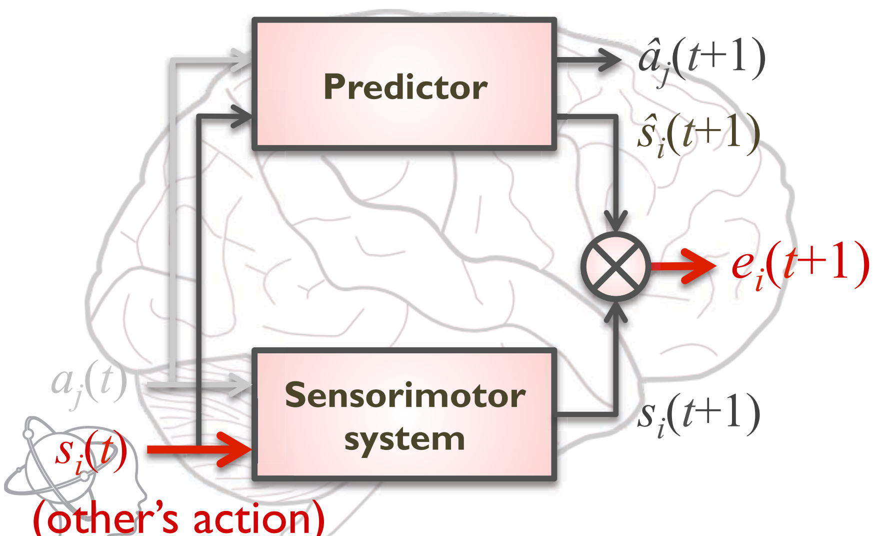
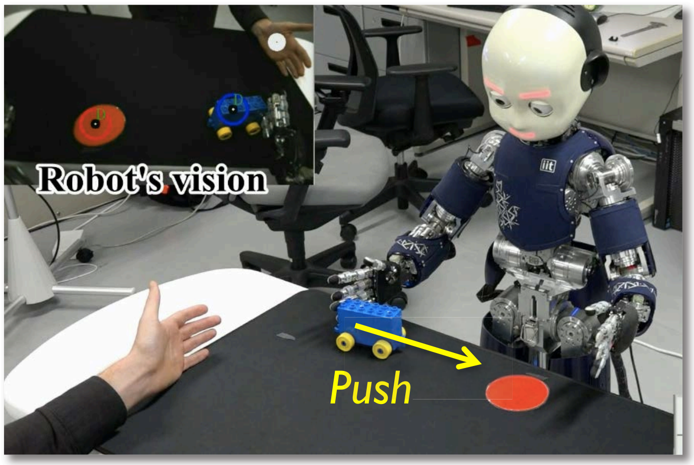


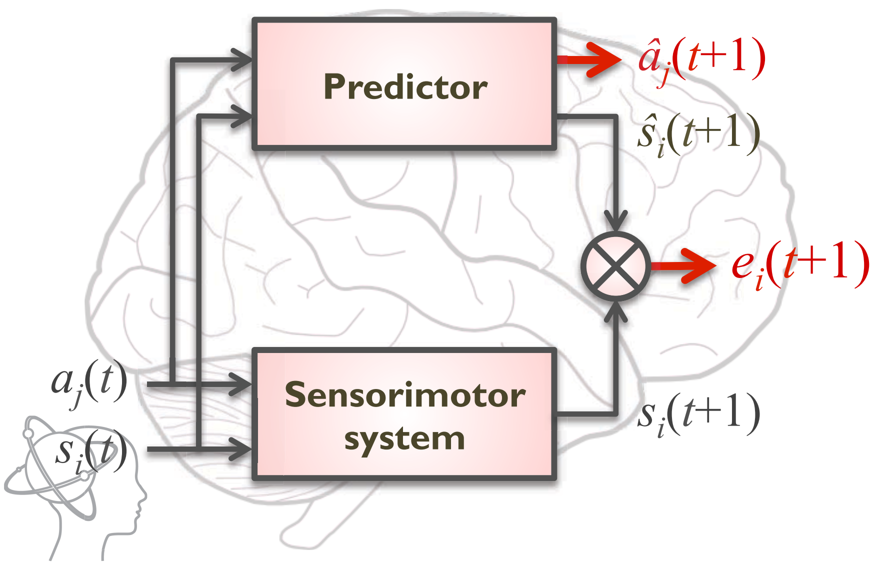


1. Update the predictor by minimizing a prediction error $e_i(t+1)$ through the robot's own experiences
2. Estimate $e_i(t+1)$ while observing others' action $s_i(t)$
   - *No* perspective difference between the self and others

[Baraglia, Nagai, & Asada, ICDL-EpiRob 2014]

Prosocial Behavior Based on Minimization of Prediction Error





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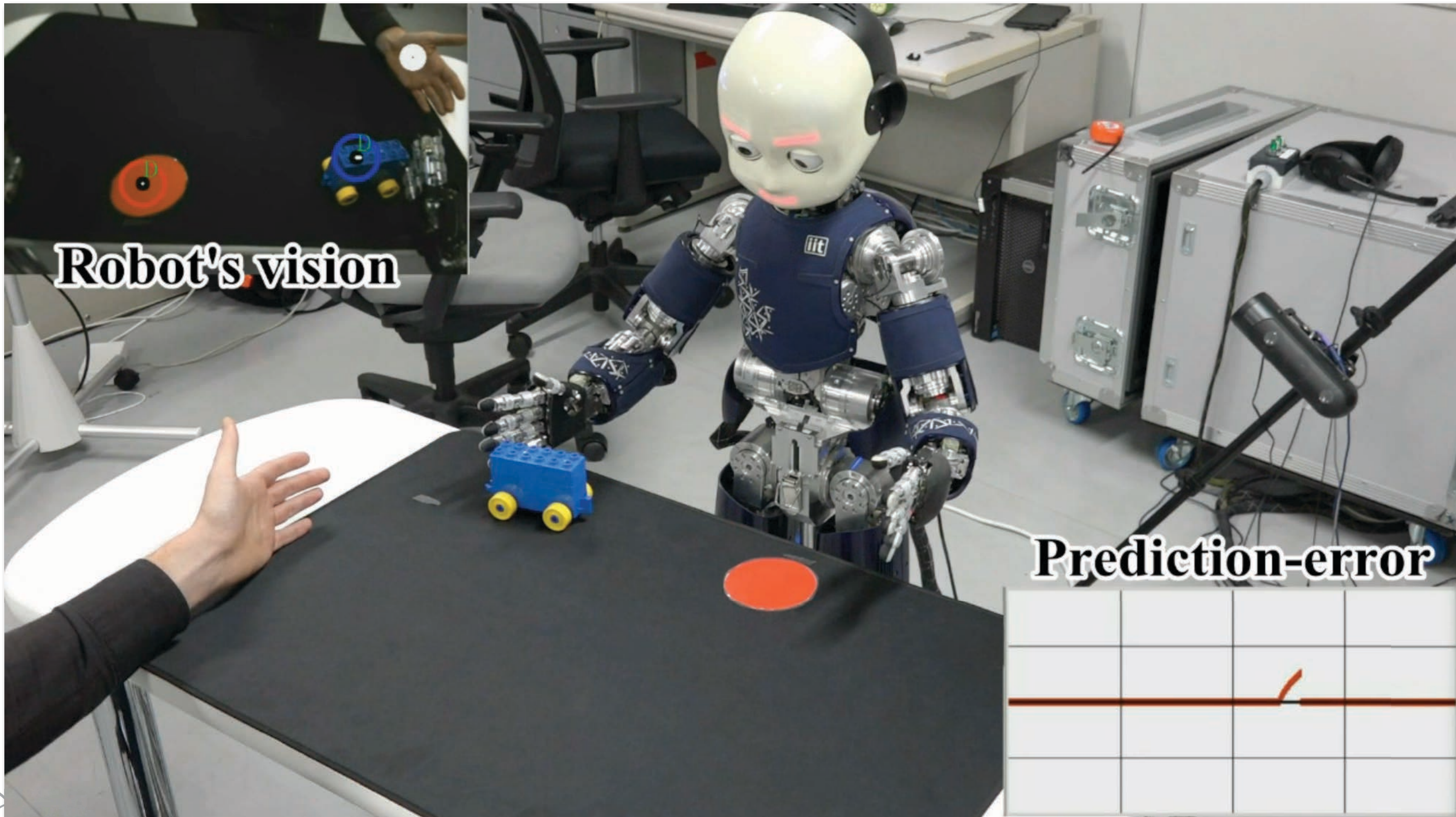
2. Estimate $e_i(t+1)$ while observing others' action $s_i(t)$
   - *No* perspective difference between the self and others
3. Execute an action $\hat{a}_j(t+1)$ to minimize $e_i(t+1)$ if $e_i(t+1) >$ threshold

→ **Help others**

[Baraglia, Nagai, & Asada, ICDL-EpiRob 2014]

Result: Emergence of Prosocial Behavior



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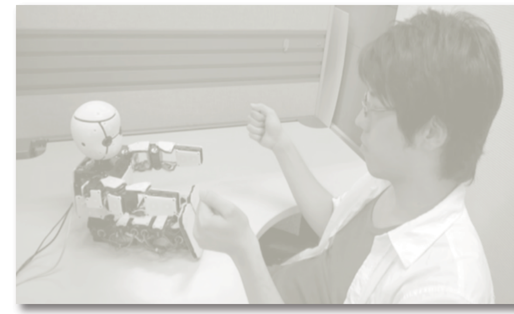

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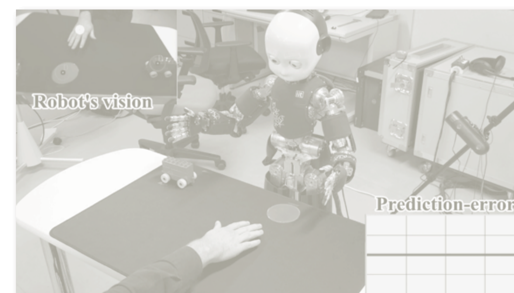

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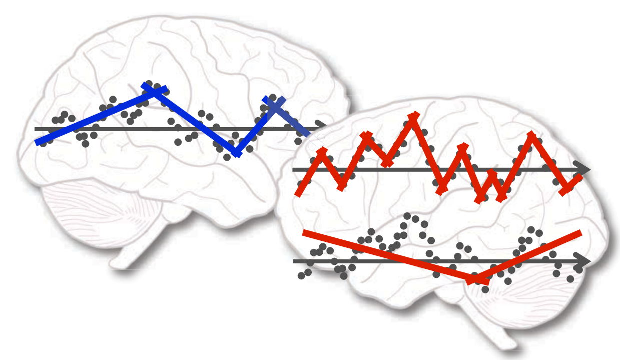


Autism Spectrum Disorder (ASD)

- Difficulties in **social interaction**
  [Baron-Cohen, 1995; Charman et al., 1997; Mundy et al., 1986]
  – Less eye contact
  – Difficulties in reading emotion
  – Lack of theory of mind, etc.

- Atypical **perception** and atypical information processing
  [O'Neill & Jones,1997; Happé & Frith, 2006; Ayaya & Kumagaya, 2008]
  – Hyperesthesia/hypoesthesia
  – Local processing bias, etc.

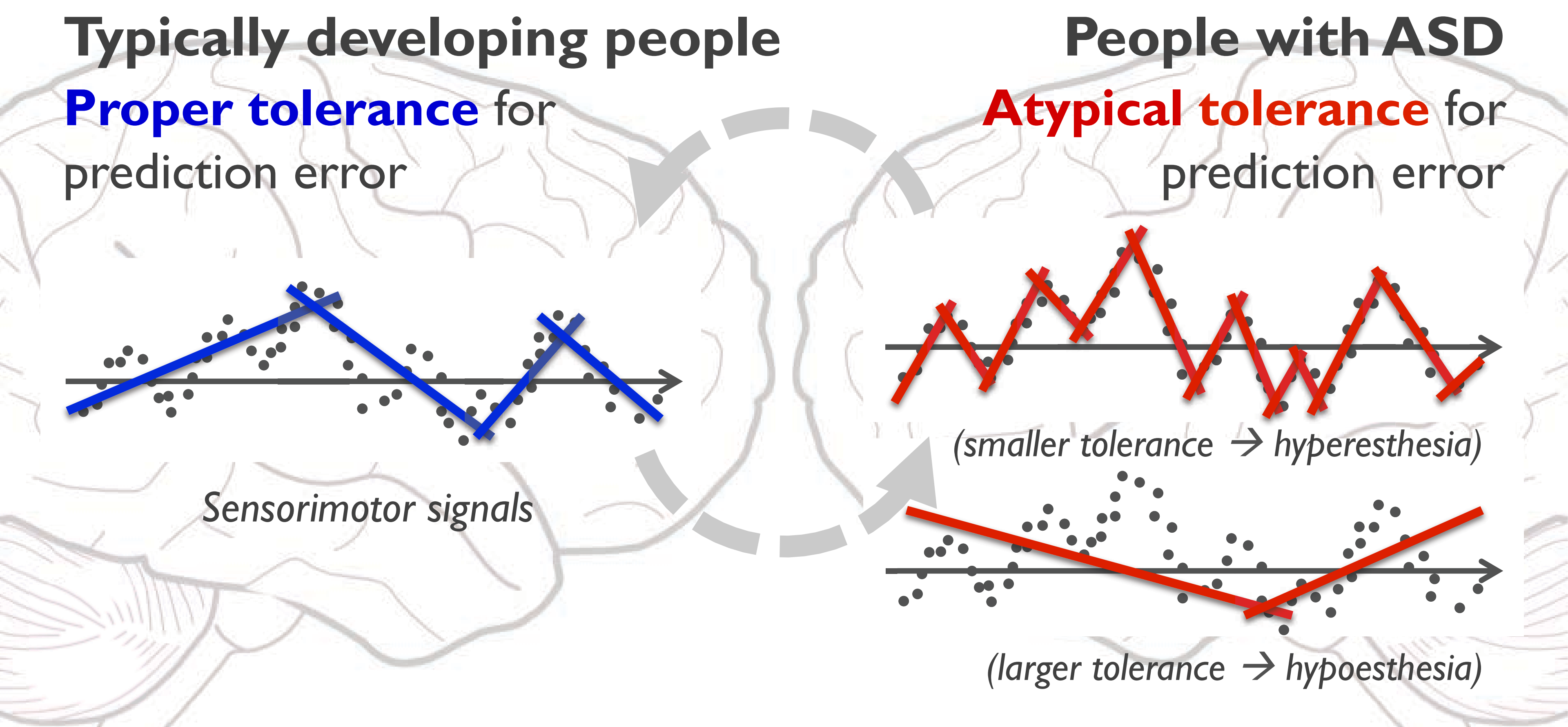
Atypical Perception in ASD

[Qin et al., ICDL-EpiRob 2014; Nagai et al., in prep.]

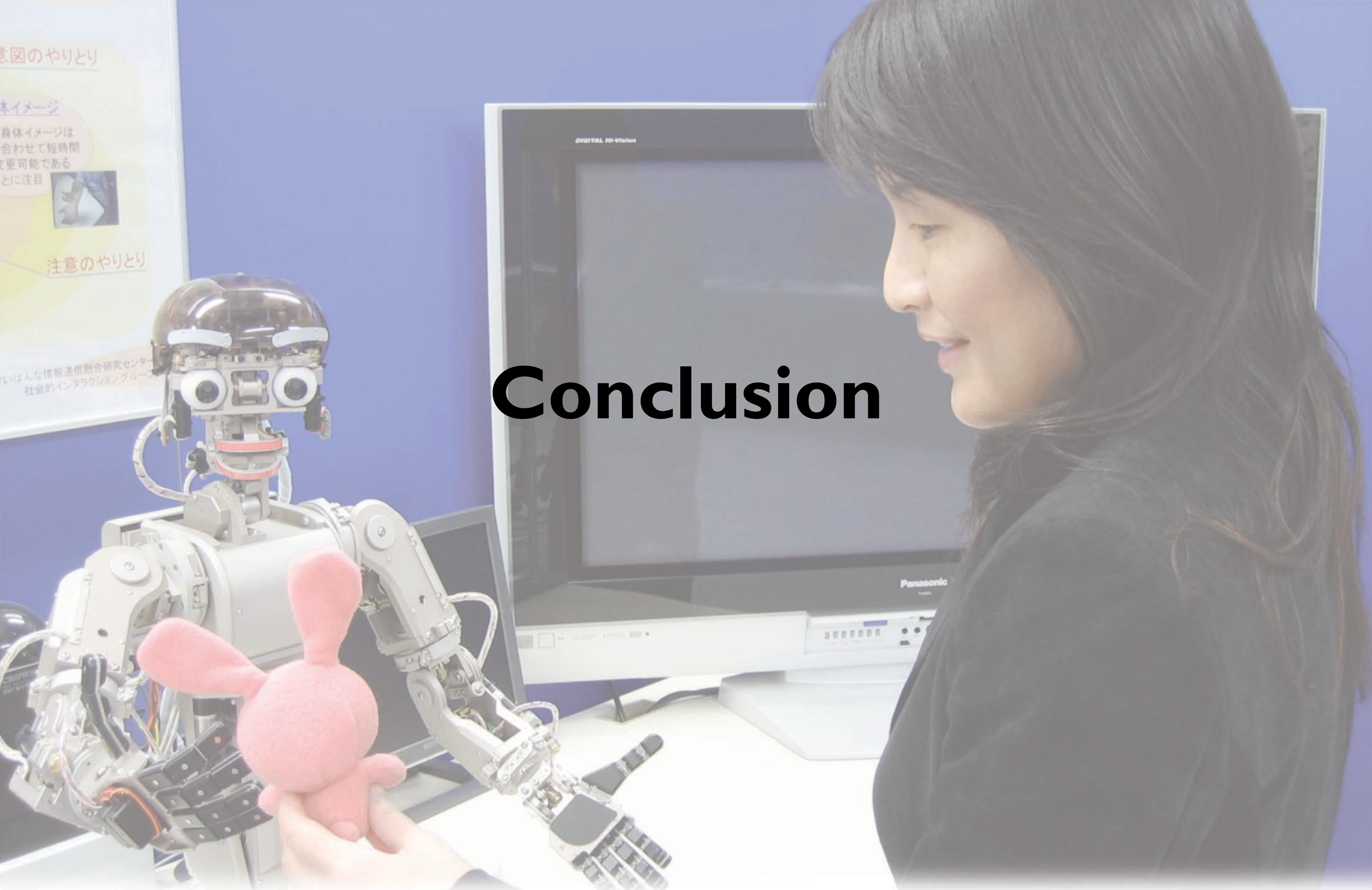

Our Hypothesis about Mechanism of ASD

[Nagai & Asada, 2015]

- **Atypical tolerances for prediction errors** may produce different internal models of ASD from TD's models.



Conclusion



Cognitive
Neuroscience
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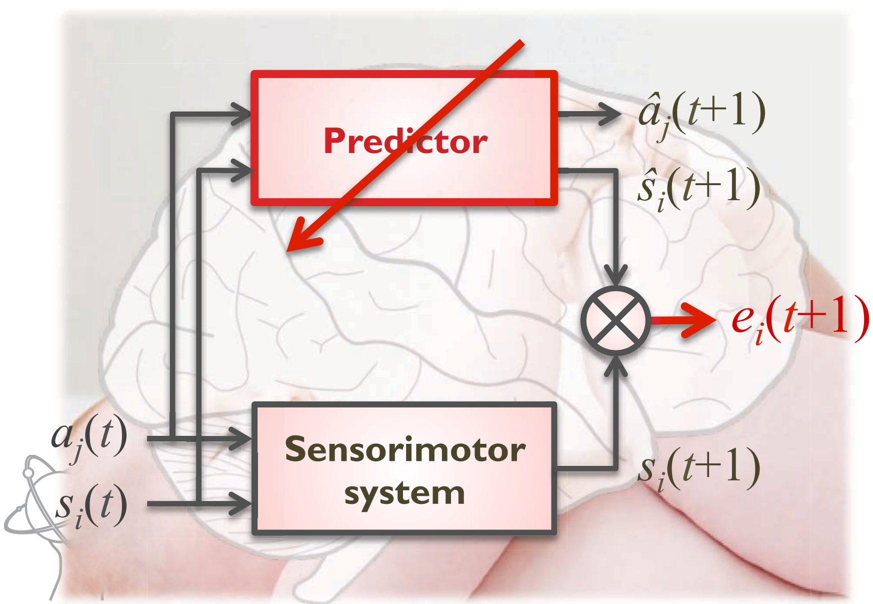

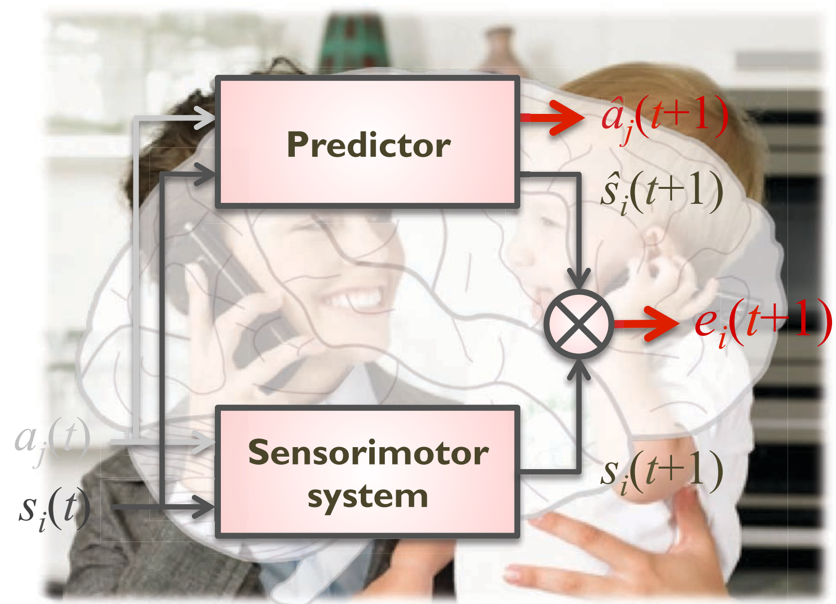

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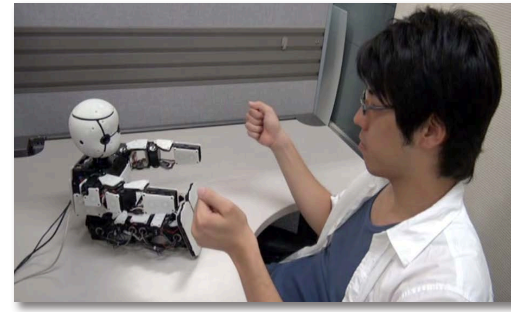

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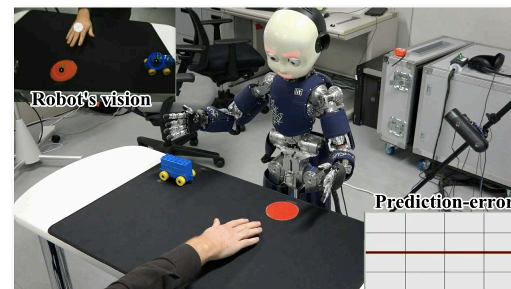

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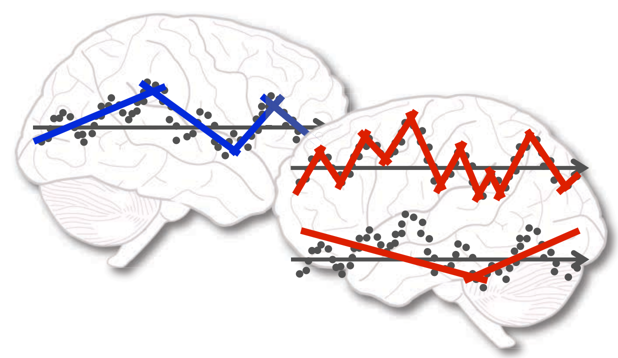


Thank You!

Osaka University

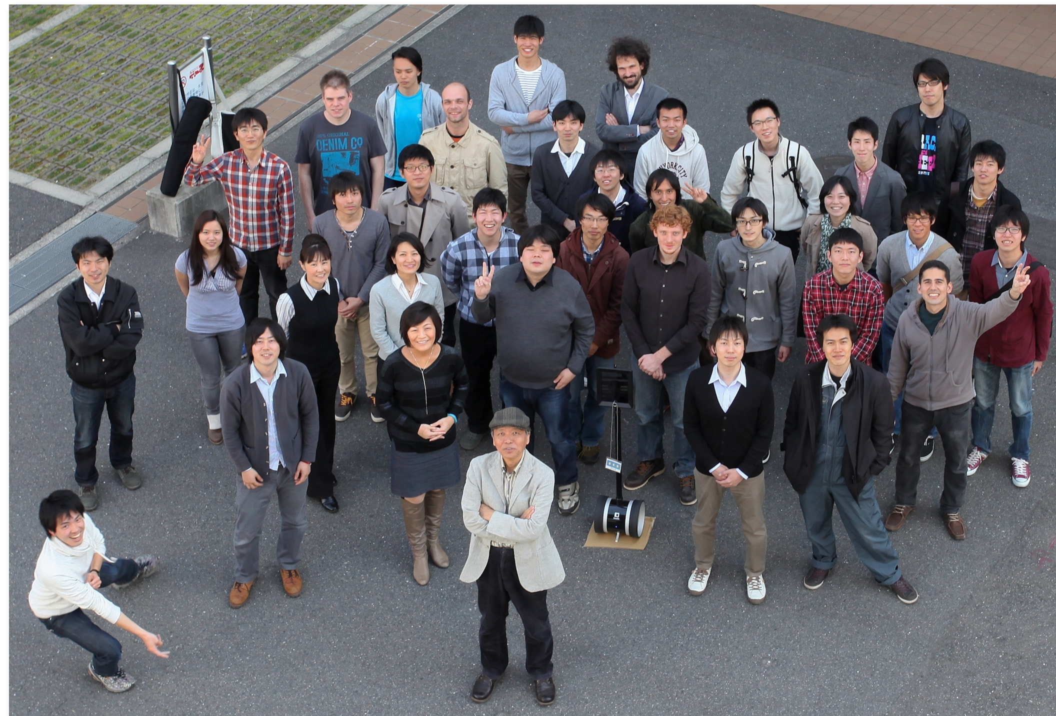
- Minoru Asada
- Jimmy Baraglia
- Yuji Kawai
- Takato Horii
- Shibo Qin
- Many students

University of Tokyo

- Shinichiro Kumagaya
- Satsuki Ayaya

KAIST

- Jun-Cheol Park



devsci
Constructive Developmental Science

Constructive Developmental Science
Based on Understanding the Process
from Neuro-Dynamics to Social Interaction

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