AI as a Tool for Investigating Human Intelligence

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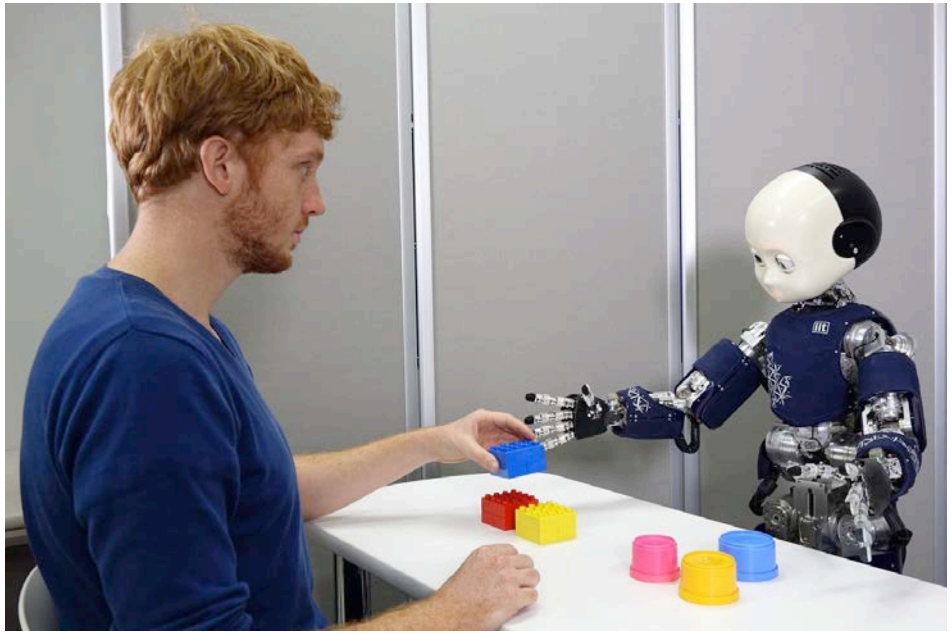
(2016.08.23, NHK)

Cognitive Developmental Robotics

[Asada et al., 2001; 2009; Cangelosi & Schlesinger, 2015]

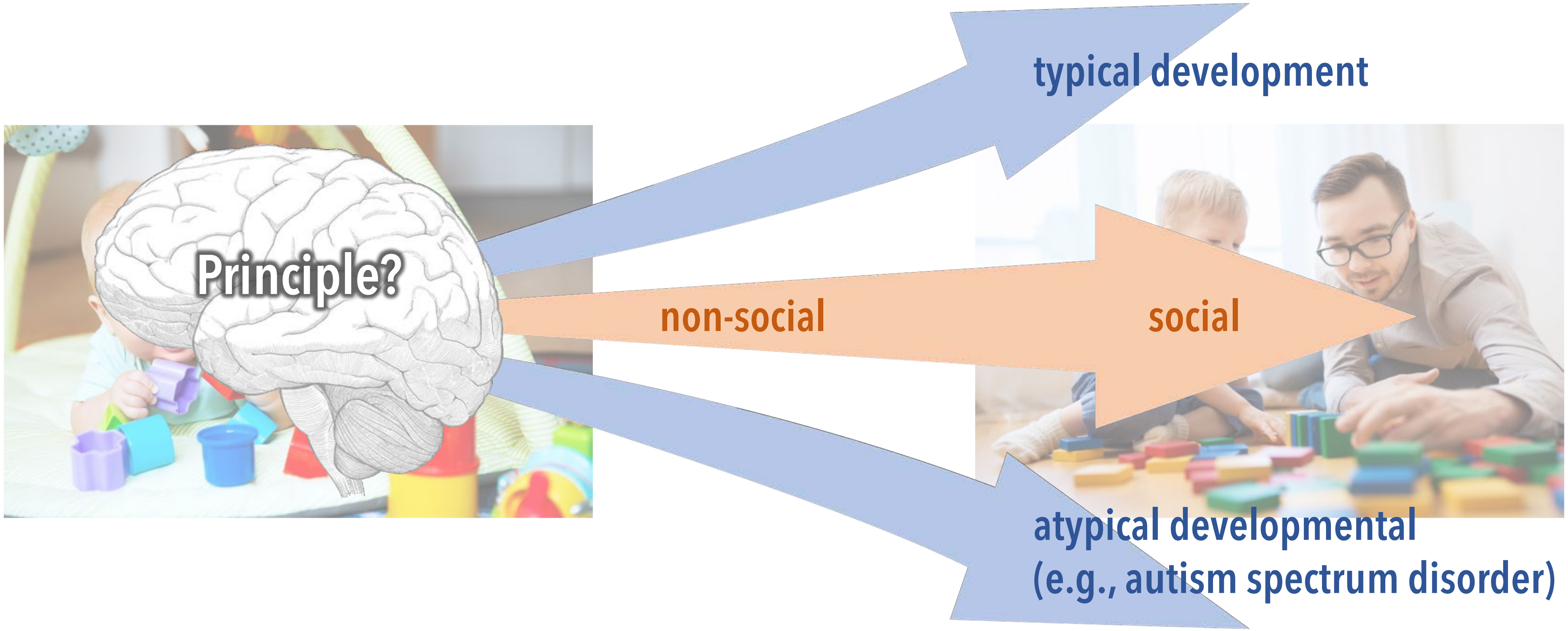


Twofold aim:

- To design robot intelligence inspired by human intelligence
- To obtain deeper insights into human intelligence by testing neuroscience/psychological hypotheses

Open Question: A Unified Principle of Cognitive Development?

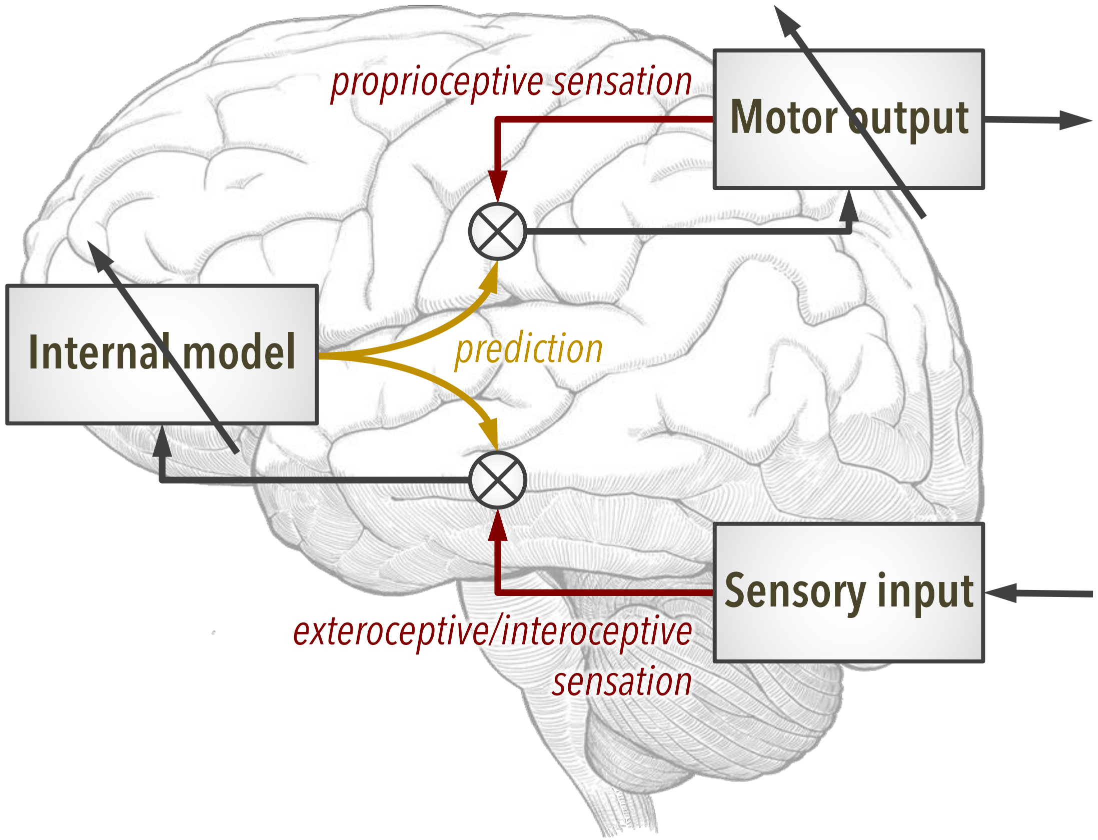
- What neural mechanisms underlie cognitive development?
- Can they account for both the continuity and diversity in development?



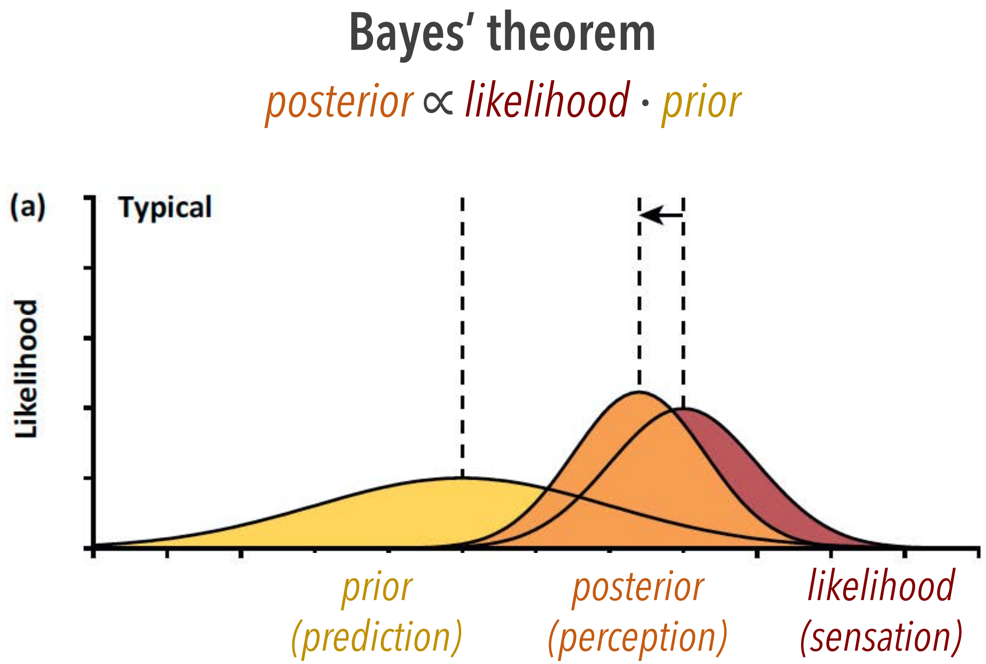
Predictive Coding: A Unified Theory of Human Brain

[Friston et al., 2006; Friston, 2010; Clark, 2013]

- The human brain perceives the world and acts on the world to minimize prediction errors (i.e., perceptual and active inference) .

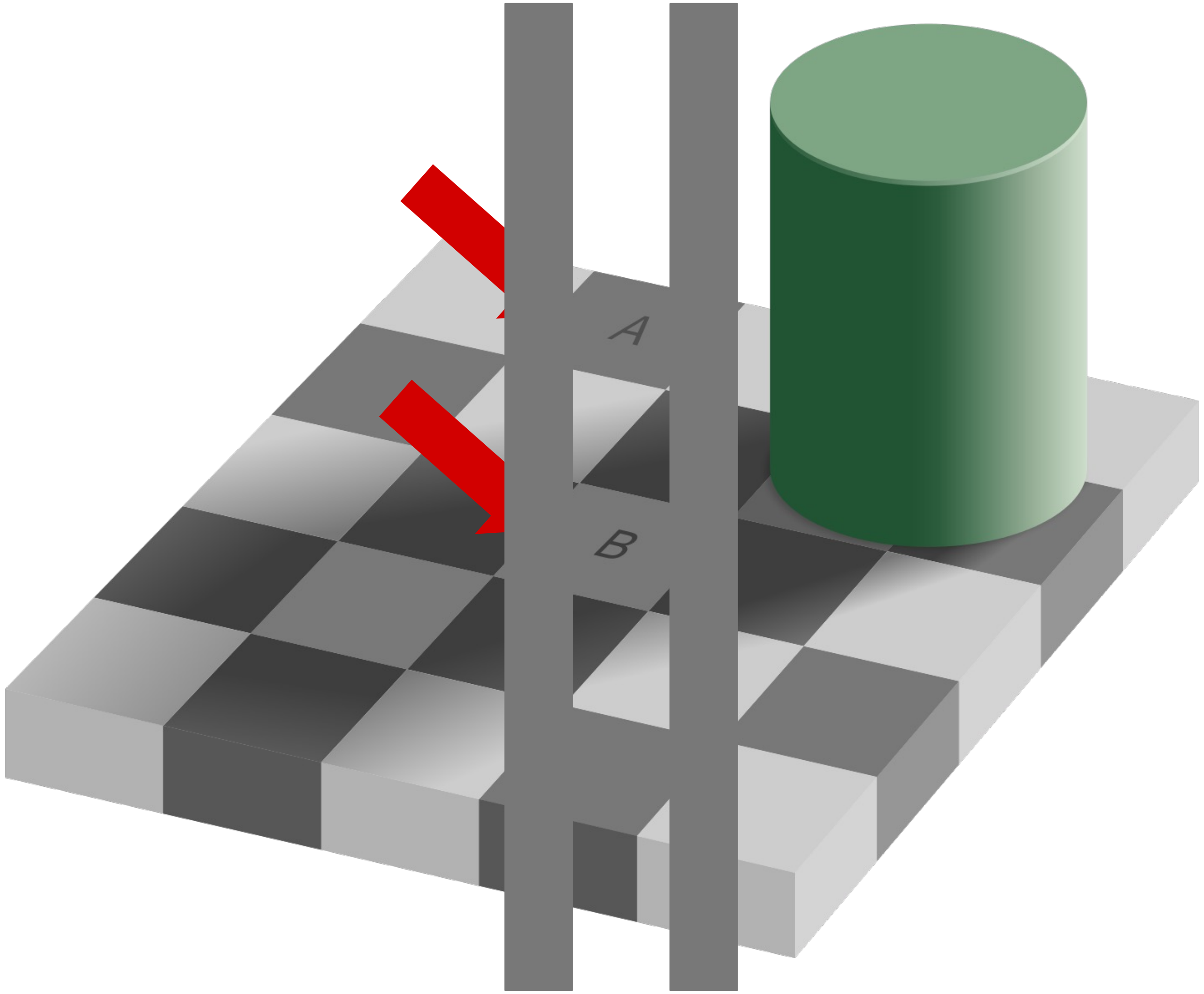


Modified from [Friston & Frith, 2015]



[Brock, 2012]

Optical Illusion Generated by Predictive Brain



Which square looks brighter, A or B?

Perception (subjective experience)

A < B

Sensation (physical stimuli)

A = B

Temporal Continuity in Cognitive Development

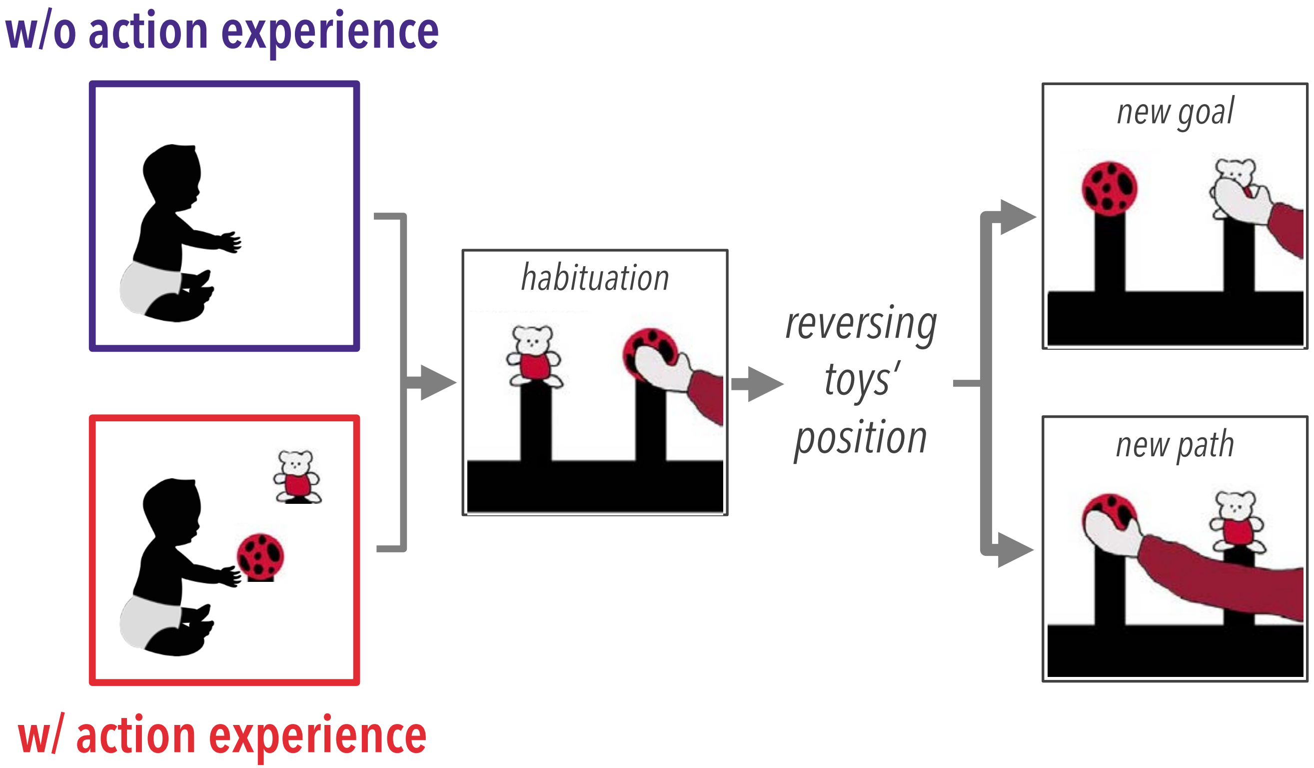
Development of Altruistic Behavior

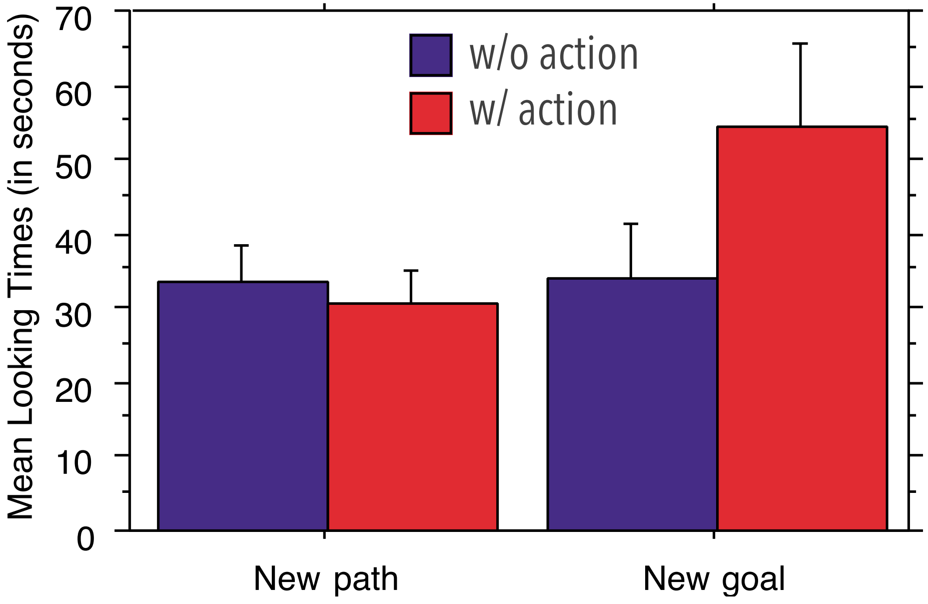
[Warneken & Tomasello, 2007]

Action Production Facilitates Action Perception in Infants

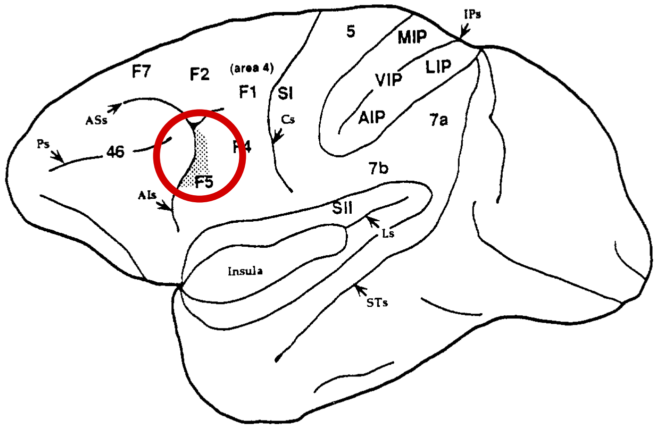
[Sommerville et al., 2005; Gerson & Woodward, 2014]

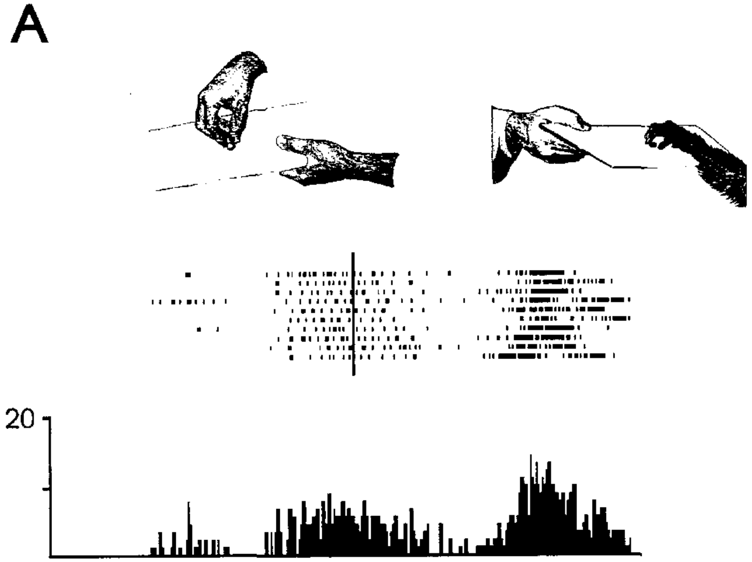
- 3-month-old infants detect the *goal-directed structure of others' actions* only when they were given experiences of *generating the same actions*.



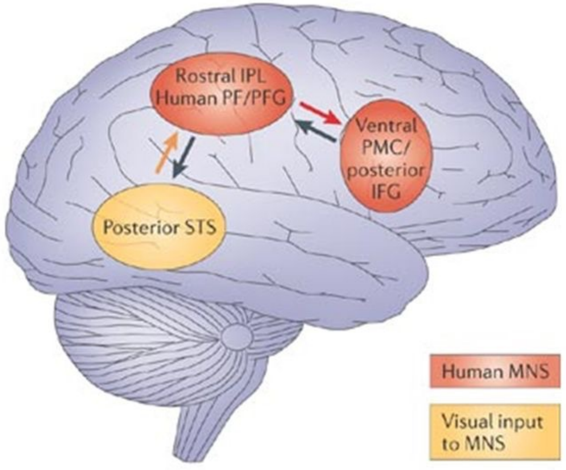


Mirror Neurons and Mirror Neuron Systems





[Rizzolatti et al., 1996]

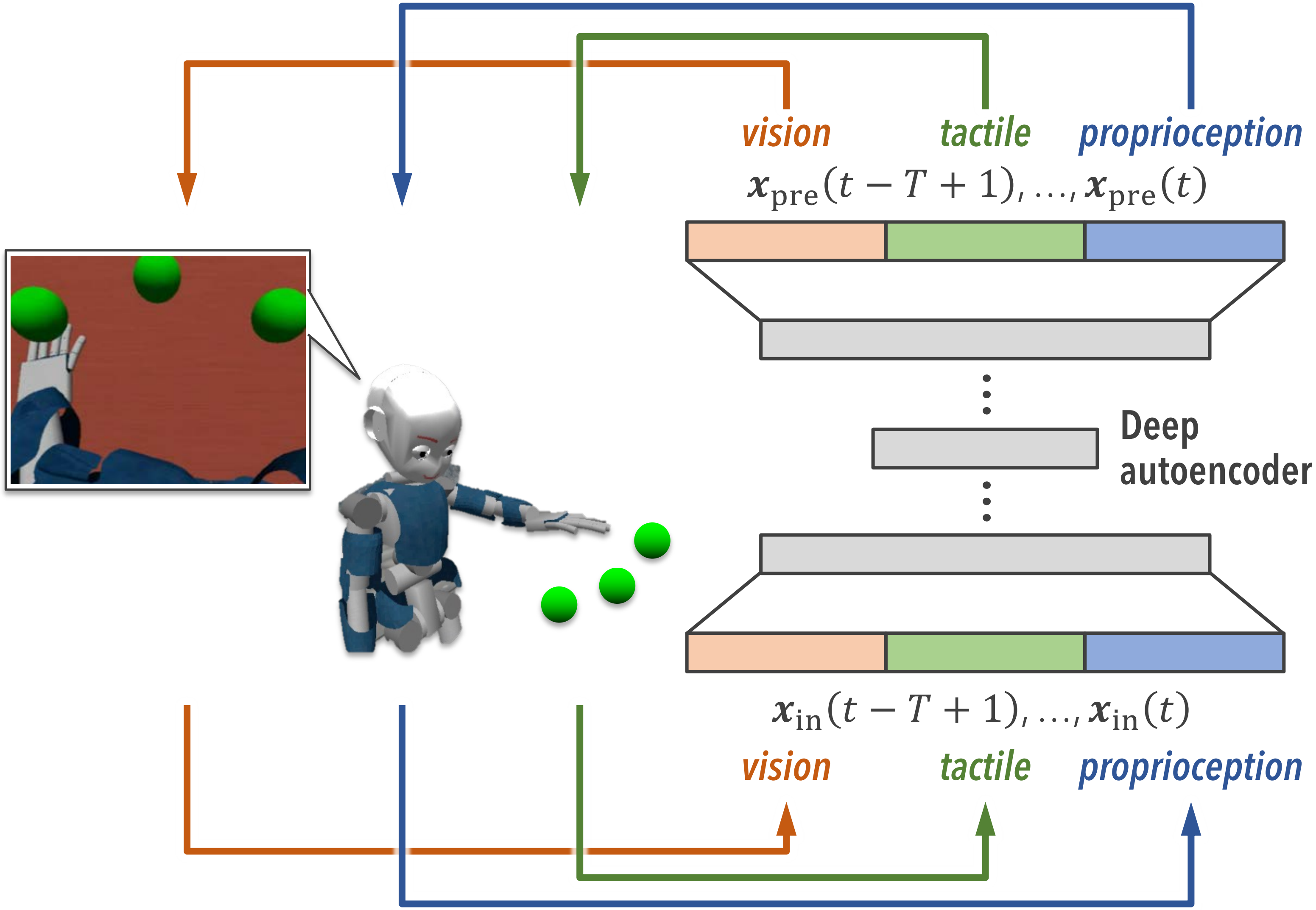


[Iacoboni & Dapretto, 2006]

- Originally found in monkey's premotor cortex
- Discharge both:
  - when *executing* own actions
  - when *observing* the same action performed by other individuals
- Emergence of social behaviors based on self-oriented sensorimotor experiences

Development of Mirror Neuron System

[Copete, Nagai, & Asada, ICDL-EpiRob 2016]

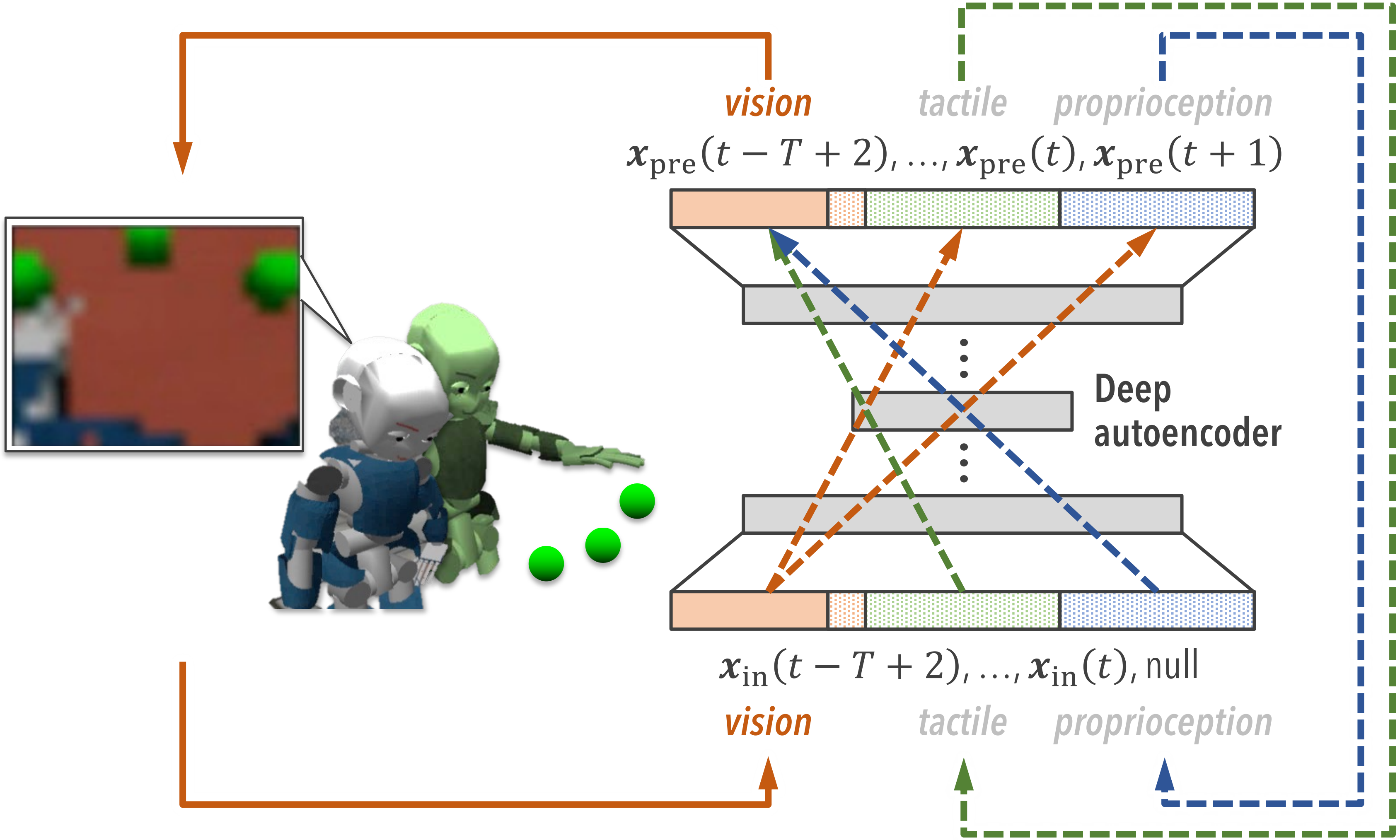


Action production:

- Predictive learning (i.e., minimizing $\|\boldsymbol{x}_{\text{in}} - \boldsymbol{x}_{\text{pre}}\|$) to associate *visual*, *tactile*, and *proprioceptive* signals

Development of Mirror Neuron System

[Copete, Nagai, & Asada, ICDL-EpiRob 2016]



Action production:

- Predictive learning (i.e., minimizing $\|\boldsymbol{x}_{\mathrm{in}} - \boldsymbol{x}_{\mathrm{pre}}\|$) to associate *visual*, *tactile*, and *proprioceptive* signals

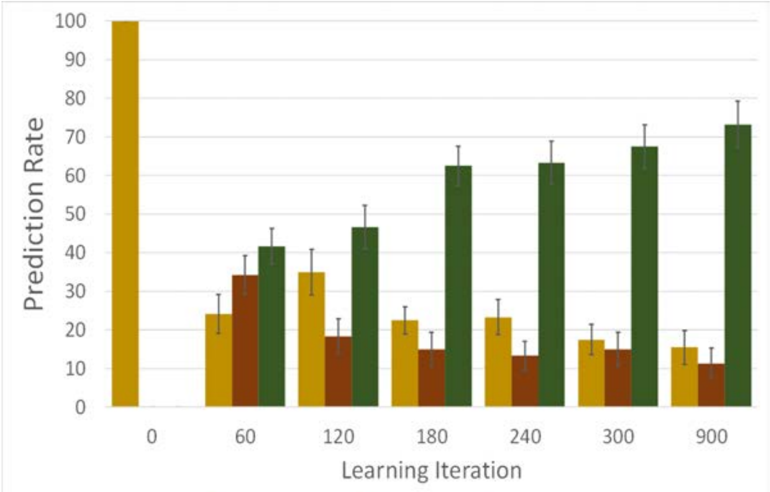
Action perception:

- *Visual* action prediction facilitated by imaginary *tactile* and *proprioceptive* signals

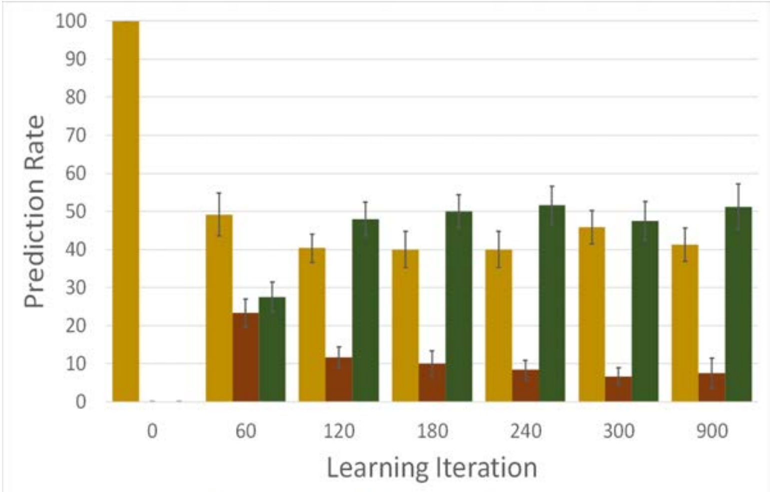
Exp: Action Perception Improved by Motor Experiences

[Copete, Nagai, & Asada, ICDL-EpiRob 2016]

Learning through action *generation*



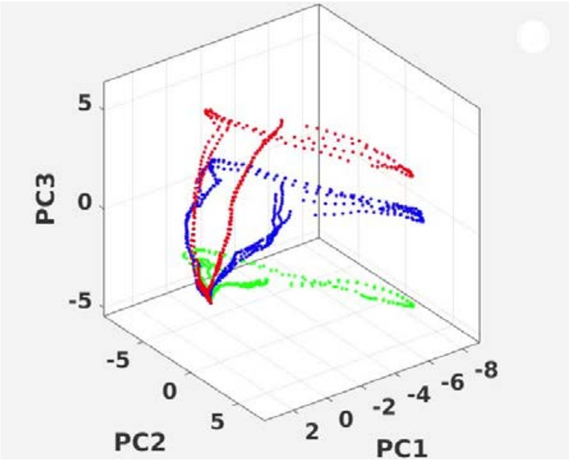
Learning through action *observation*

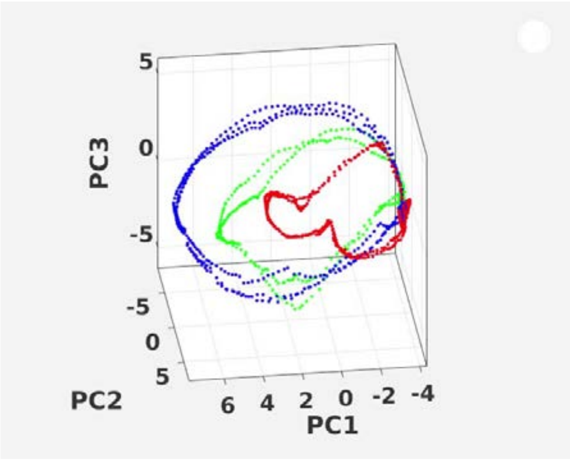


Correct goal

Incorrect goal

No goal

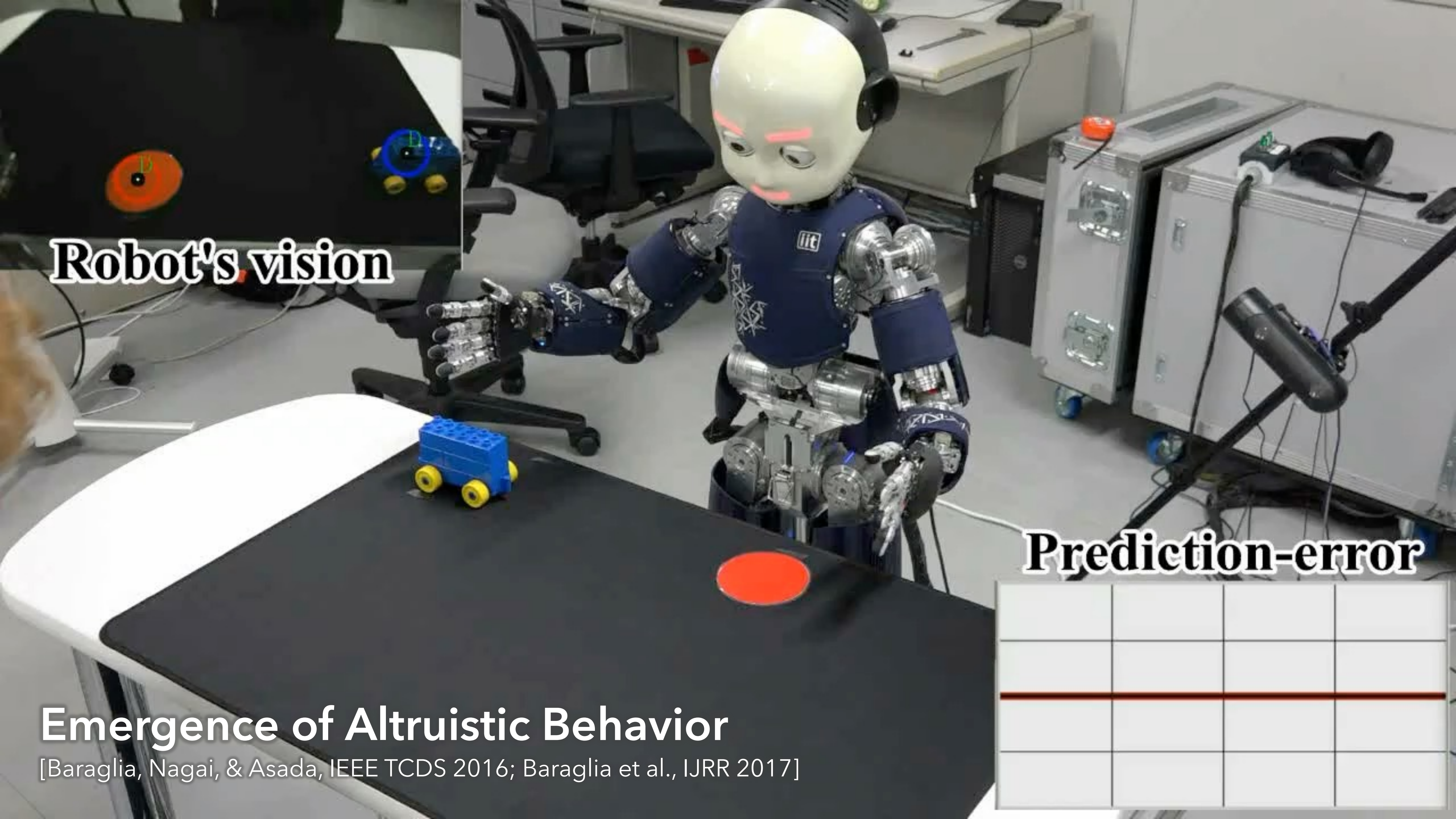




Reaching for left

Reaching for center

Reaching for right



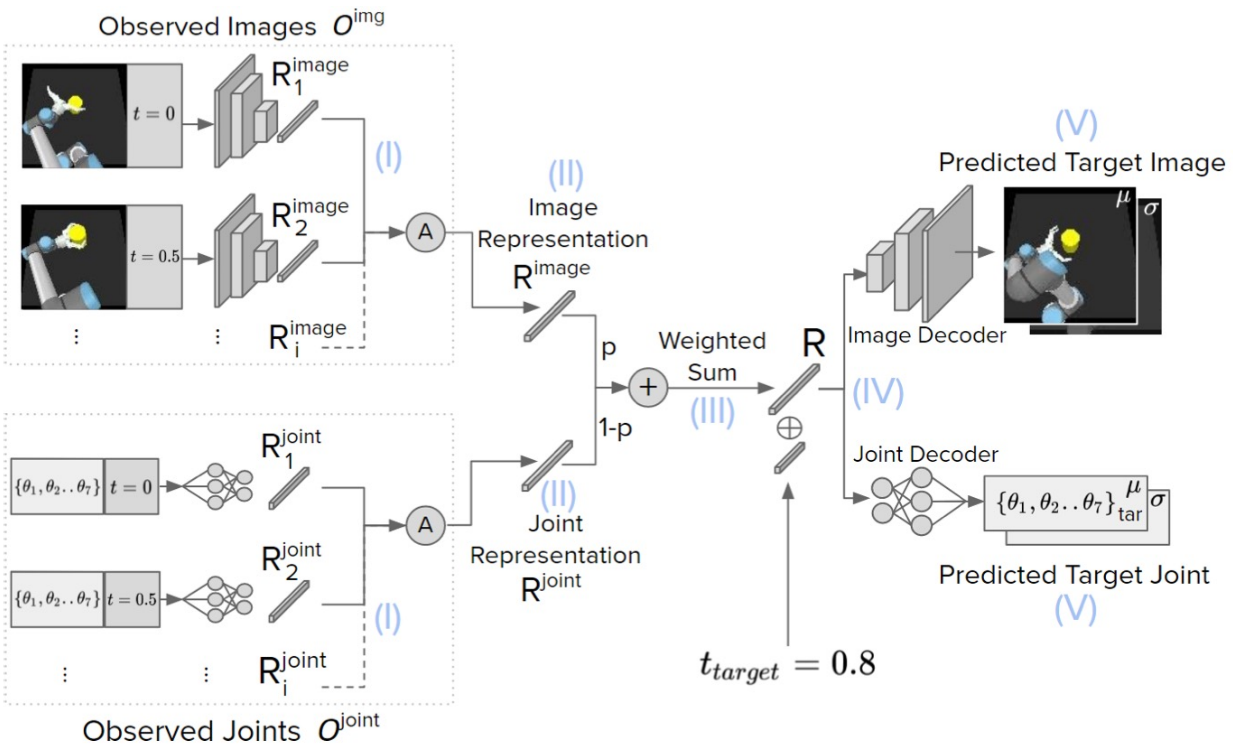
Emergence of Altruistic Behavior

[Baraglia, Nagai, & Asada, IEEE TCDS 2016; Baraglia et al., IJRR 2017]

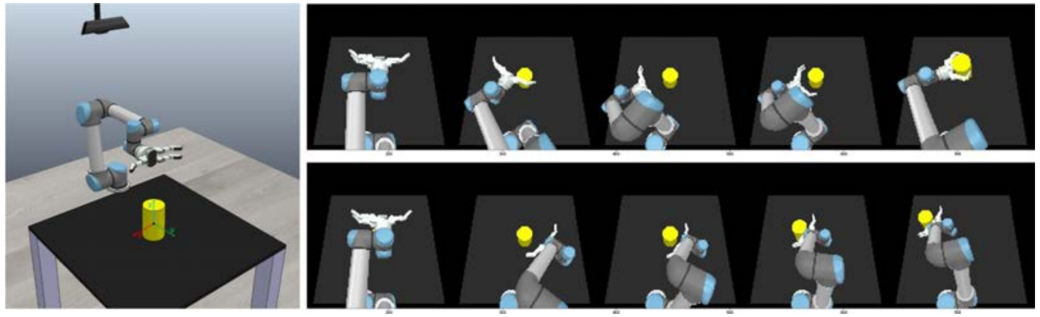
Adaptive Imitation Based on Perspective Taking

[Seker et al., Neural Networks 2022]

- Deep modality blending network that learns to integrate multimodal signals (i.e.,vision, proprioception) through action generations
- Imitation of other's actions based on perspective taking



Observation of *own* actions



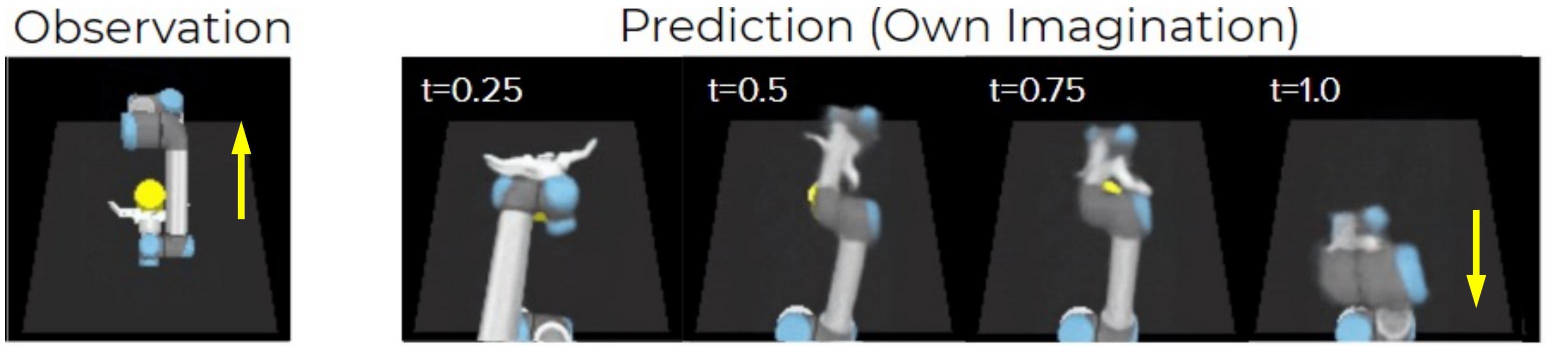
Observation of *other's* actions

Exp: Adaptive Imitation Induced by Different Observation

[Seker et al., Neural Networks 2022]

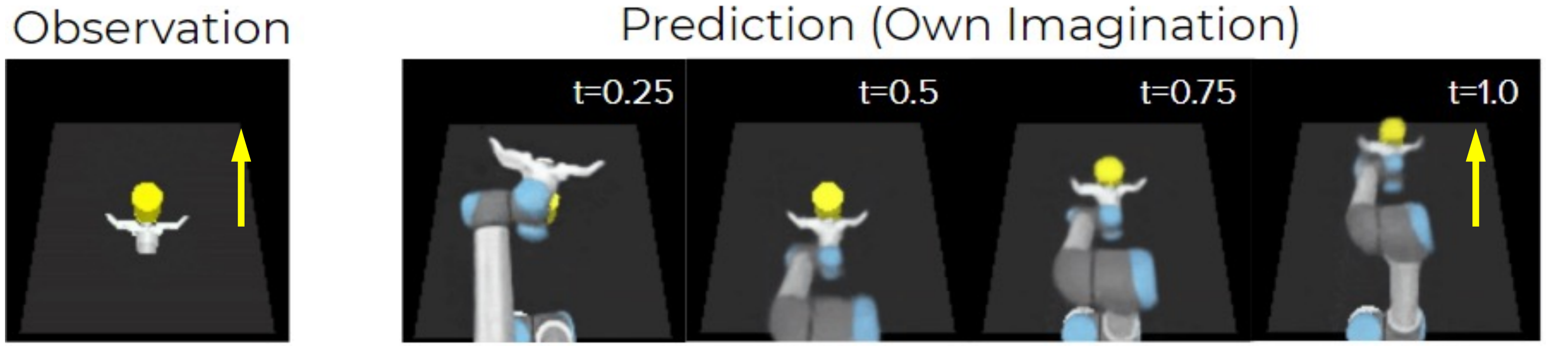
Whole body

Body-centered coordinate



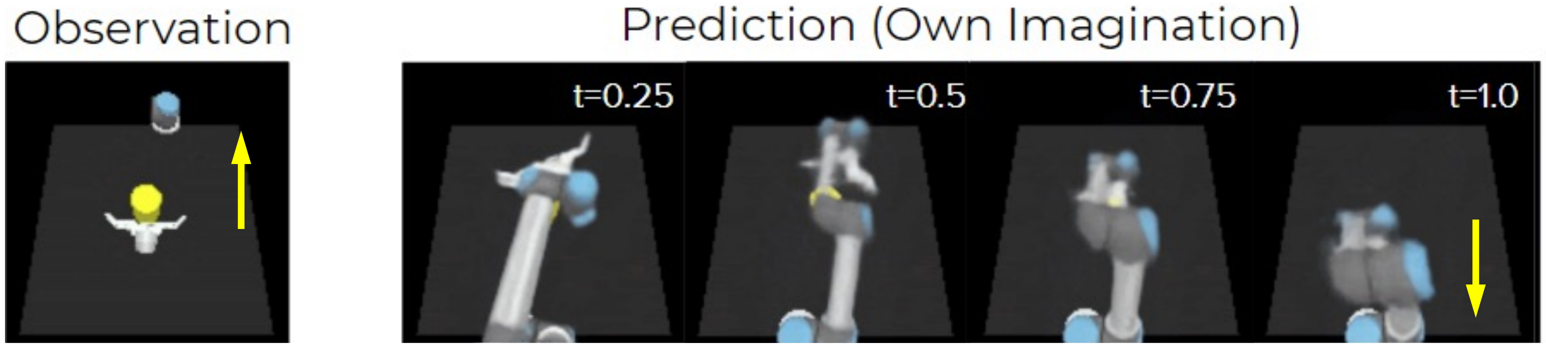
Hand

World-centered coordinate



Hand + part of arm

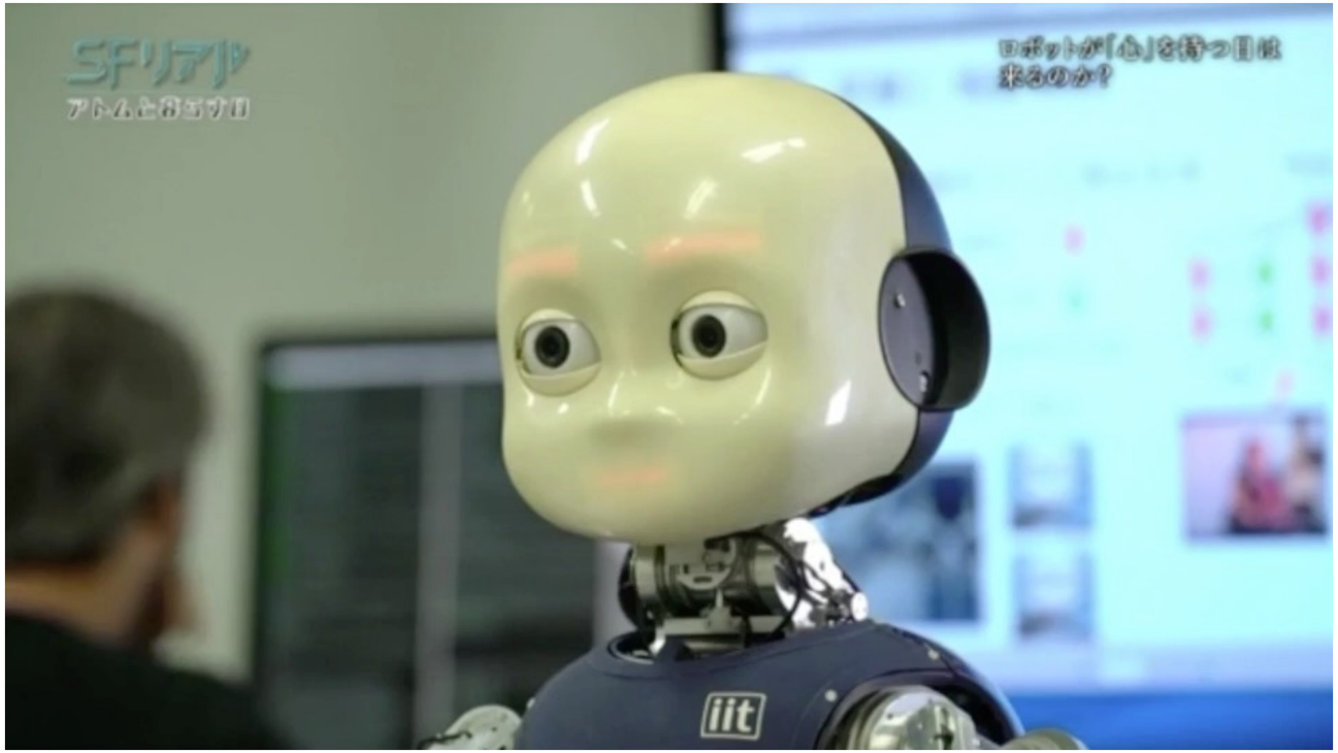
Body-centered coordinate



Development of Emotion and Its Inference

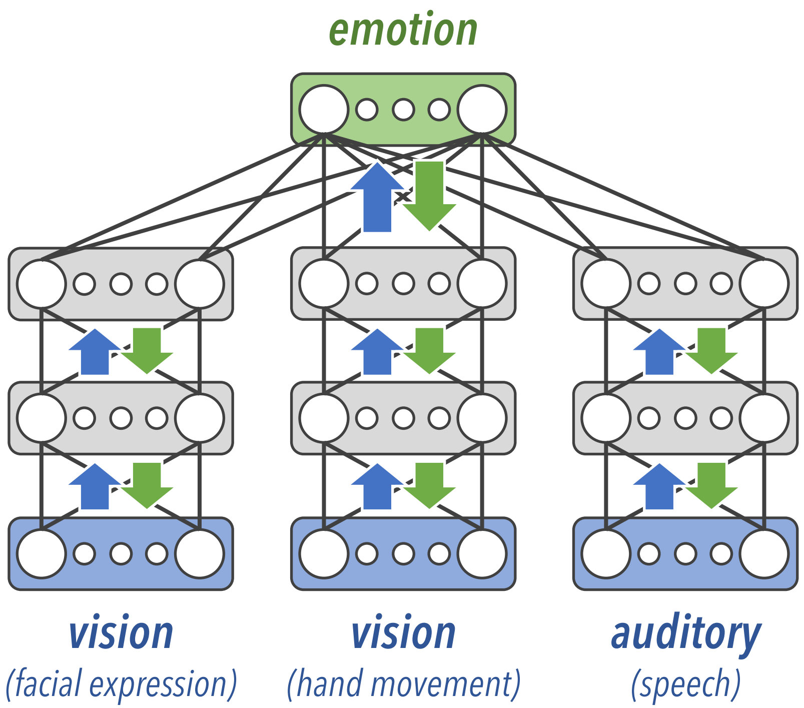
[Horii, Nagai, & Asada, Paladyn 2016; IEEE TCDS 2018]

- Prediction error minimization of multimodal sensory signals enables robots to acquire emotion categories and the ability to infer other's emotion.



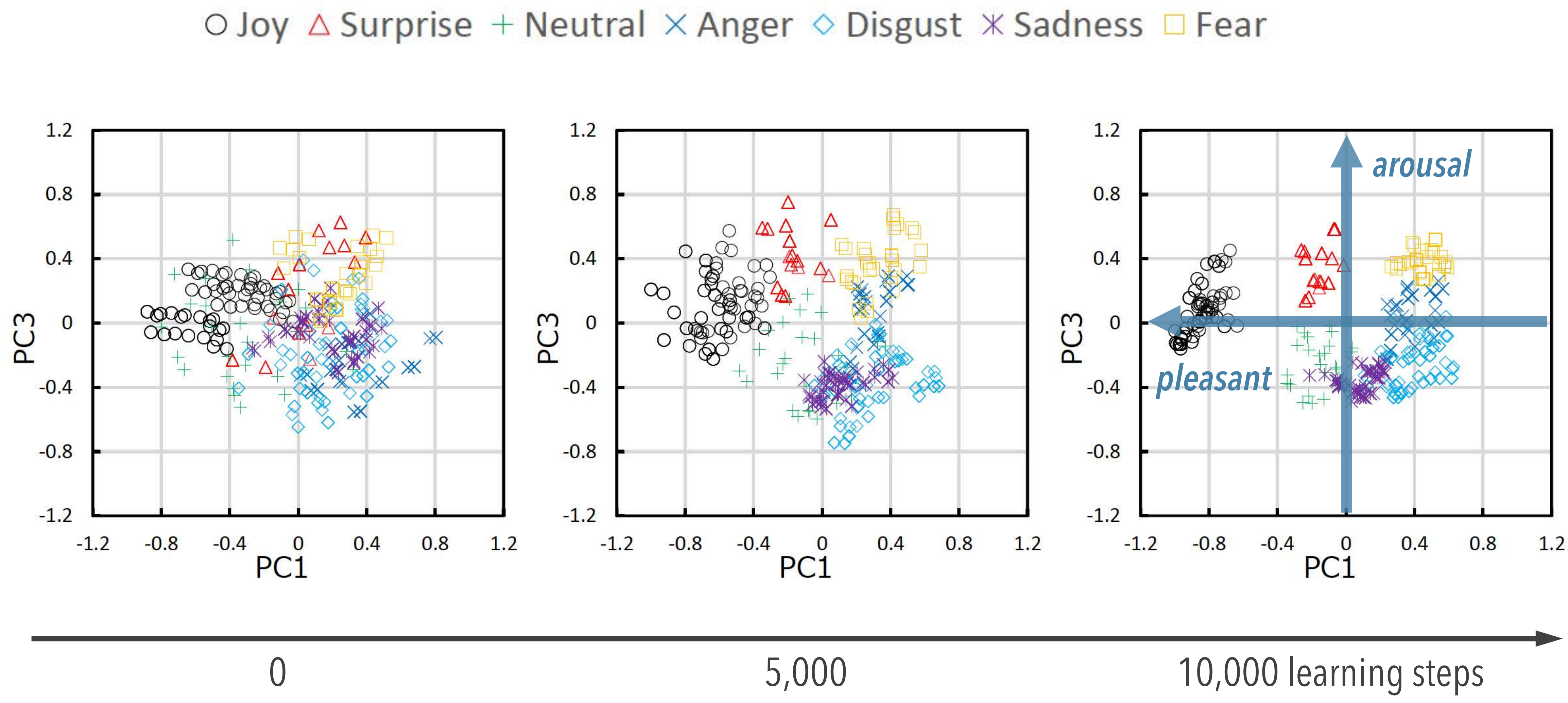
(NHK, 2016.08.23)

Multimodal deep belief network



Exp 1: Developmental Differentiation of Emotion

[Horii, Nagai, & Asada, IEEE TCDS 2018]



Exp 2: Emotion Estimation Facilitated by Mental Simulation

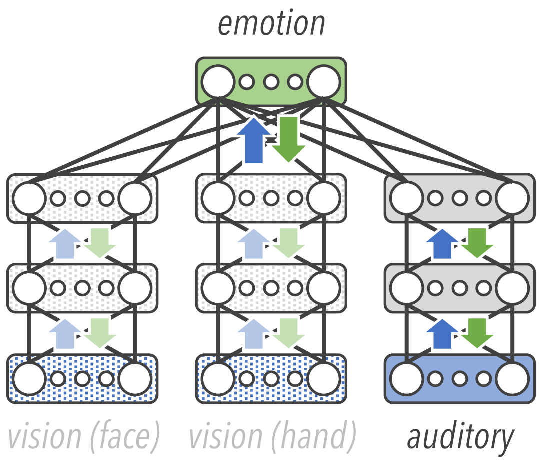
[Horii, Nagai, & Asada, Paladyn 2016]

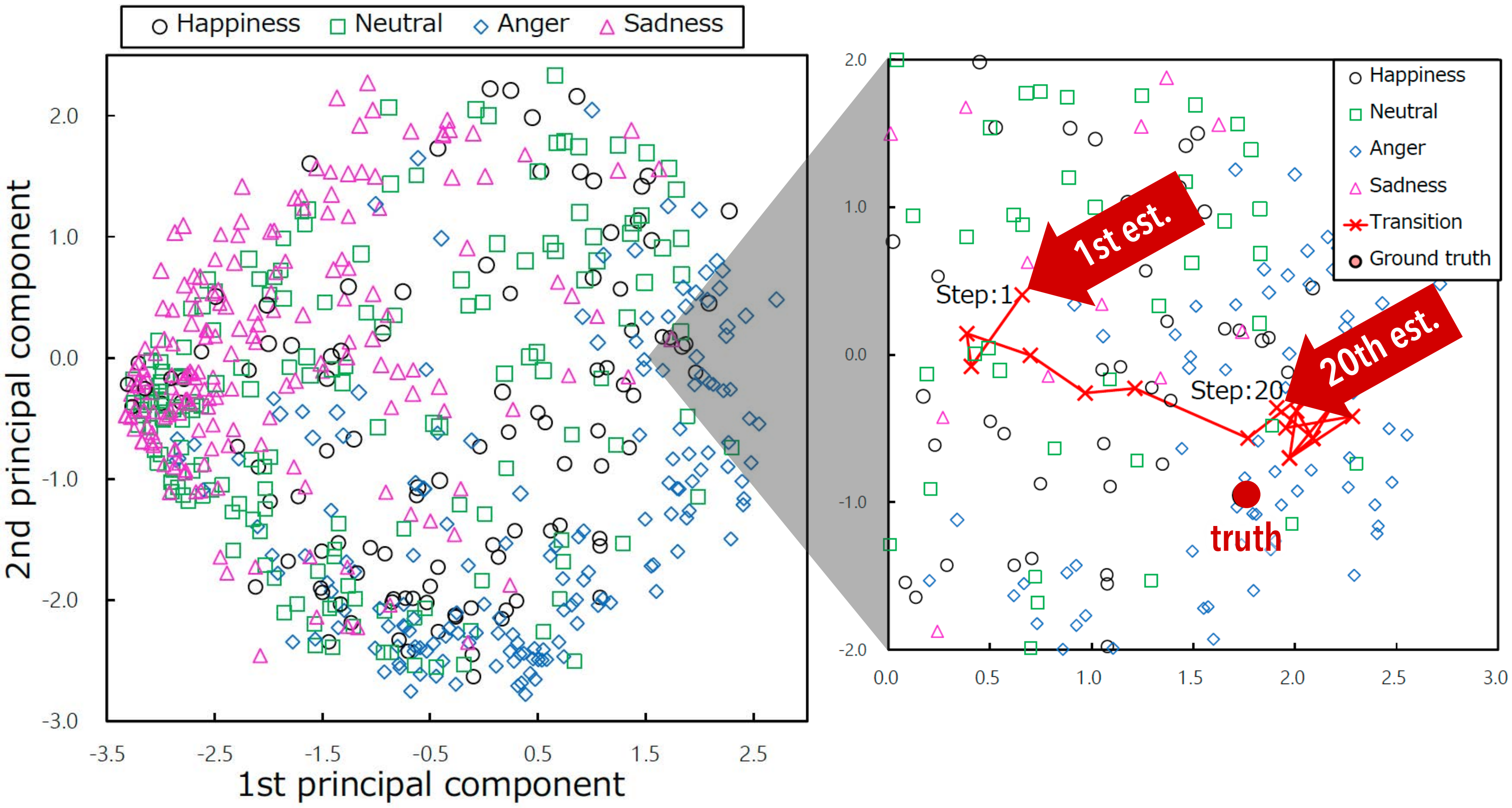
Training

- Given all modality signals

Testing:

- Given only auditory signal
  → prediction of imaginary visual signals

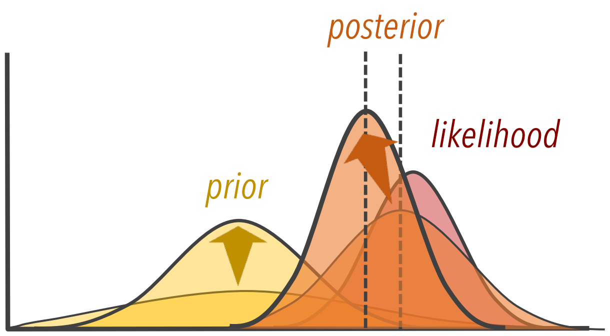




Summary: Social Development Based on Predictive Coding

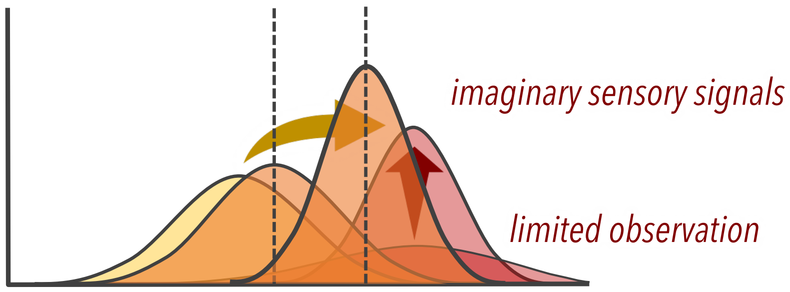
Development of sensorimotor abilities

To acquire precise priors through sensorimotor experiences



Emergence of social abilities

To estimate other's intention by
predicting imaginary sensory signals using MNS



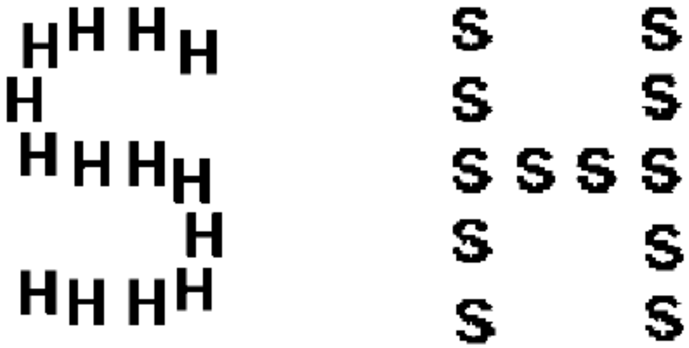
Individual Diversity in Cognitive Development

Autism Spectrum Disorder (ASD)

- Neurodevelopmental disorder characterized by:
  - Impaired social interaction and communication
  - Repetitive behaviors and restricted interests

  [Baron-Cohen, 1995; Charman et al., 1997; Mundy et al., 1986]

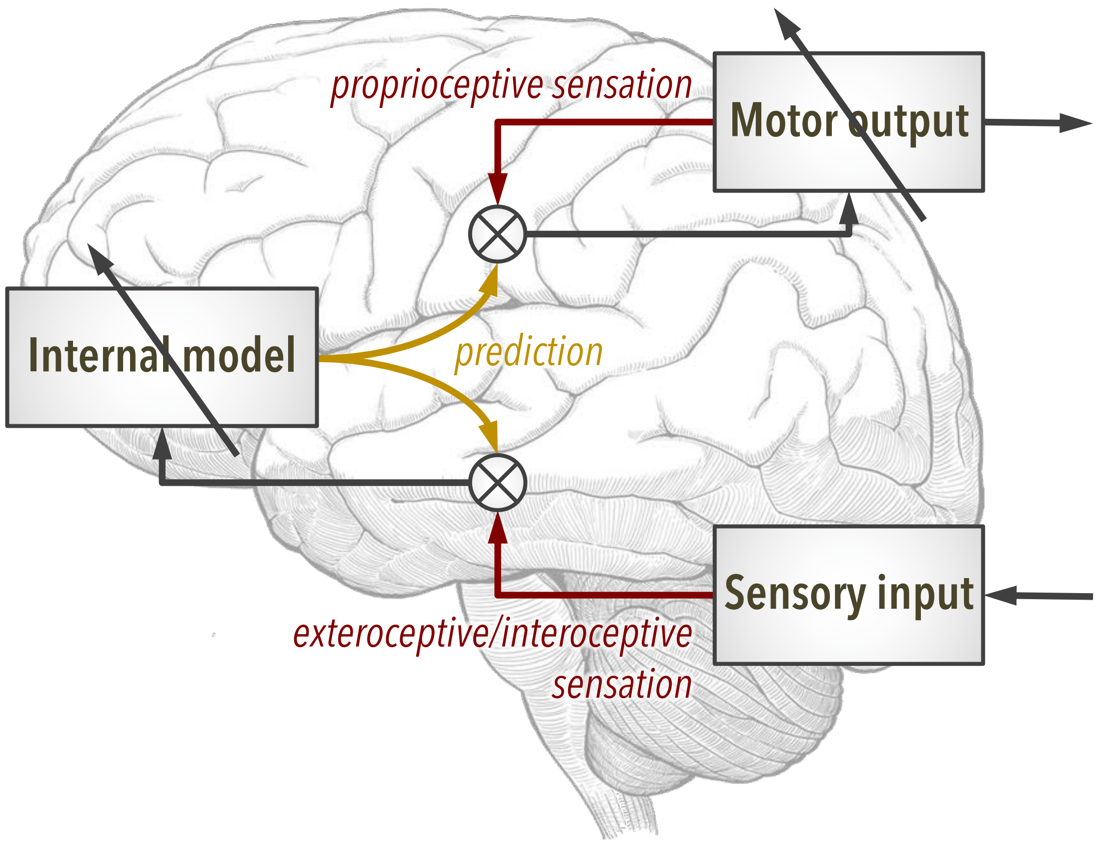
- Specific perceptual-cognitive style described as a limited ability to understand global context
  - Weak central coherence [Happé & Frith, 2006]
  - Local information processing bias
    [Behrmann et al., 2006; Jolliffe & Baron-Cohen, 1997]



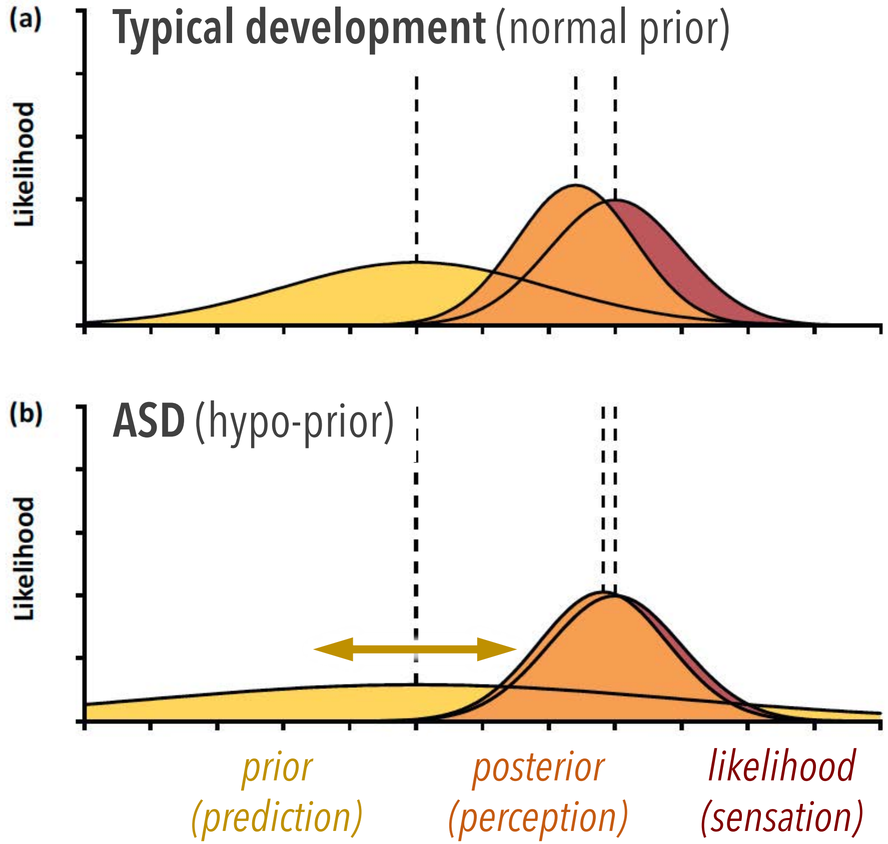
[Behrmann et al., 2006]

Predictive Coding Account for ASD

- Aberrant precision of top-down predictions may cause atypical cognitive abilities in ASD. [Brock, 2012]

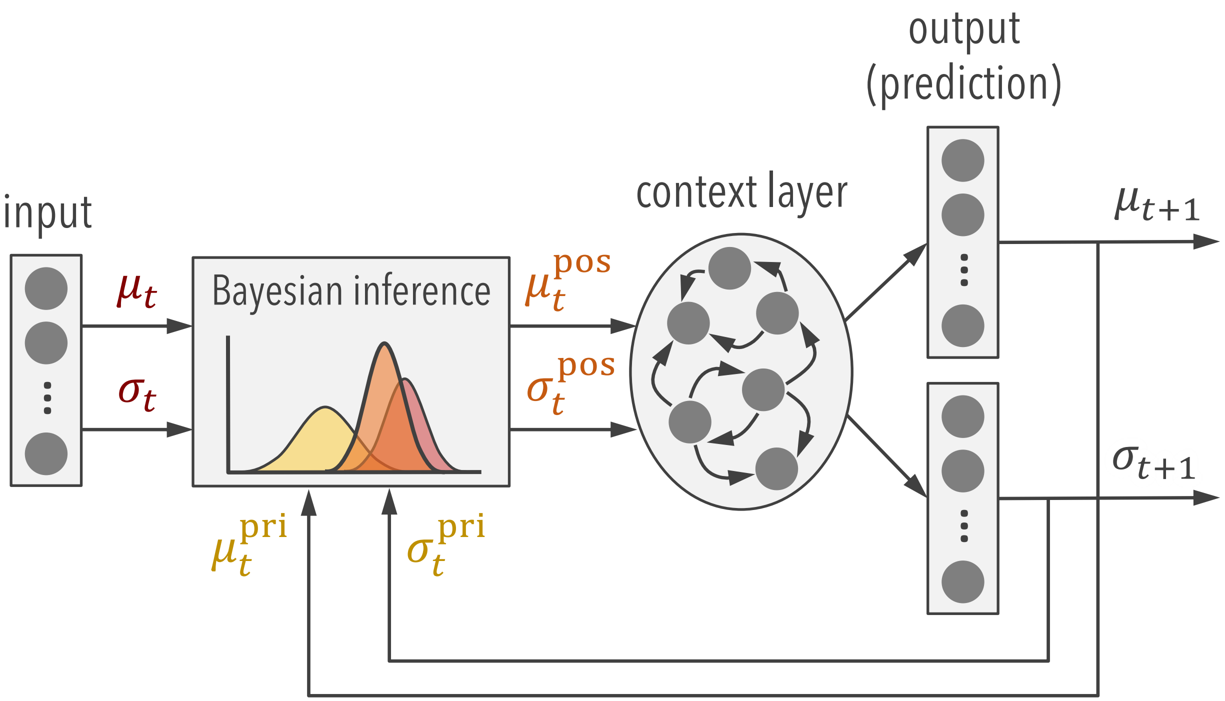


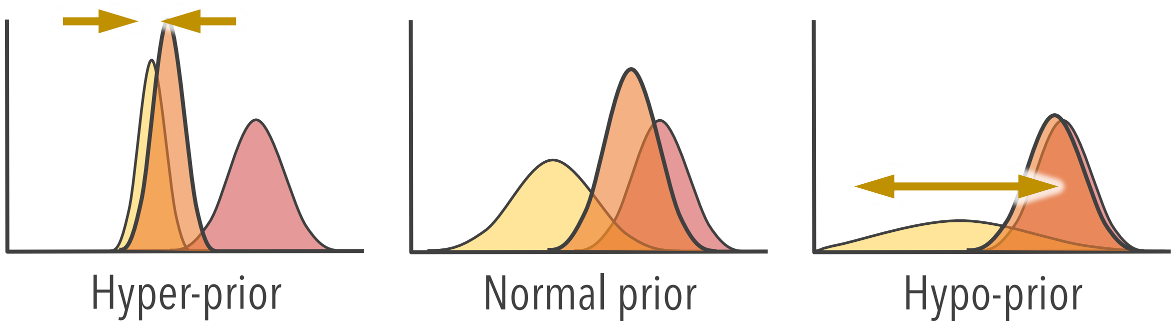
Modified from [Friston & Frith, 2015]



[Brock, 2012]

Recurrent Neural Network of Bayesian-Based Predictive Coding [Oliva, Philippsen, & Nagai, ICDL-EpiRob 2019]

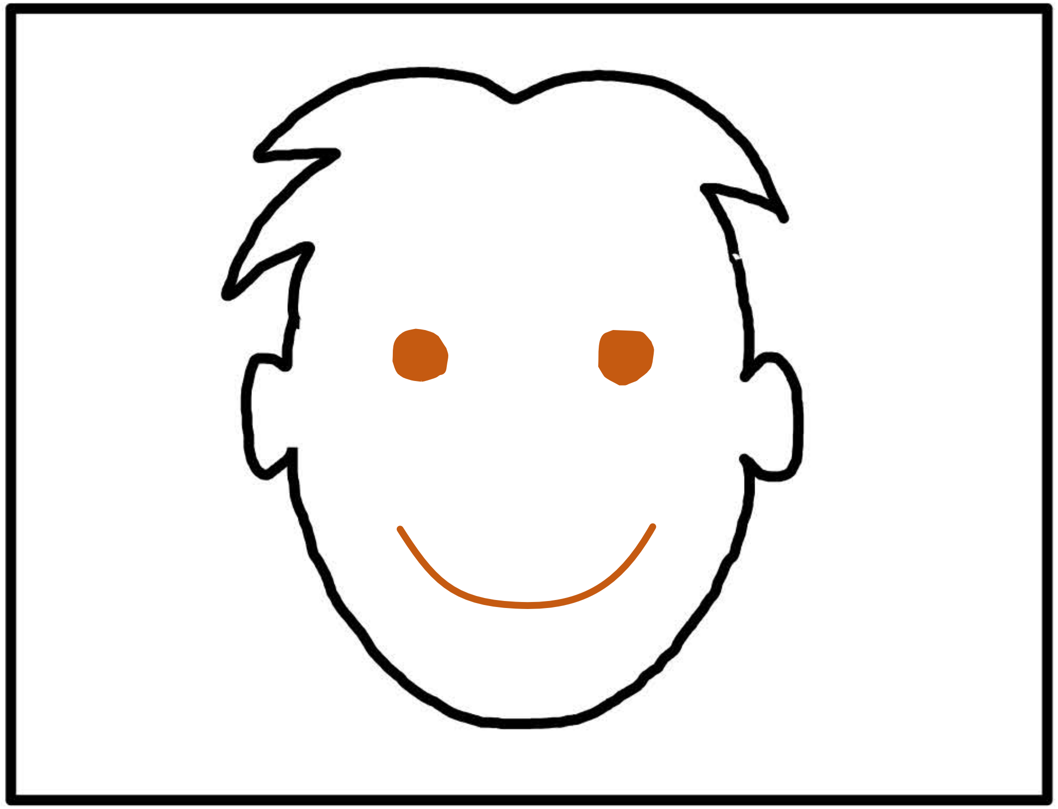


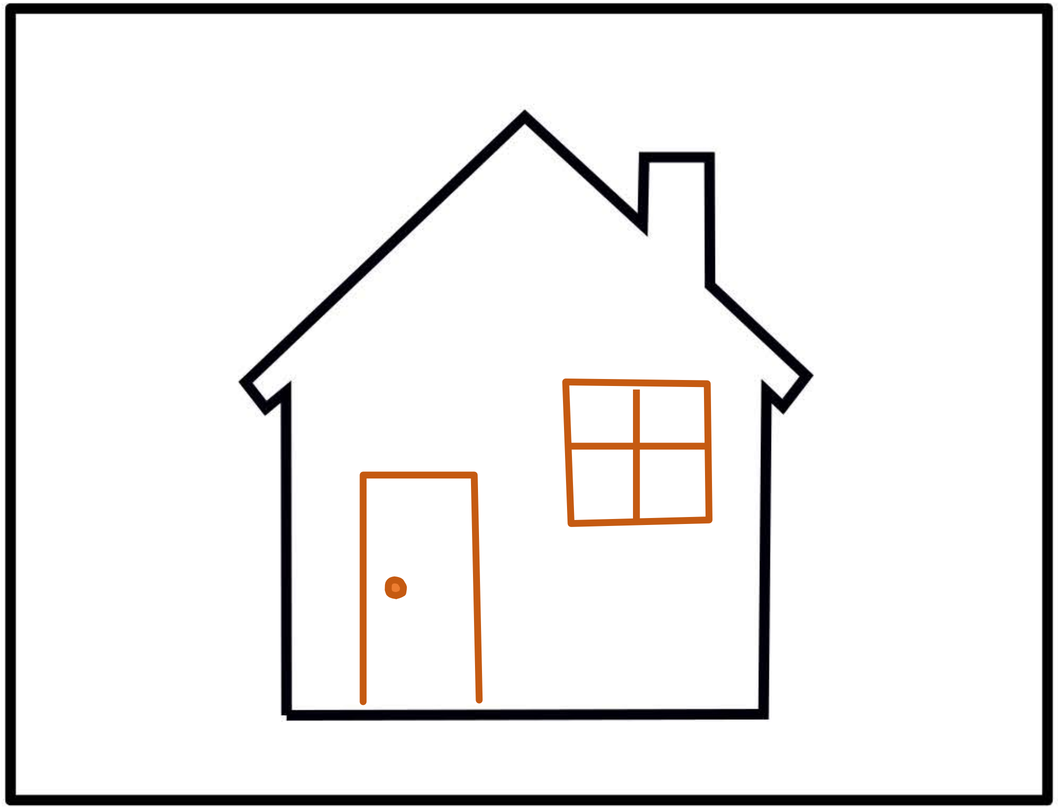


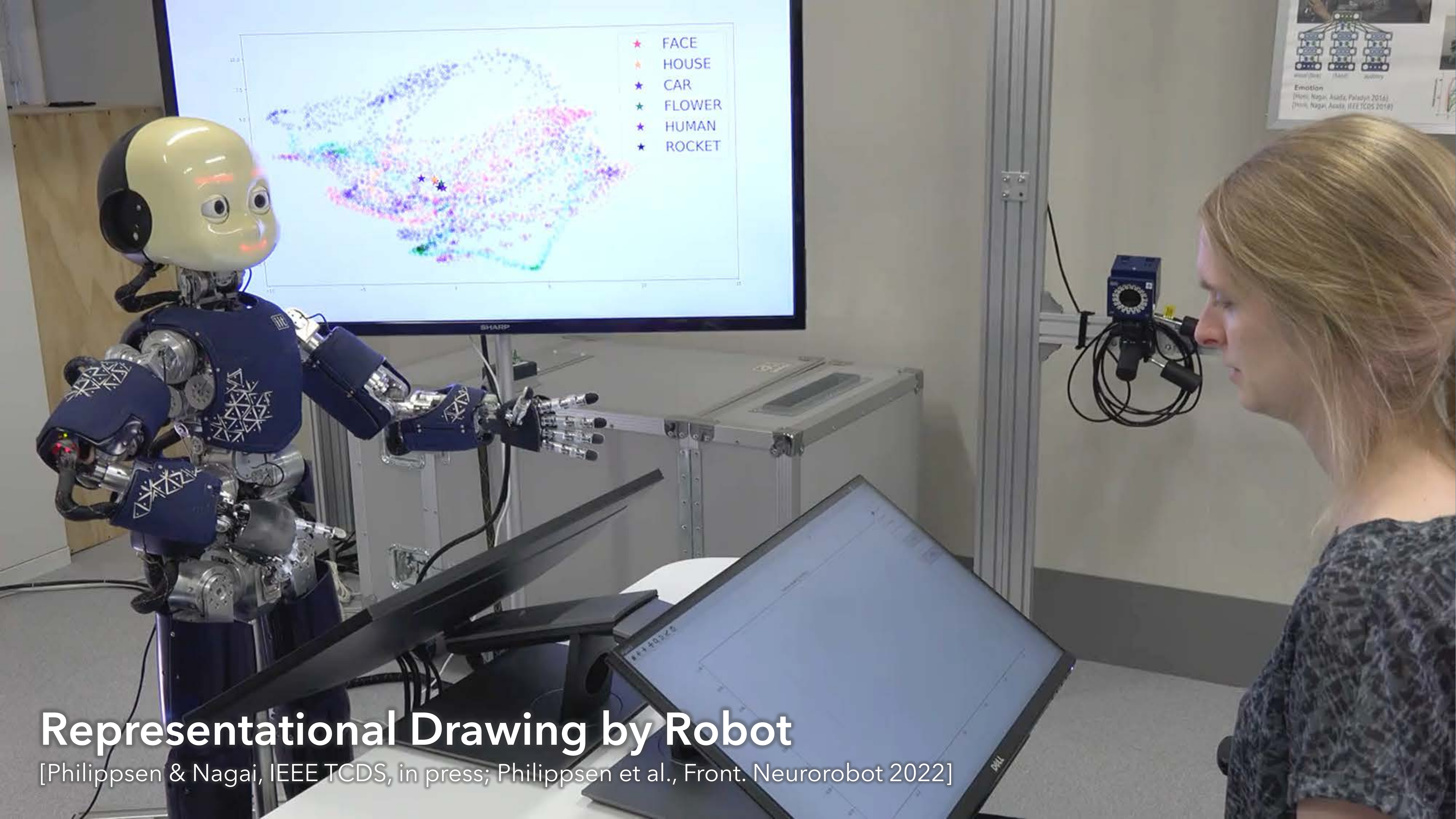
- To learn to predict the mean and variance $(\boldsymbol{\mu}_{t+1}, \boldsymbol{\sigma}_{t+1})$ of the sensory signal at the next time step based on $(\boldsymbol{\mu}_t, \boldsymbol{\sigma}_t)$
  [Murata et al., 2013]
- To generate the posterior $\boldsymbol{\mu}_t^{\text{pos}}$ by integrating $\boldsymbol{\mu}_t$ with the prior $\boldsymbol{\mu}_t^{\text{pri}}$ based on Bayes' theorem

- **Our hypothesis**
  – Hyper-priors as well as hypo-priors produce atypical cognitive abilities in ASD

Cognitive Task: What to Draw?





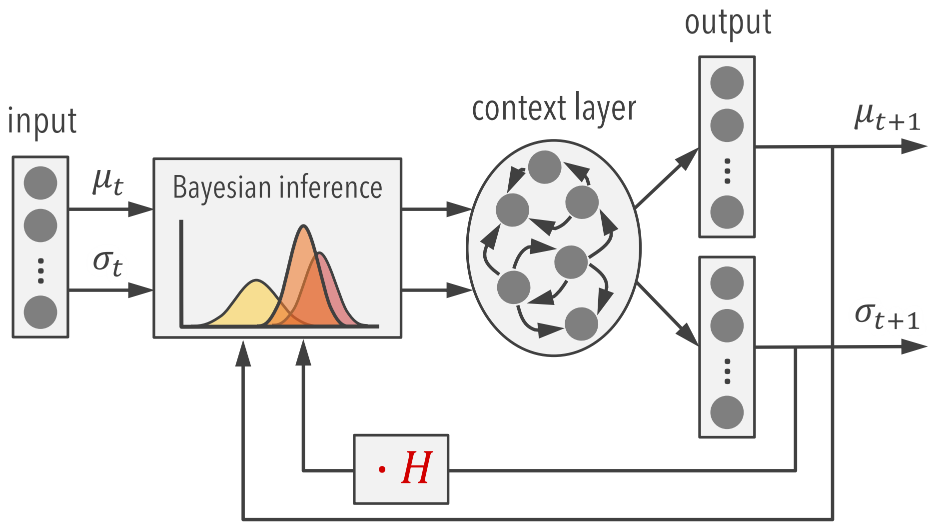


Representational Drawing by Robot

[Philippsen & Nagai, IEEE TCDS, in press; Philippsen et al., Front. Neurorobot 2022]

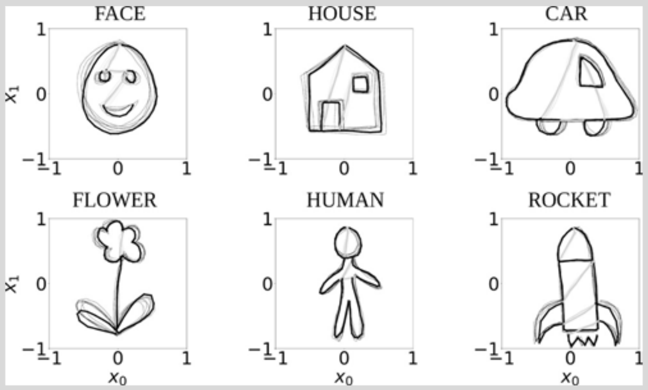
Learning of Representational Drawing with RNN

[Philippsen & Nagai, IEEE TCDS, in press; Philippsen et al., Front. Neurorobot 2022]

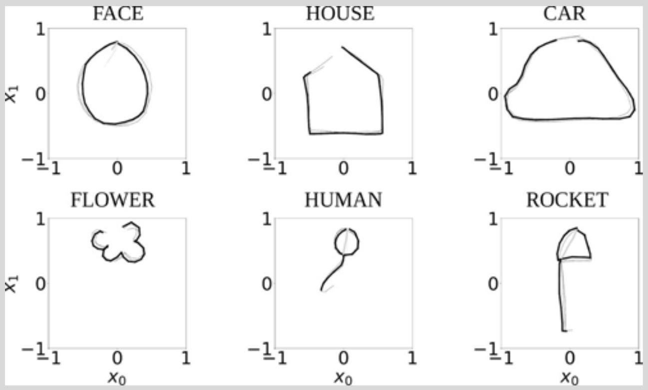


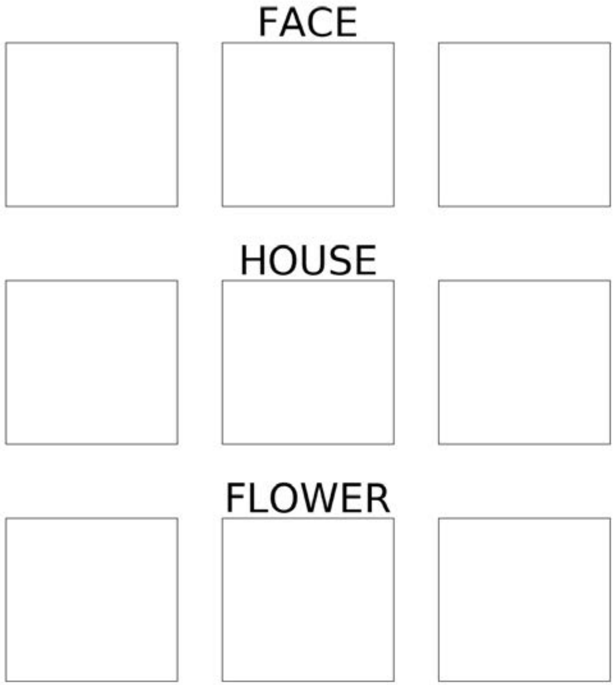
- How aberrant precision of predictions H affects the drawing ability of a neural network
  - Training: learn to draw six types of objects
  - Testing: infer the intended objects from the first 33% of trajectories and complete missing parts

Training data



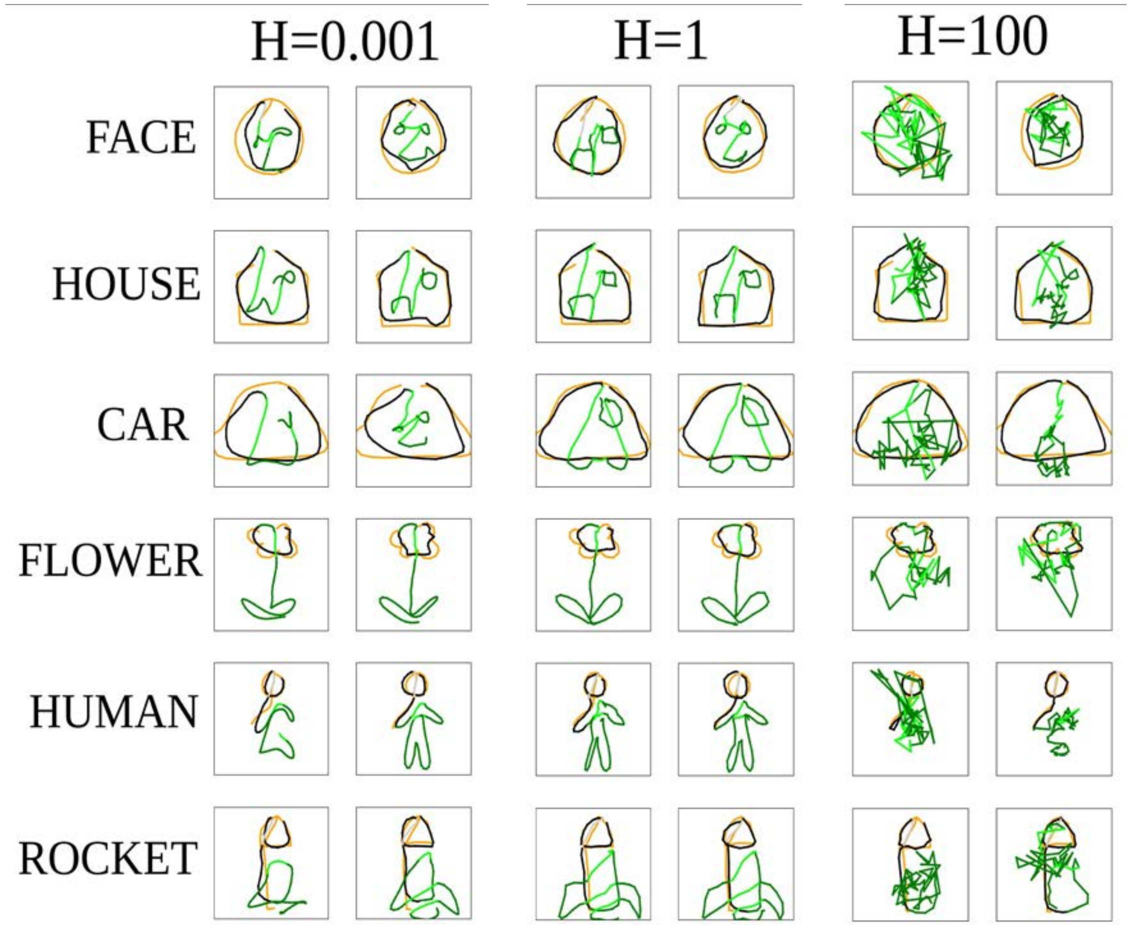
Testing data



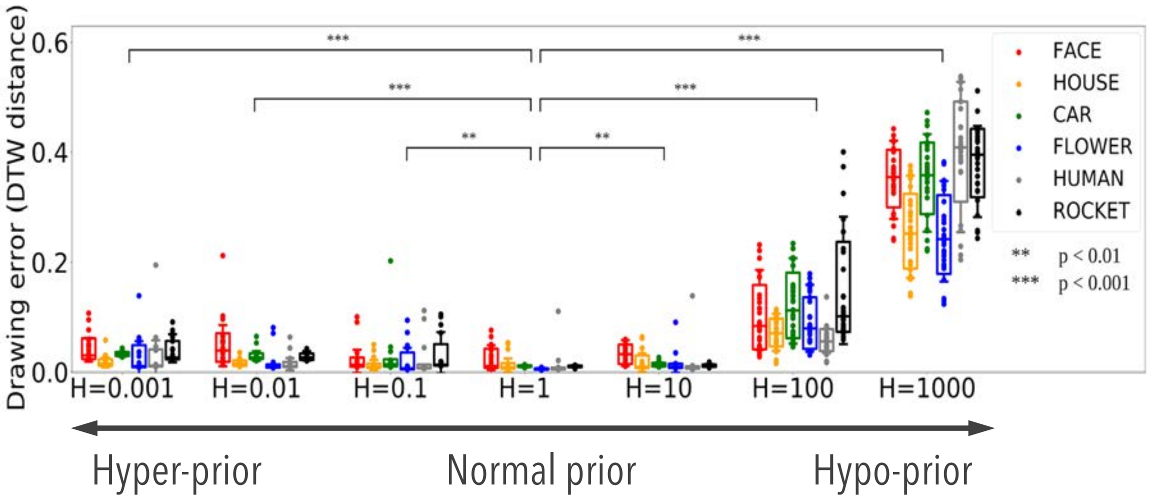


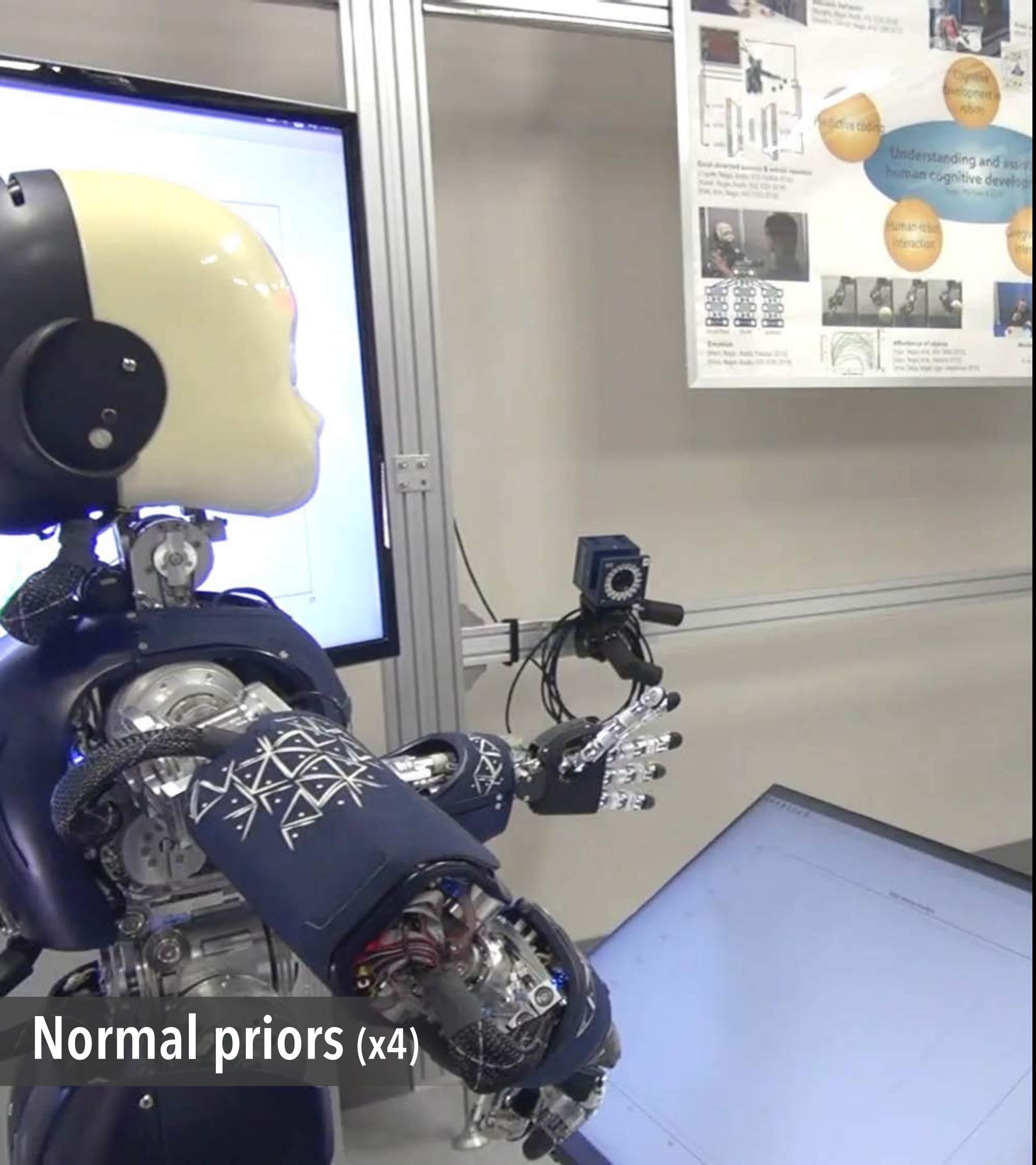
Exp 1: Influence of Aberrant Prediction on Drawing

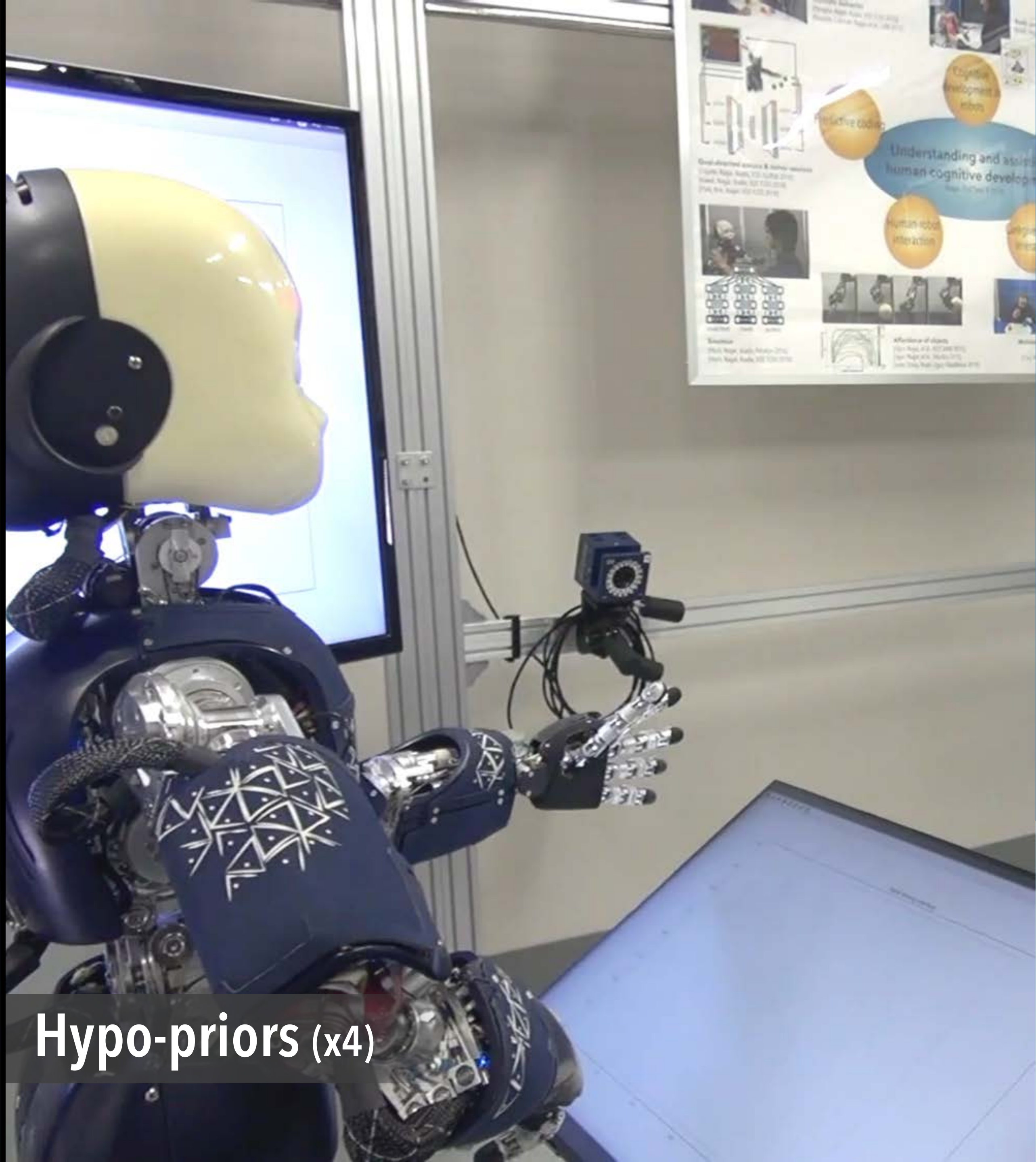
[Philippsen & Nagai, IEEE TCDS, in press; Philippsen et al., Front. Neurorobot 2022]



- Influences of precision H
  - Hyper-priors ($H \ll 1$): misinterpretation of intended patterns, abstract drawing
  - Normal priors ($H \approx 1$): successful completion
  - Hypo-priors ($H \gg 1$): tracing, scribbling



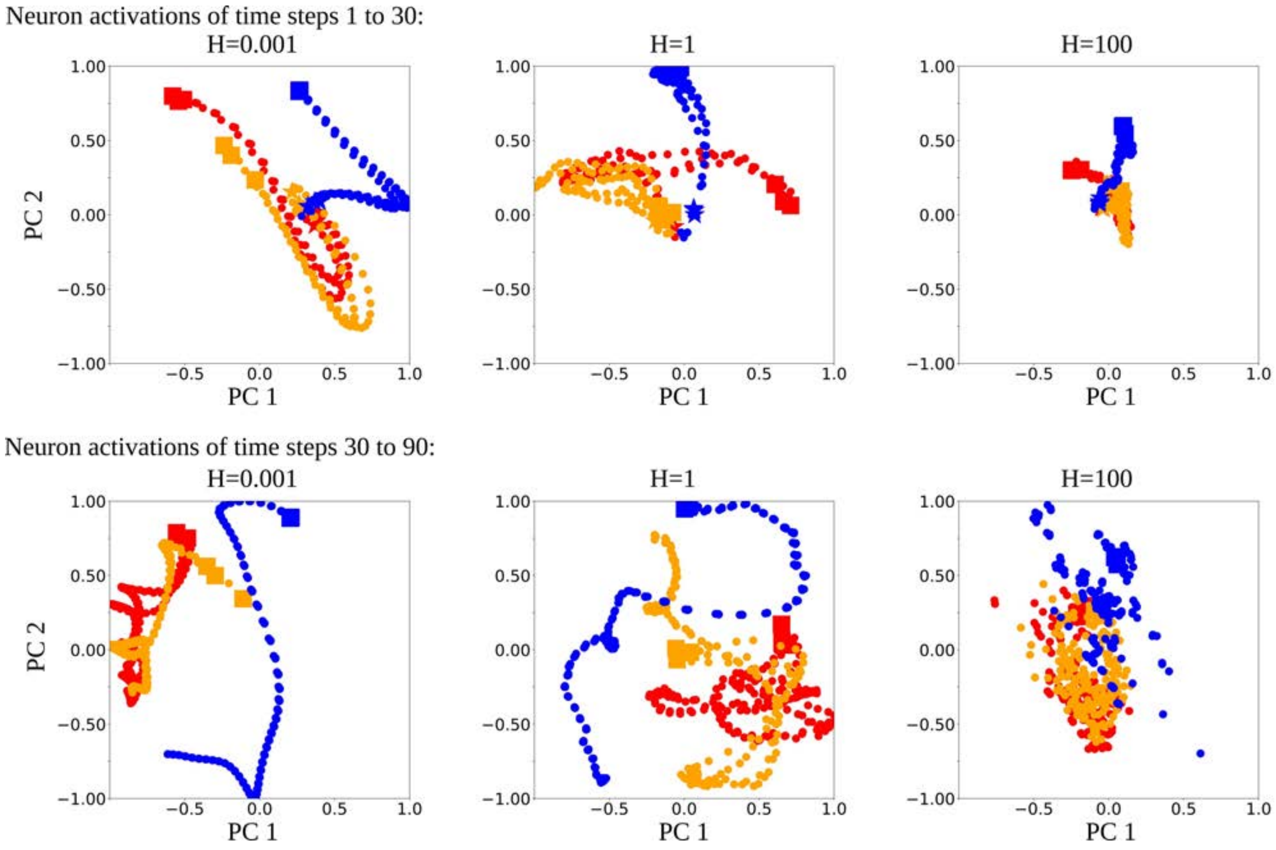

Normal priors (x4)


Hypo-priors (x4)

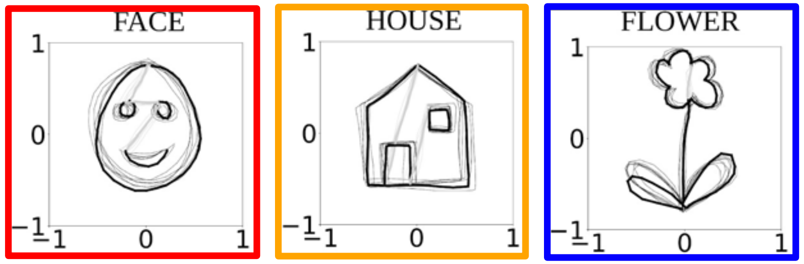
Exp 2: Influence of Aberrant Prediction on Internal Model

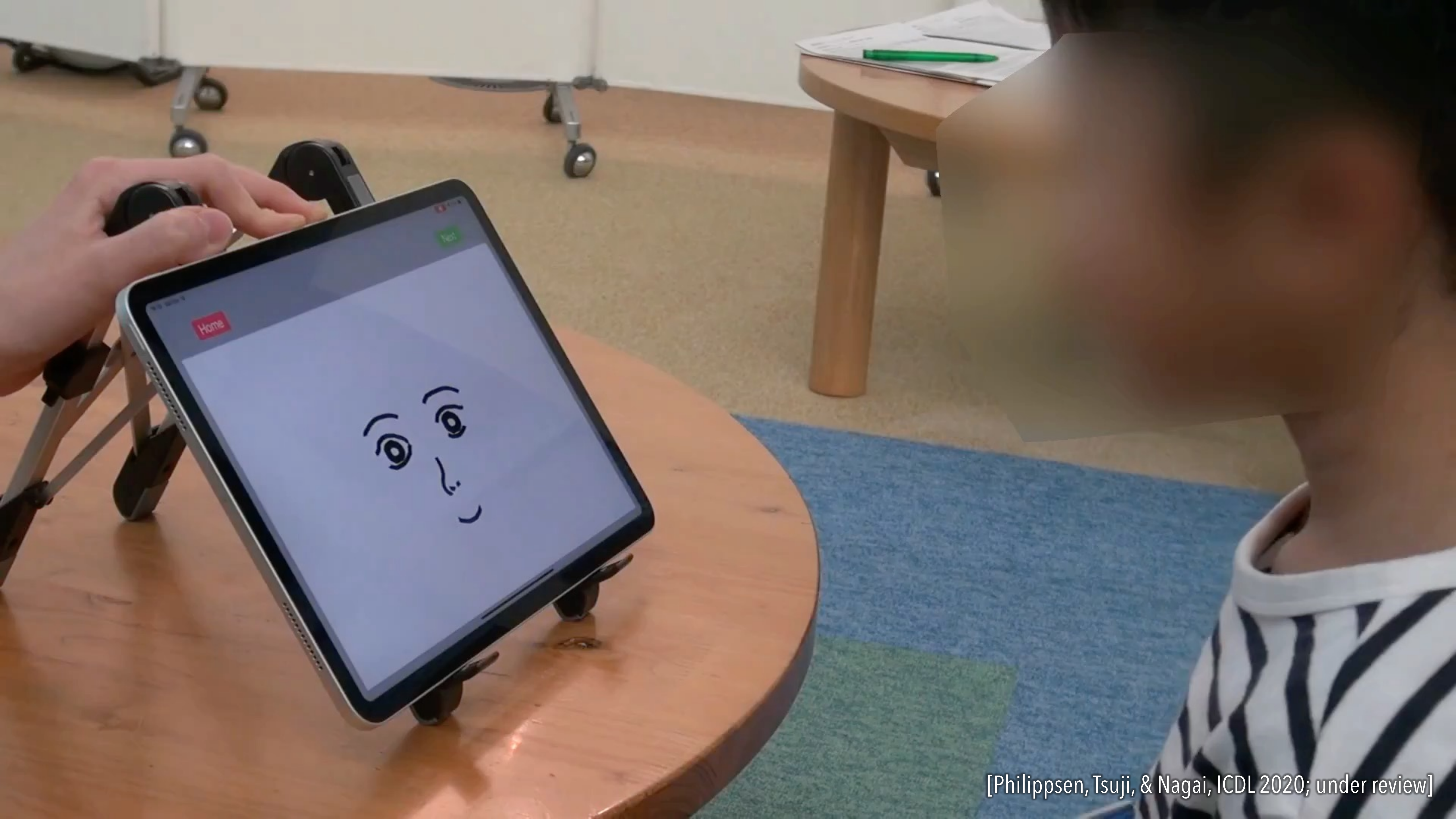
[Philippsen & Nagai, IEEE TCDS, in press; Philippsen et al., Front. Neurorobot 2022]

PCA space of 100 context neurons



- Influences of precision H
  - Hyper-priors ($H \ll 1$): undifferentiated strong attractors
  - Normal priors ($H \approx 1$): properly differentiated attractors
  - Hypo-priors ($H \gg 1$): no/weak attractors





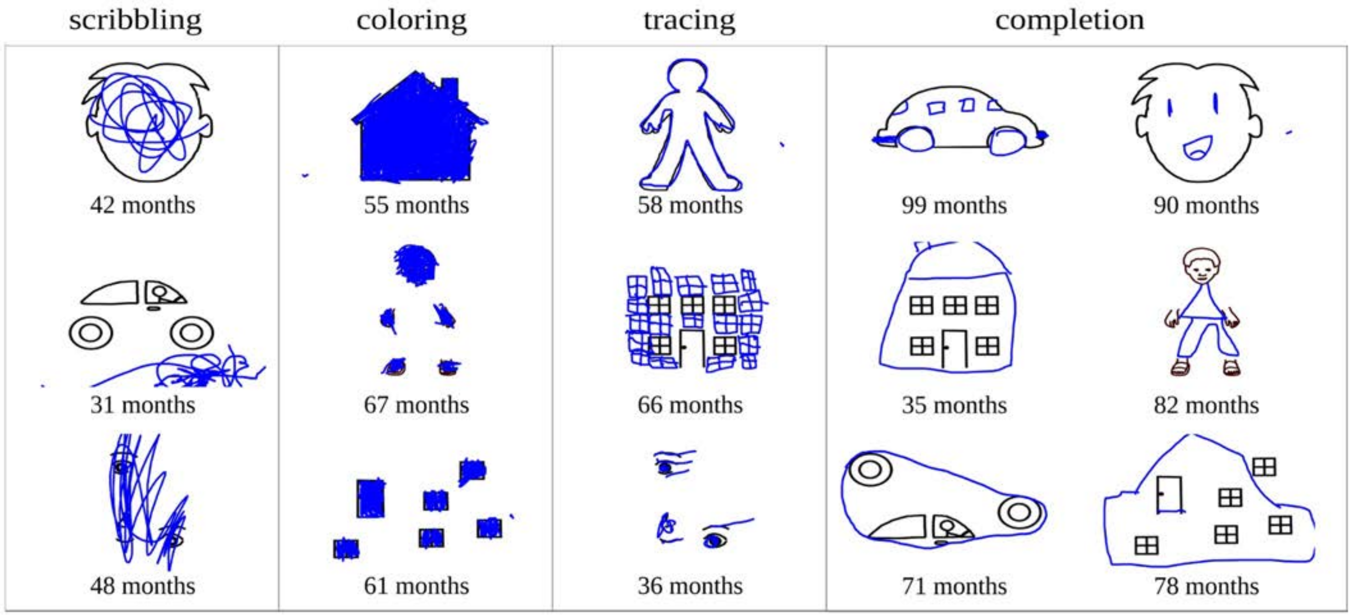
[Philippsen, Tsuji, & Nagai, ICDL 2020; under review]

Development of Representational Drawing in Children

[Philippsen, Tsuji, & Nagai, ICDL 2020; under review]

- How the drawing ability based on predictive processing develops with age
  - 104 typically-developing children (2-8 years old, 62M+42F)
  - 621 drawing data (given only outer/inner features)
  - AQ scores assessed by parents

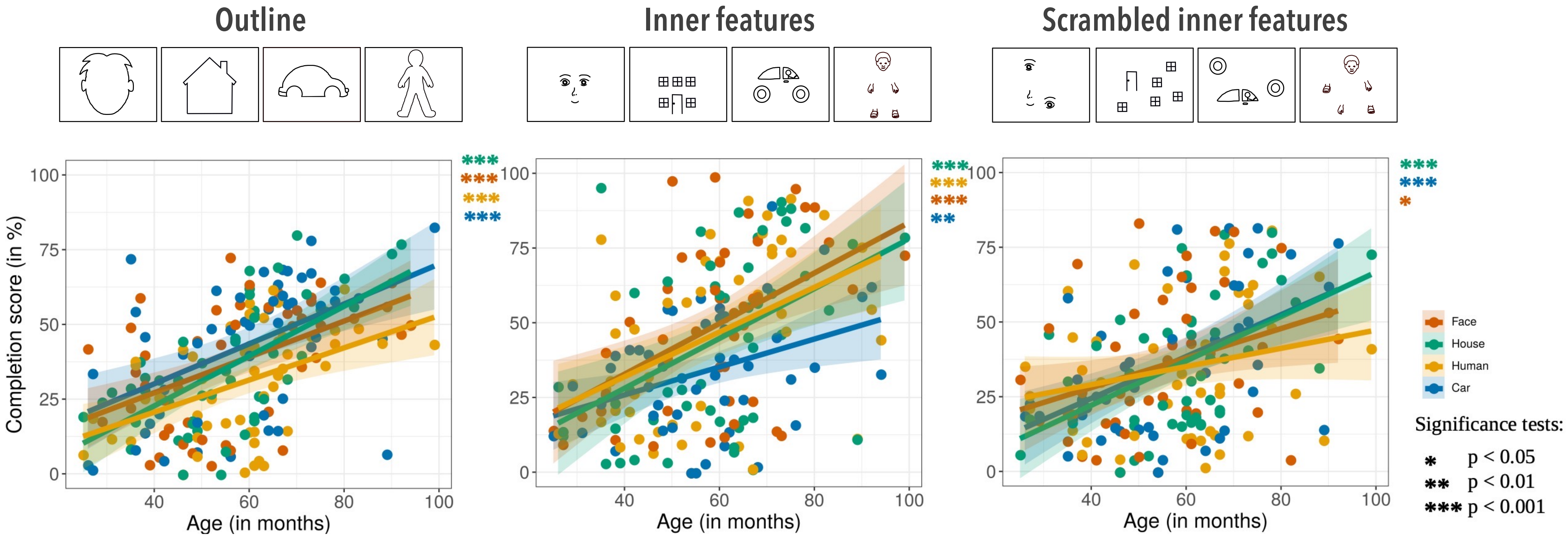
Children



Adults

Exp 1: Subjective Evaluation by Adult Rating

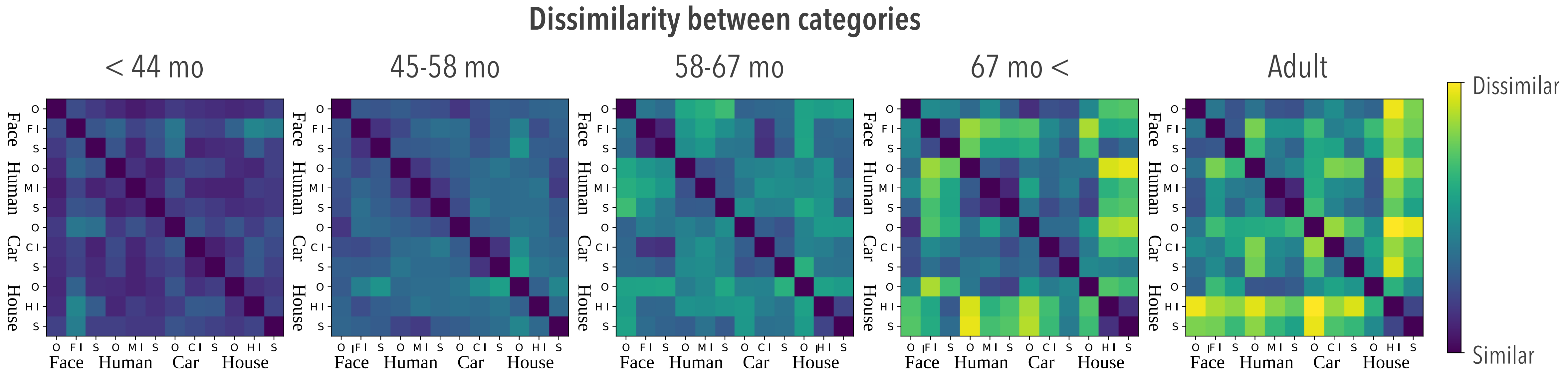
[Philippsen, Tsuji, & Nagai, ICDL 2020; under review]



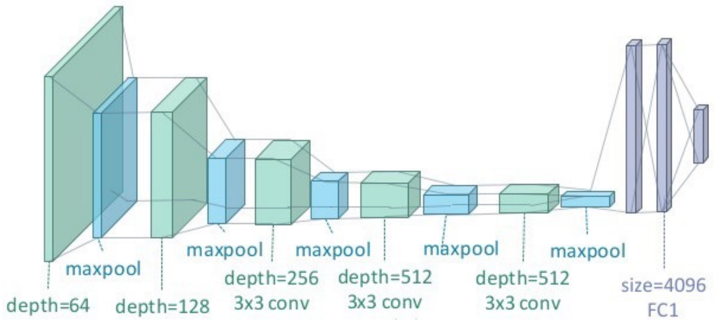
- Linear improvement in prediction and completion abilities with age
- More significant improvement in outline/inner features conditions

Exp 2: Categorical Drawings Evaluated by Convolutional NN

[Philippsen, Tsuji, & Nagai, ICDL 2020; under review]



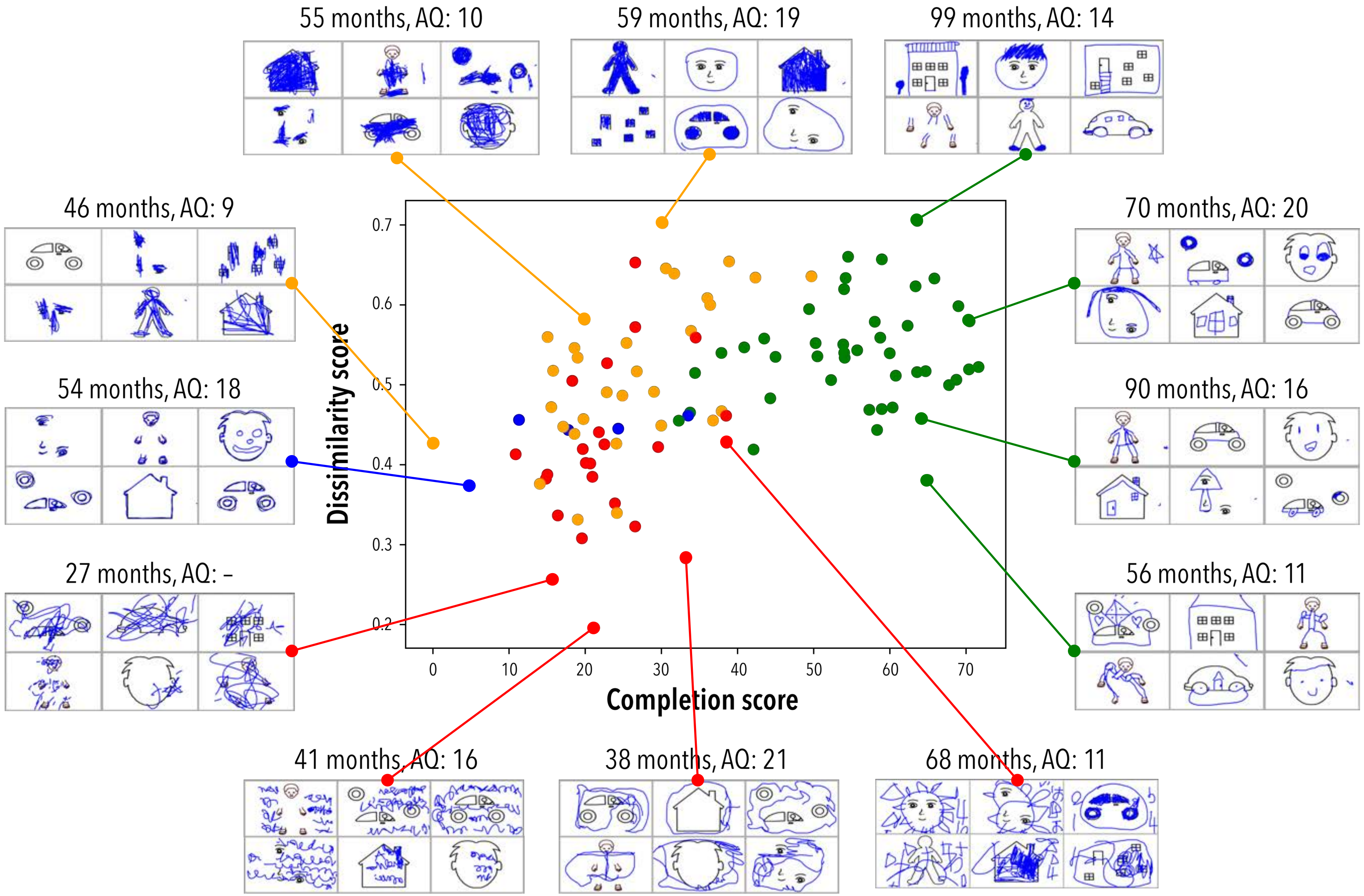
- Development of categorical representations with age
  - Younger childres: undifferentiated categories
  - Older children and adults: properly differentiated categories



DCNN pretrained on ImageNet dataset
[Simonyan & Zisserman, 2014]

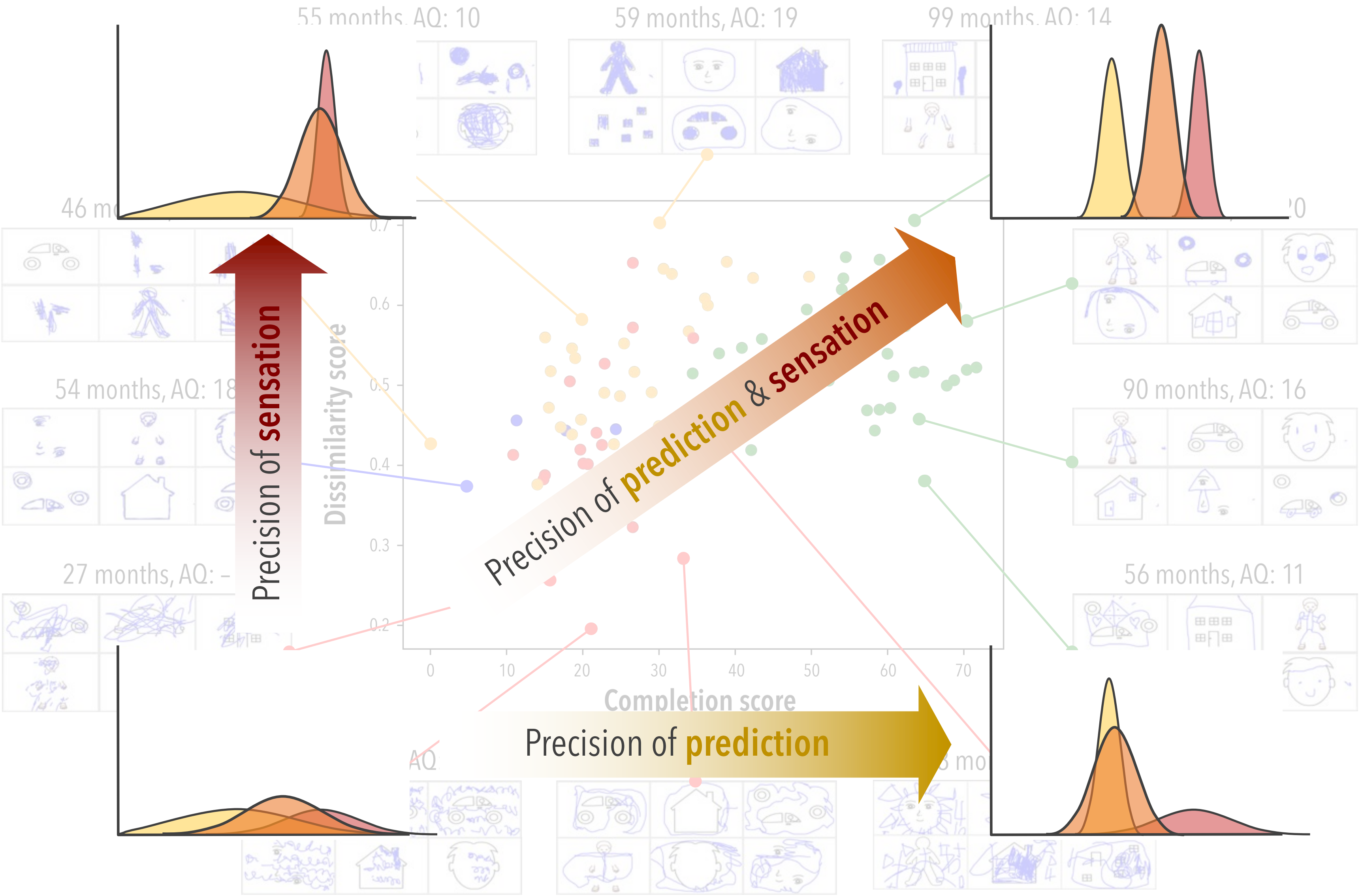
Exp 3: Developmental Diversity in Drawing

[Philippsen, Tsuji, & Nagai, under review]



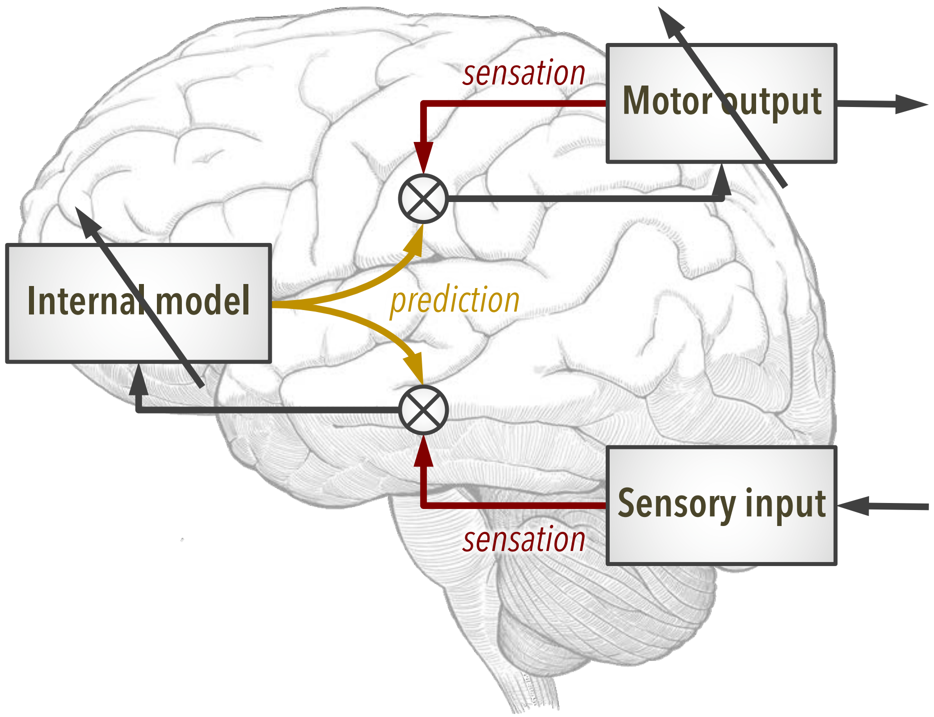
Exp 3: Developmental Diversity in Drawing

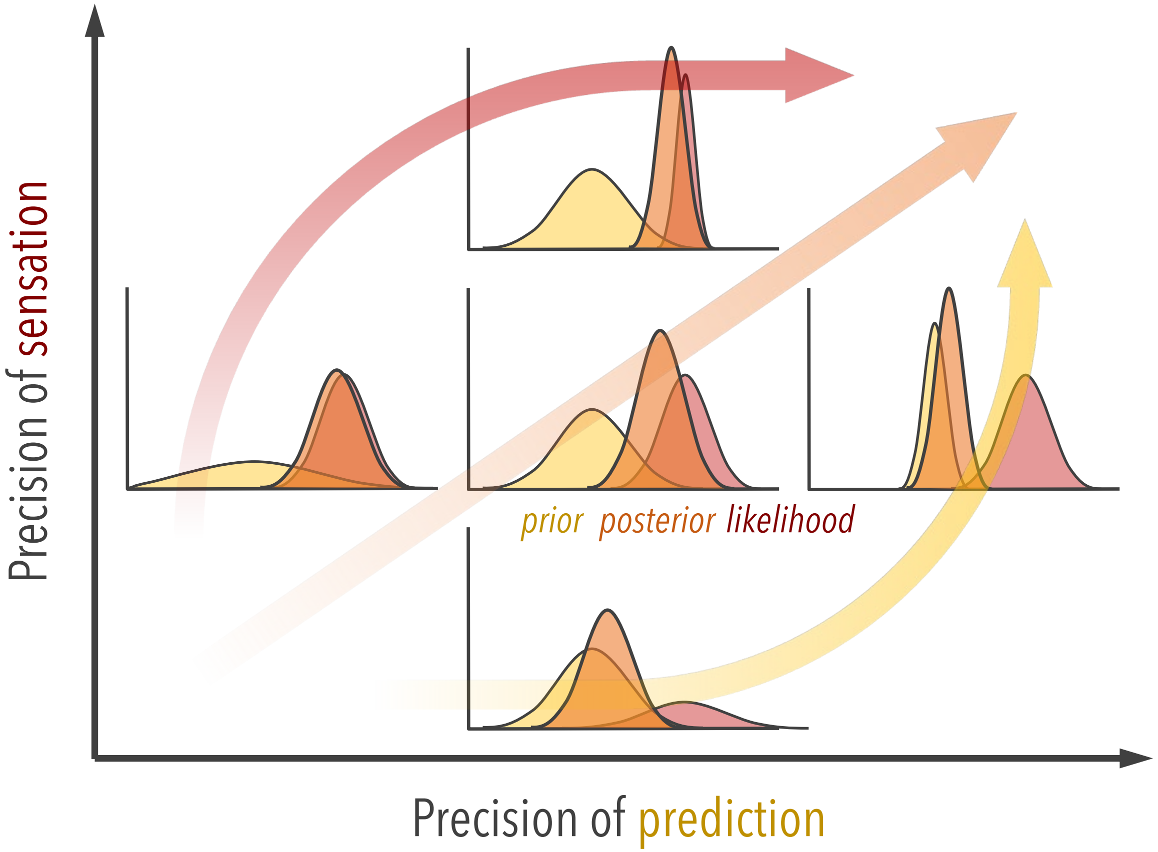
[Philippsen, Tsuji, & Nagai, under review]



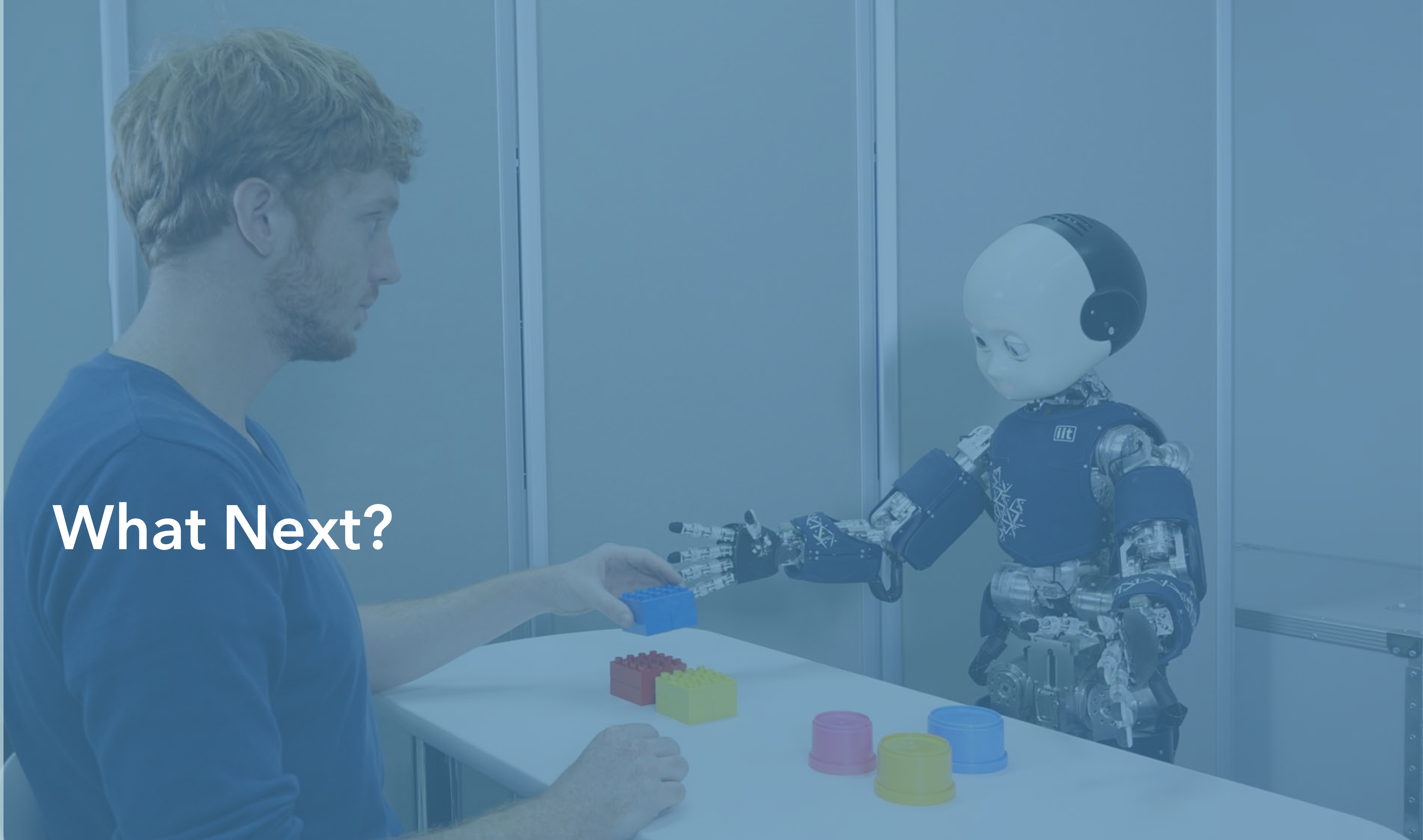
Summary: Indivisual Diversity Based on Predictive Coding

- Improvement in prediction and sensation leads to social cognitive development.
- Imbalance between prediction and sensation produces individual diversities.

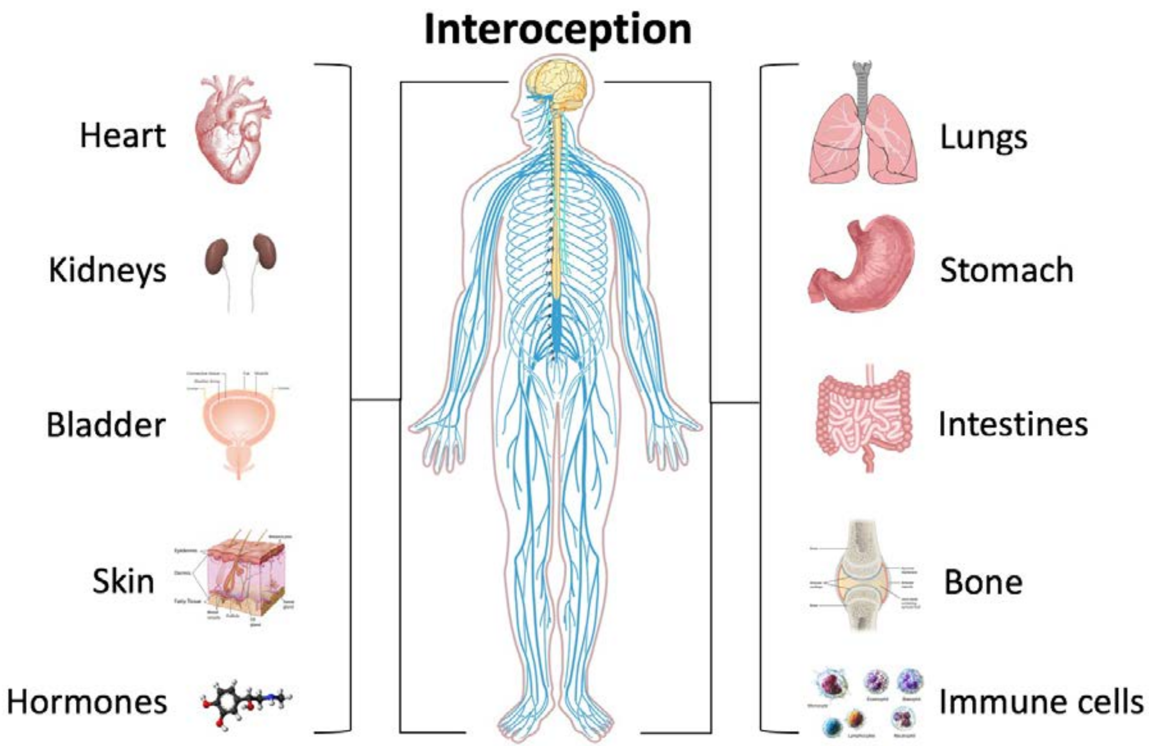




What Next?

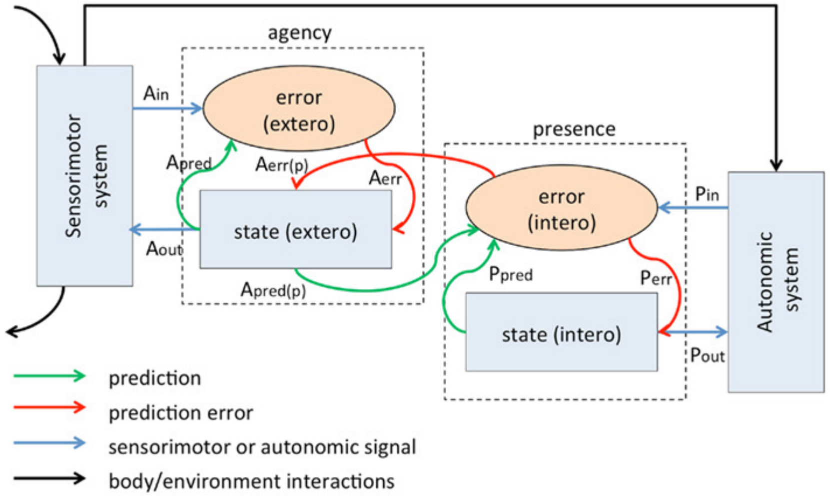


Predictive Coding with Interoception

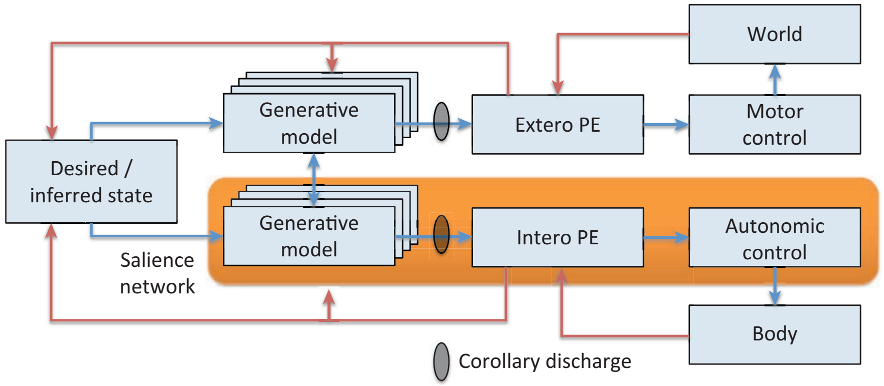


- Self recognition and emotion based on interoceptive and exteroceptive predictive coding [Seth et al., 2012; Seth & Friston, 2016]
- Interoception and prediction error
  - Conscious interoception caused by prediction errors or updates of internal models [Barrett & Simmons, 2015; Khalsa et al., 2015]
  - Autonomic nervous responses produced by interoceptive prediction errors [Thayer & Lane, 2000]
- Atypical interoception in ASD
  - Lower accuracy and higher sensitivity of interoceptive perception [Critchley & Garfinkel, 2017]

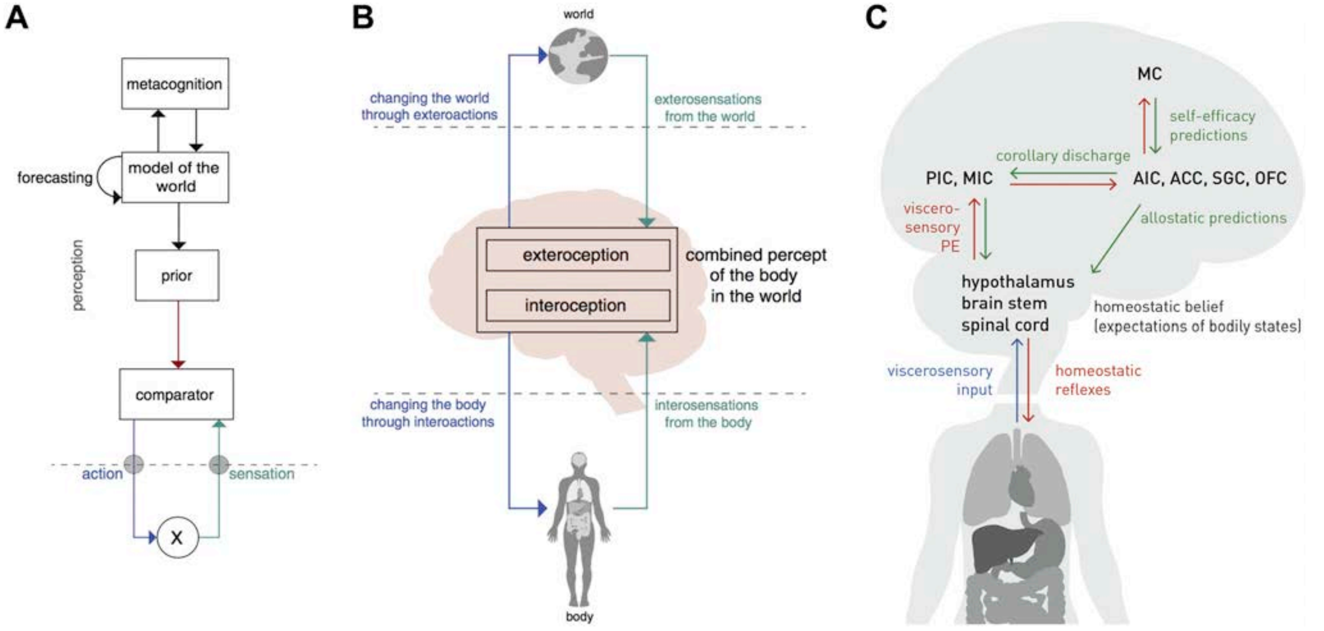
How to Integrate Interoception and Exteroception?



[Seth, Suzuki, & Critchley, 2012]

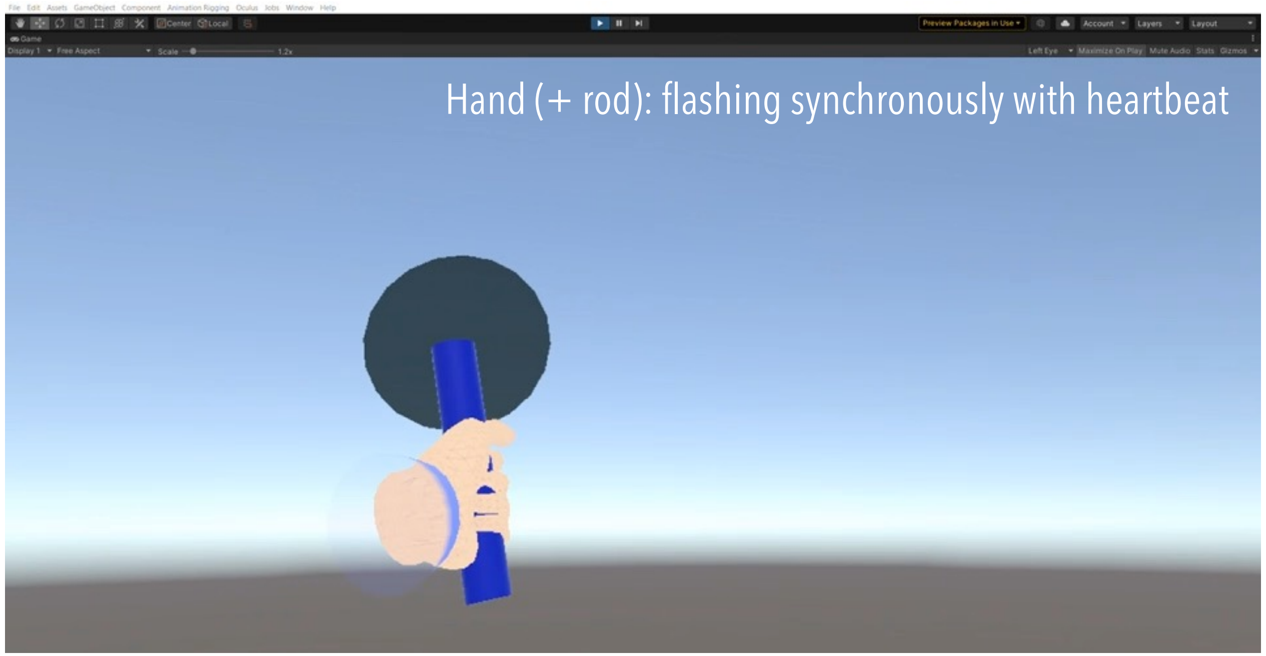


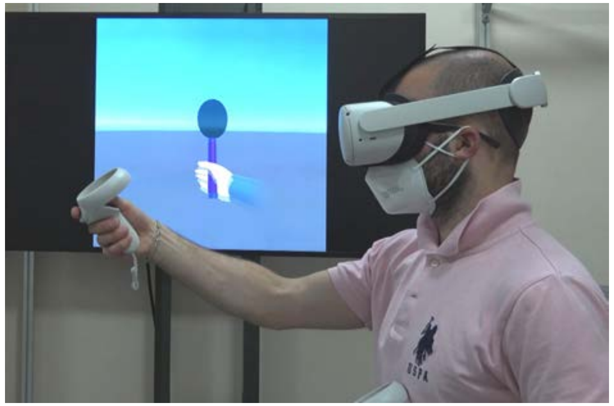
[Seth, 2013]

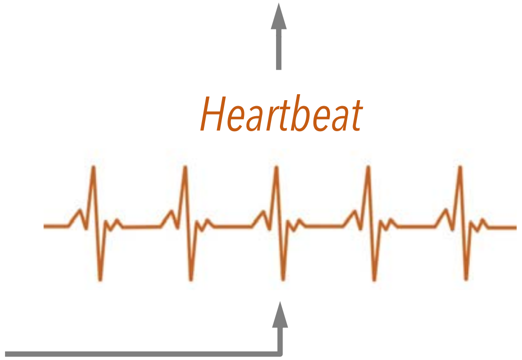


[Khalsa et al., 2018]

Ongoing Experiment [Holgado et al., 2021; Lynch et al., 2021]

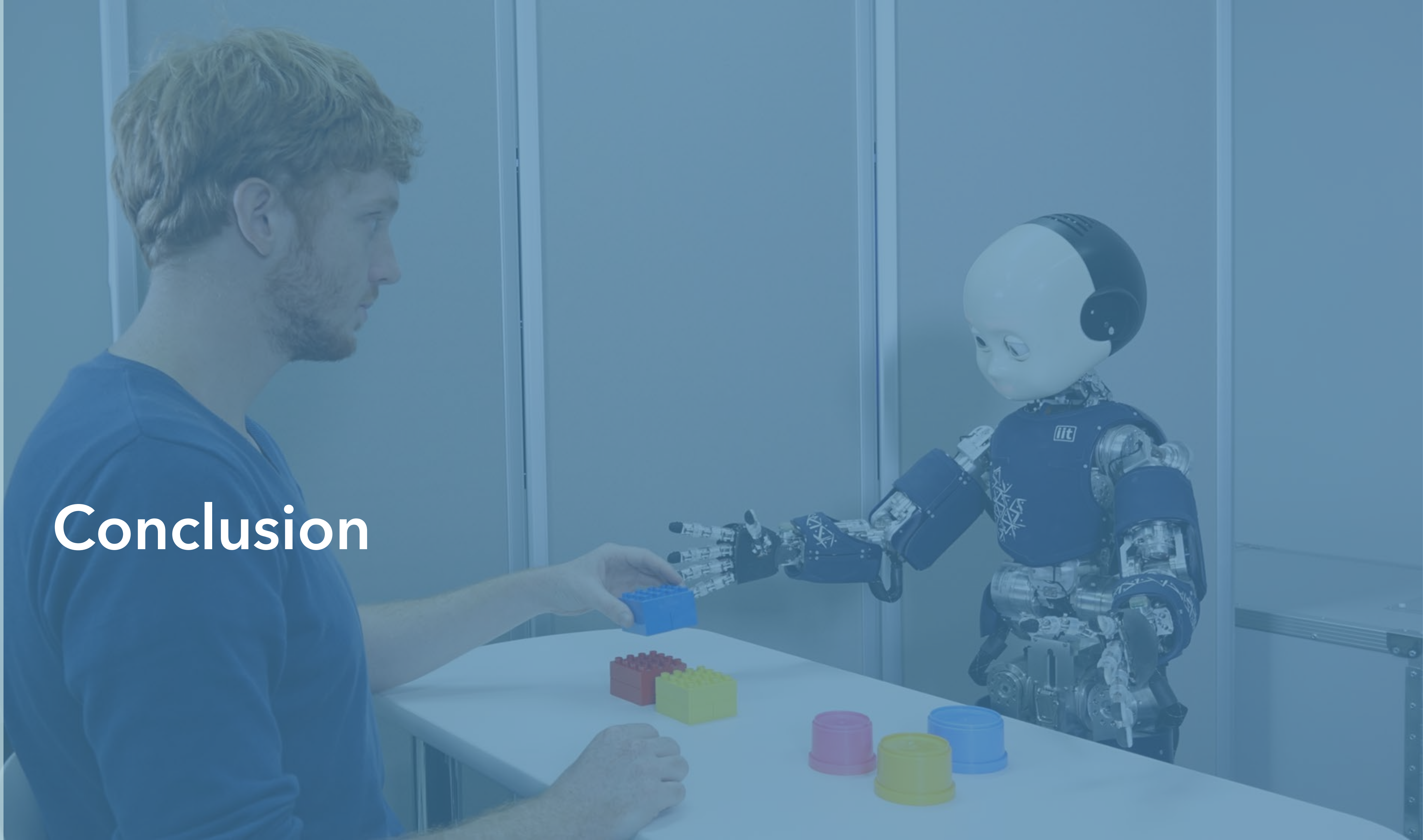






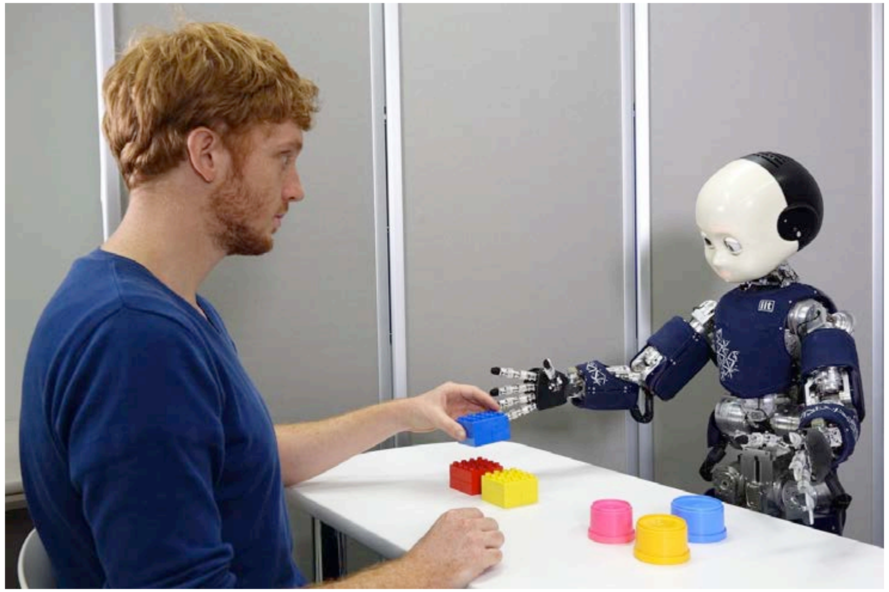
- Body ownership and tool-body assimilation facilitated by cardio feedback
  - Different roles of cardio-visual/audio/tactile feedback
  - Stronger/weaker effects in ASD

- Body illusion caused by cardio-visual feedback [Suzuki et al., 2013; Heydrich et al., 2018]



Conclusion

AI for Understanding Human Intelligence



Twofold aim of cognitive developmental robotics:

- To design robot intelligence inspired by human intelligence
- To obtain deeper insights into human intelligence by testing neuroscience/psychological hypotheses

Advantages:

- To bridge the gap between neuroscience and psychology
- To reveal the roles of embodiment and social interaction

For Further Studies …

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Predictive learning: its key role in early cognitive development

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Review

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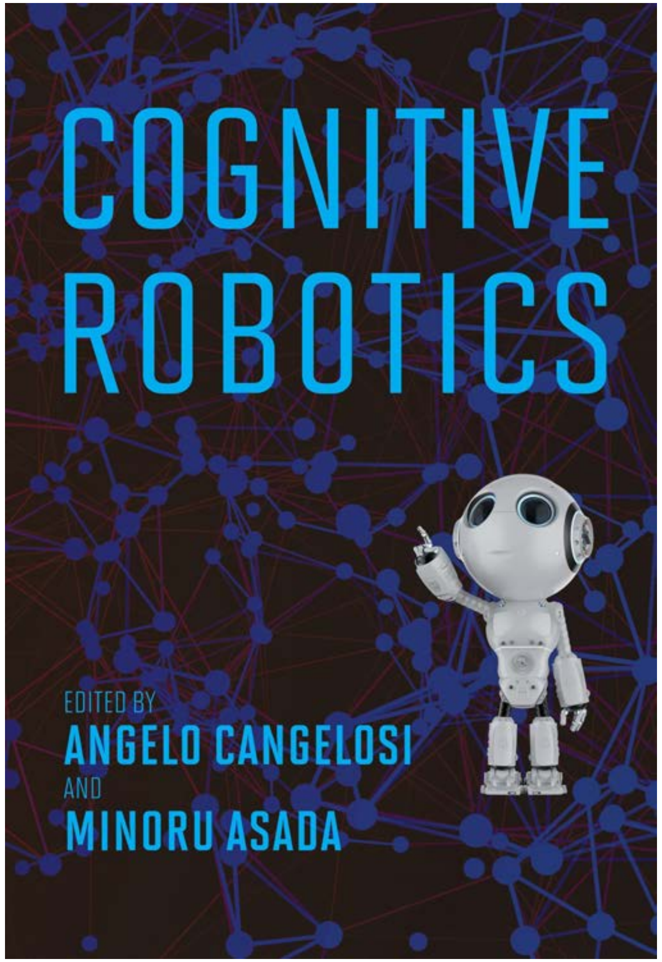
One contribution of 17 to a theme issue 'From social brains to social robots: applying neurocognitive insights to human–robot interaction'.

Subject Areas:
cognition, computational biology

Keywords:
predictive learning, predictive coding,

What is a fundamental ability for cognitive development? Although many researchers have been addressing this question, no shared understanding has been acquired yet. We propose that predictive learning of sensorimotor signals plays a key role in early cognitive development. The human brain is known to represent sensorimotor signals in a predictive manner, i.e. it attempts to minimize prediction error between incoming sensory signals and top–down prediction. We extend this view and suggest that two mechanisms for minimizing prediction error lead to the development of cognitive abilities during early infancy. The first mechanism is to update an immature predictor. The predictor must be trained through sensorimotor experiences because it does not inherently have prediction ability. The second mechanism is to execute an action anticipated by the predictor. Interacting with other individuals often increases prediction error, which can be minimized by executing one's own action corresponding to others' action. Our experiments using robotic systems replicated developmental dynamics observed in infants. The capabilities of self–other cognition and goal-directed action were acquired based on the first mechanism, whereas imitation and prosocial behaviours emerged based on the second mechanism. Our theory further provides a potential mechanism for autism spectrum condition. Atypical tolerance for prediction error is hypothesized to be a cause of perceptual and social difficulties.

This article is part of the theme issue 'From social brains to social robots: applying neurocognitive insights to human–robot interaction'.



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Thank You!








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