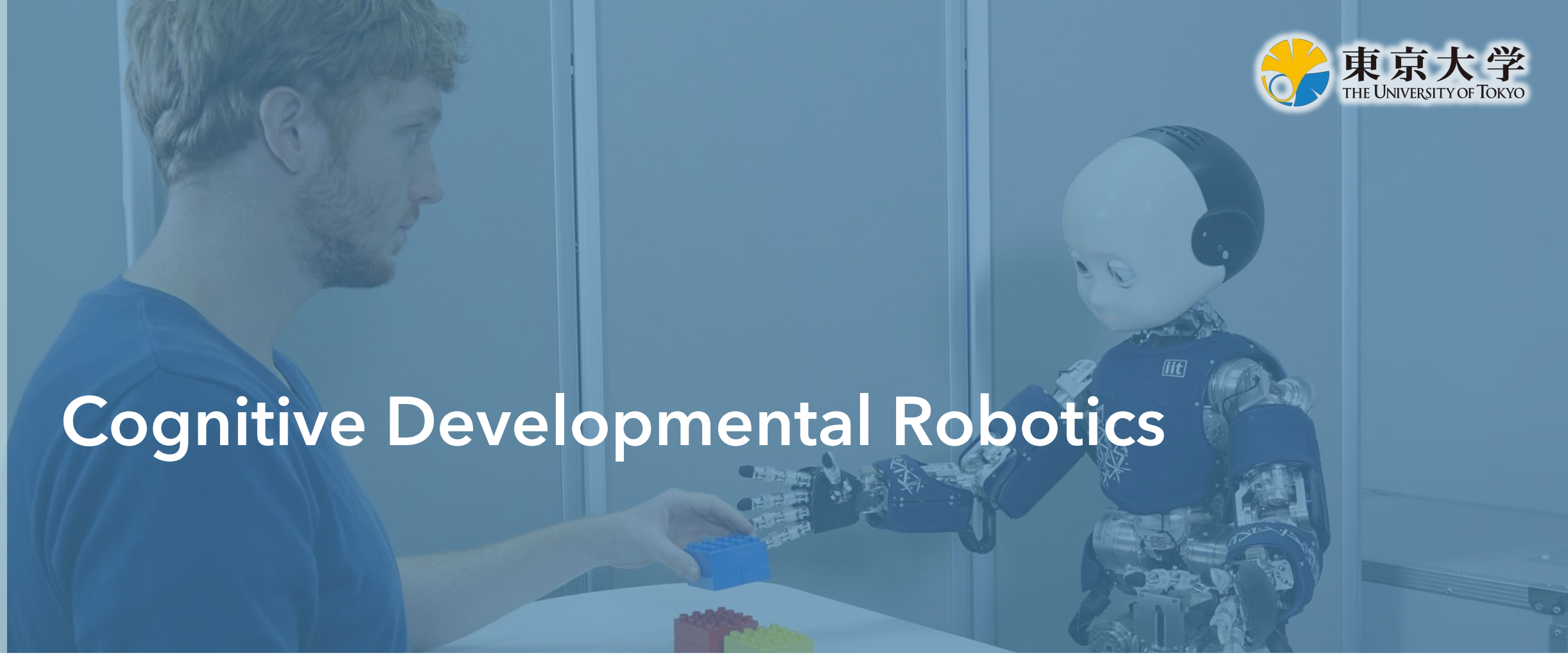
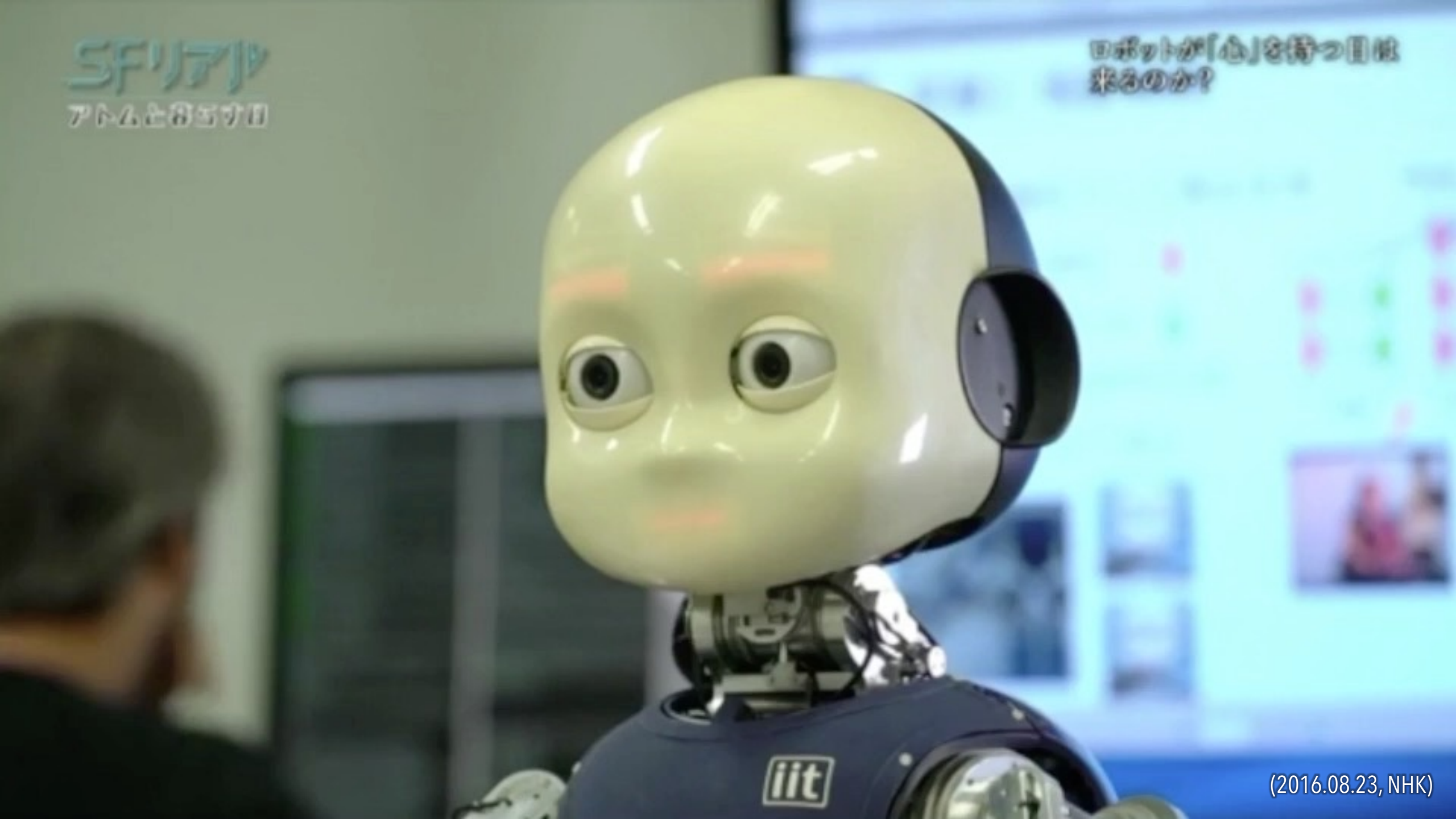


Cognitive Developmental Robotics

Yukie Nagai

IRCN, The University of Tokyo

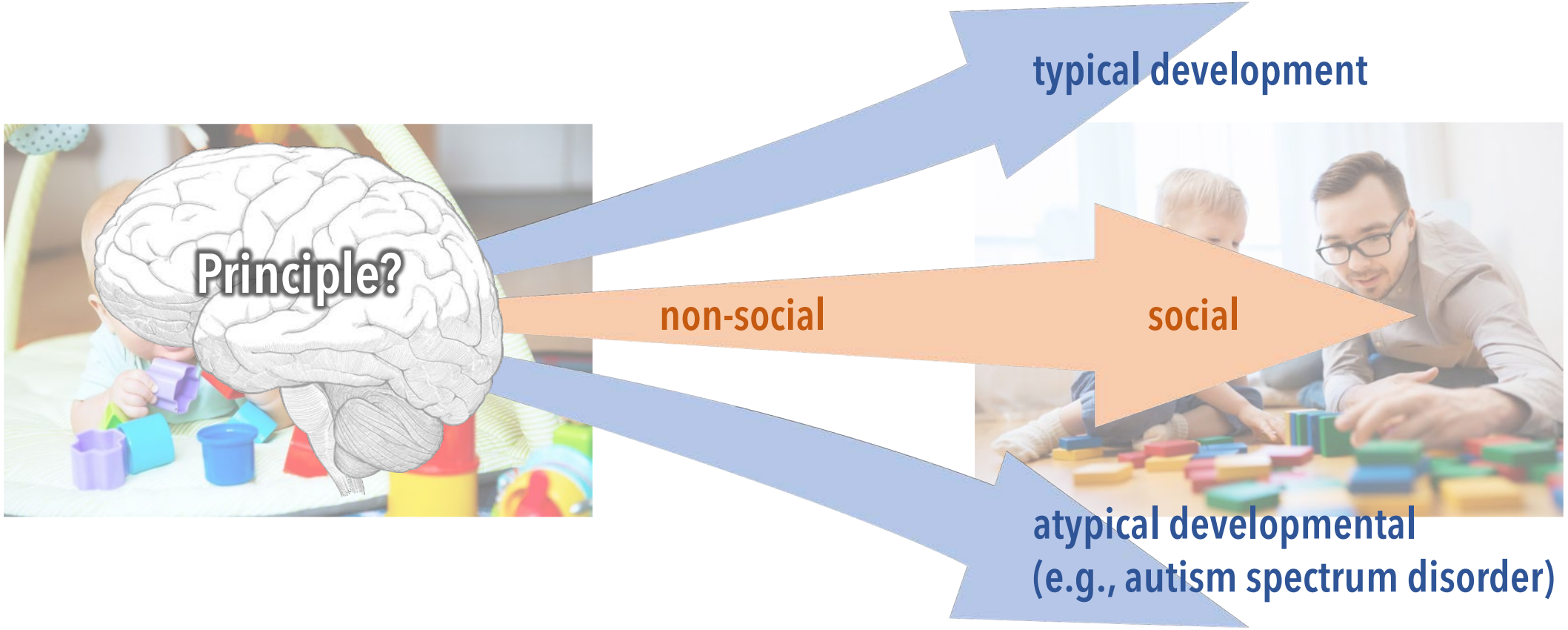
ShanghAI Lectures 2022 @ Online, November 24, 2022



(2016.08.23, NHK)

Open Question: A Unified Principle of Cognitive Development?

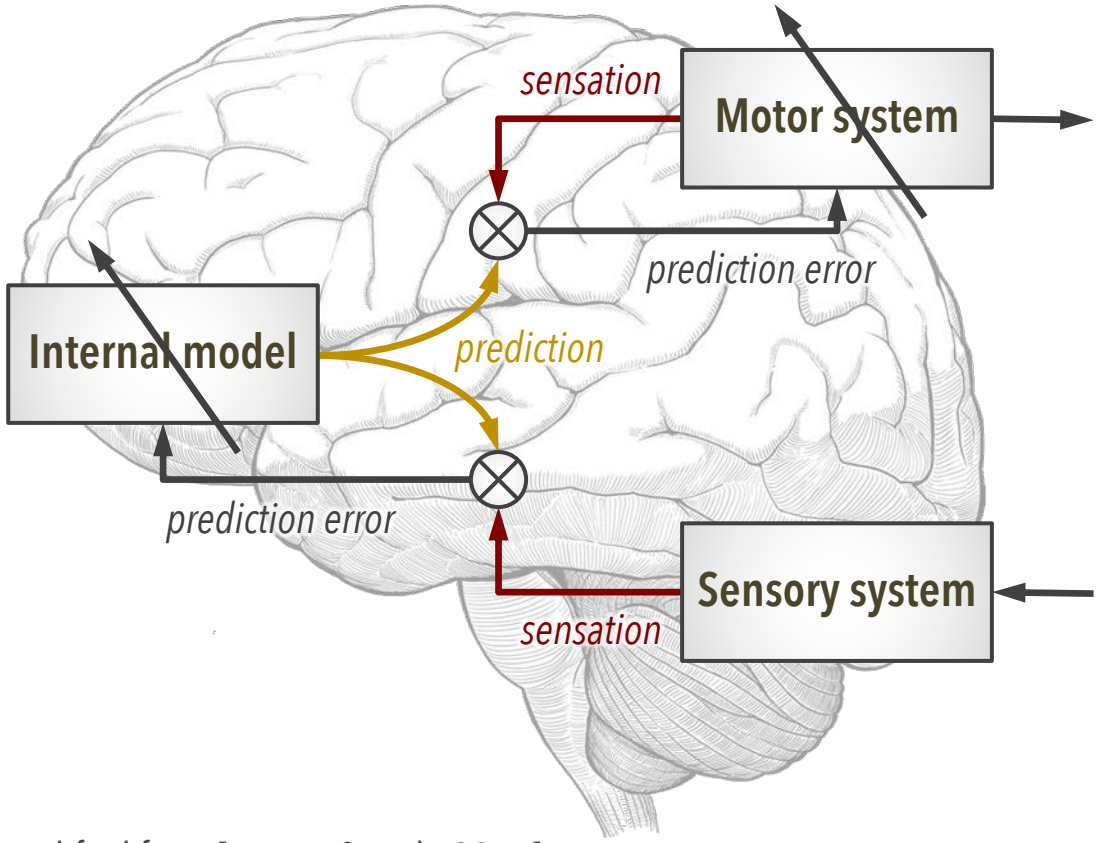
- What neural mechanisms underlie cognitive development?
- Can they account for both the continuity and diversity in development?



Predictive Coding: A Unified Theory of Human Brain

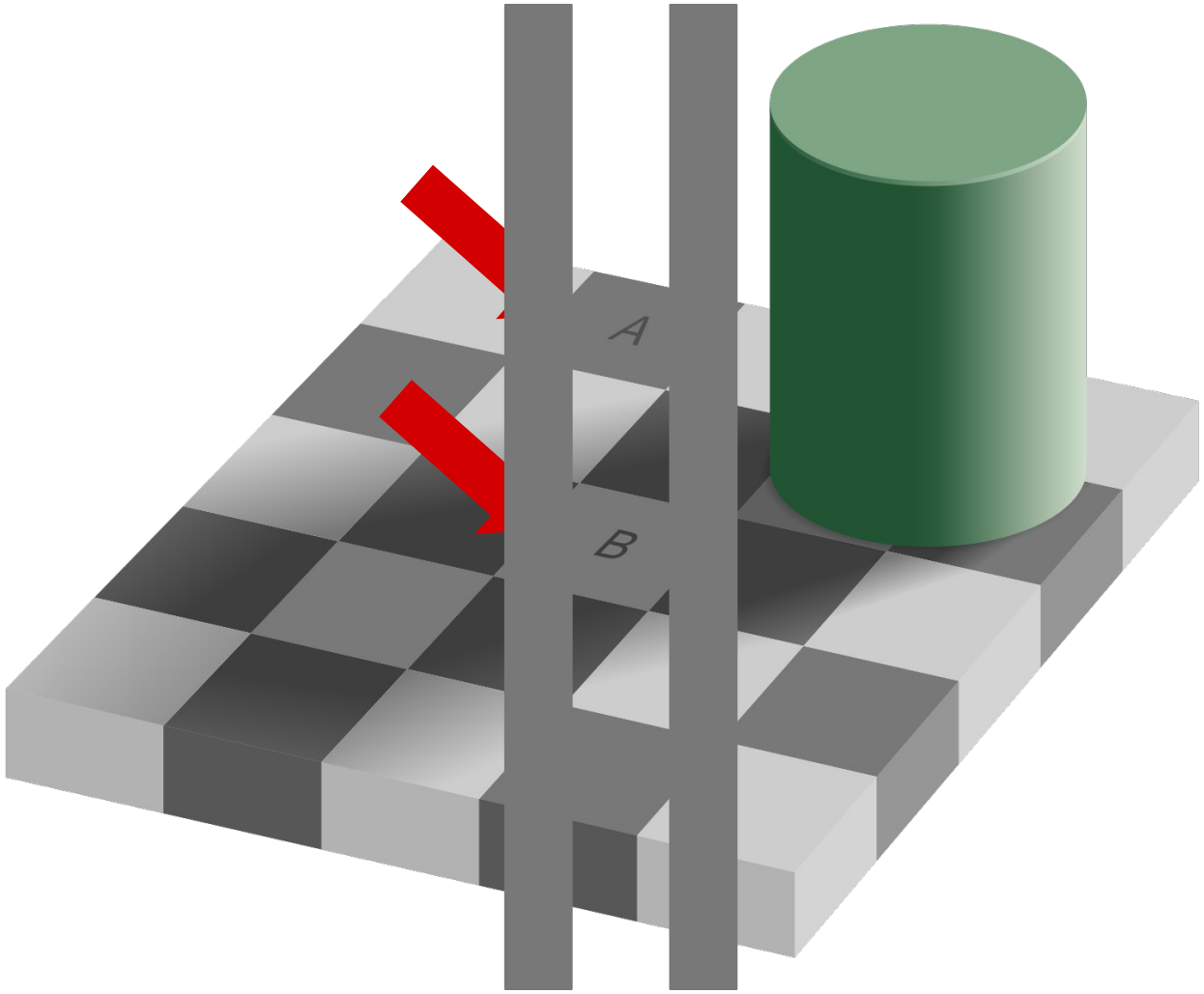
[Friston et al., 2006; Friston, 2010; Clark, 2013]

- 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]

Optical Illusion Generated by Predictive Brain



Which square looks brighter, A or B?

Subjective perception

A < B

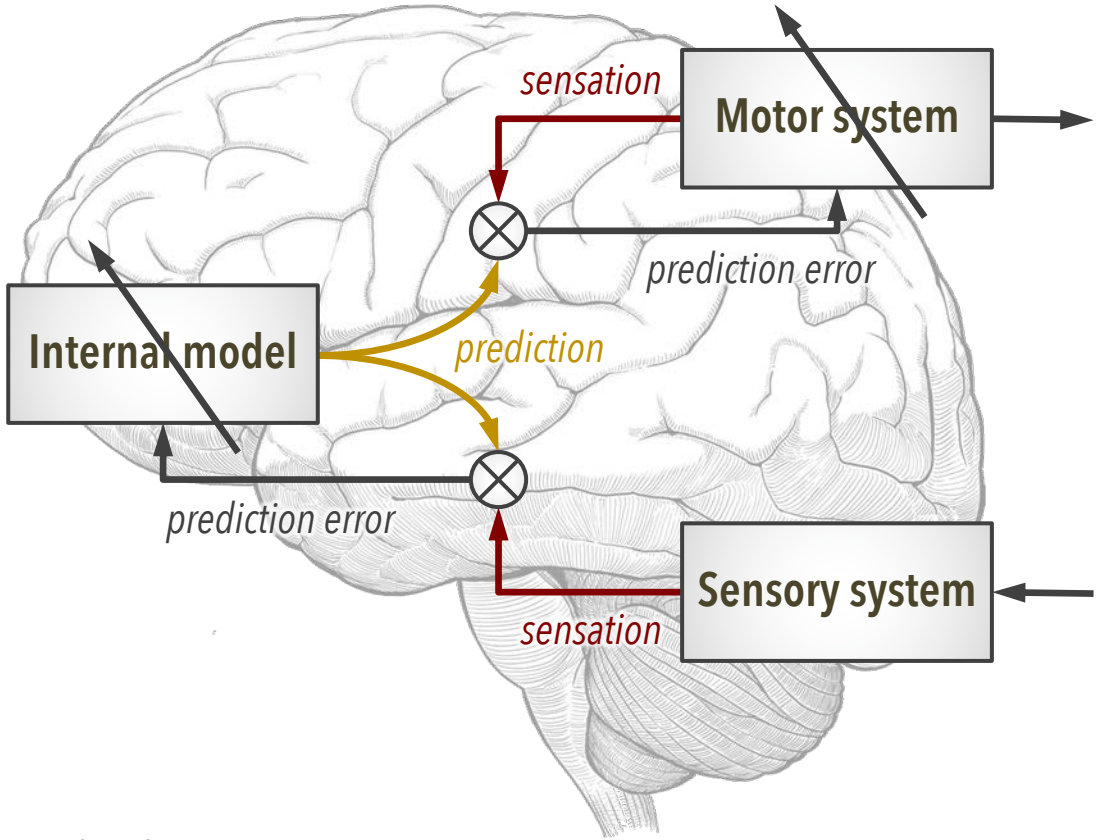
Physical stimuli

A = B

Predictive Coding: A Unified Theory of Human Brain

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

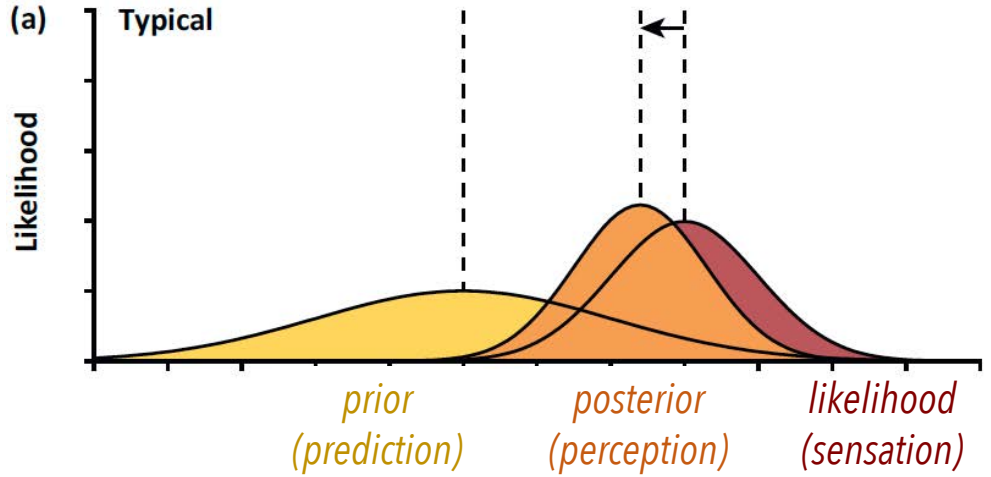
- The human brain perceives the world and acts on the world to minimize prediction errors (i.e., perceptual and active inference) .



Modified from [Friston & Frith, 2015]

Bayes' theorem

$$posterior \propto likelihood \cdot prior$$



[Brock, 2012]

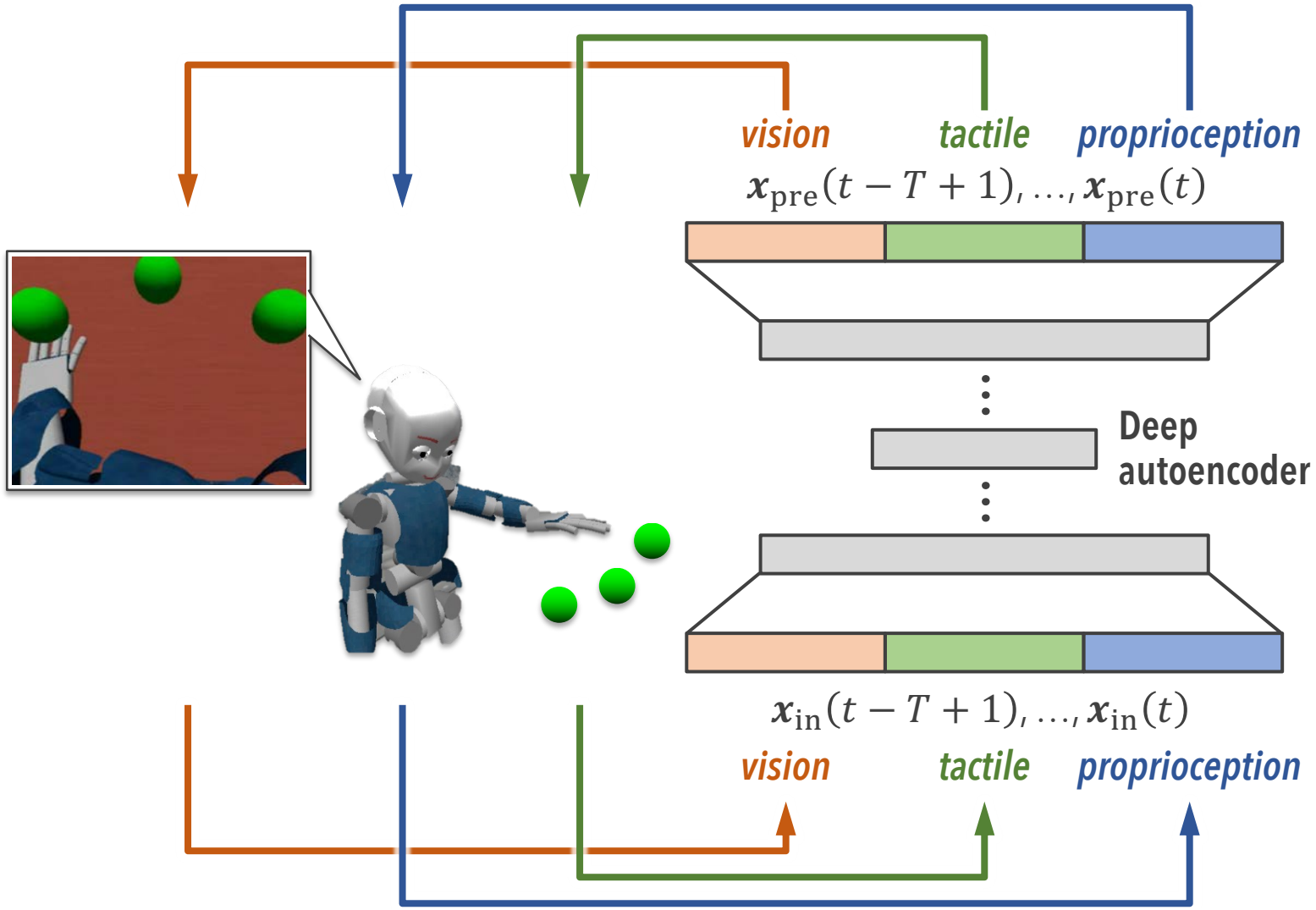
Development from Non-Social to Social Cognition

Development of Altruistic Behavior

[Warneken & Tomasello, 2007]

Development of Action Production and Perception

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

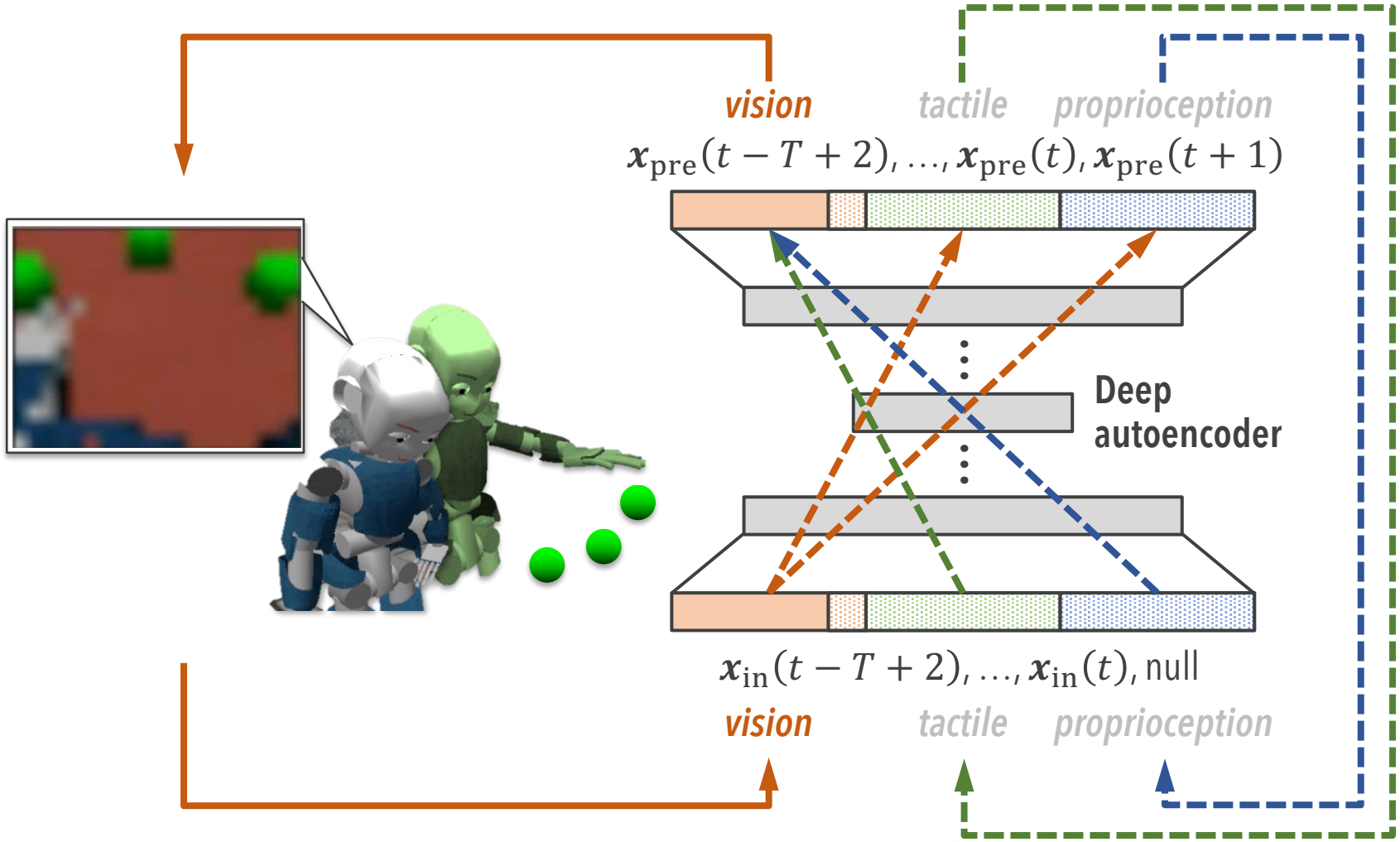


Action production:

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

Development of Action Production and Perception

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



Action production:

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

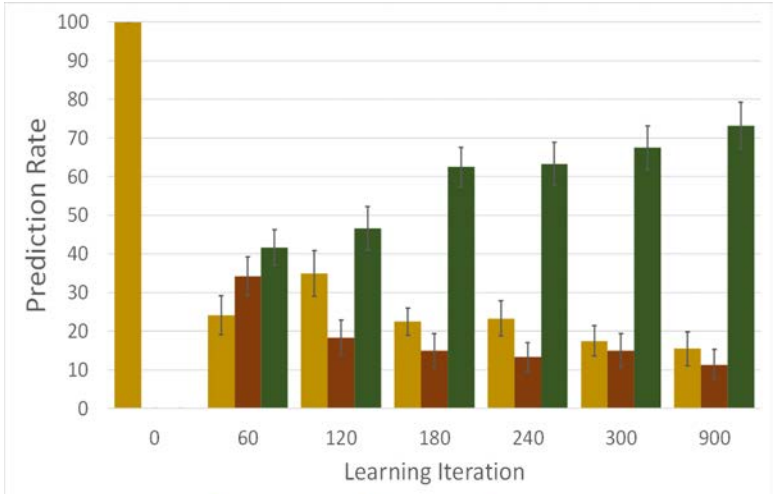
Action perception:

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

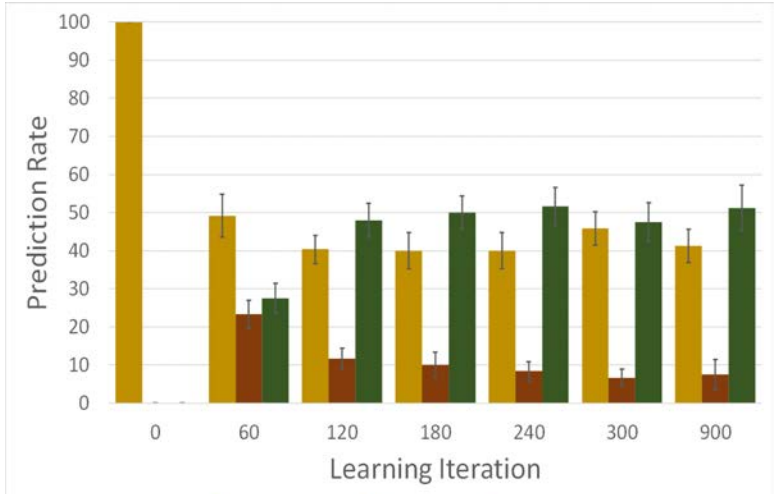
Exp: Action Perception Improved by Motor Experiences

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

Learning through action *generation*



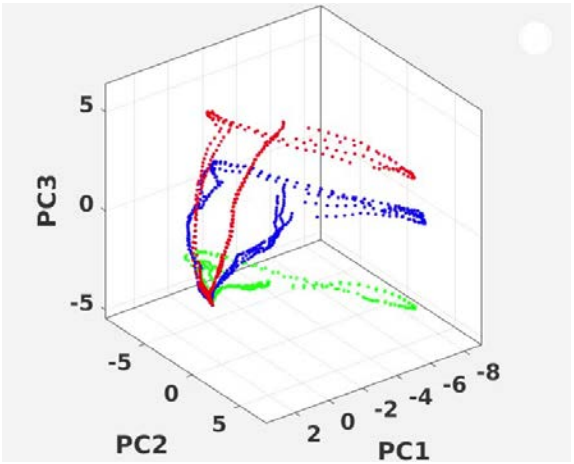
Learning through action *observation*

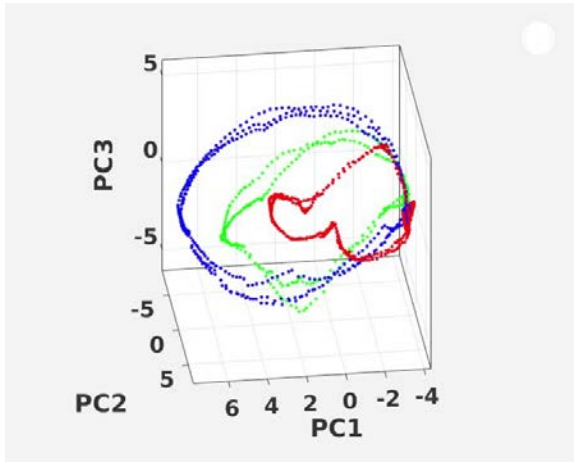


Correct goal

Incorrect goal

No goal

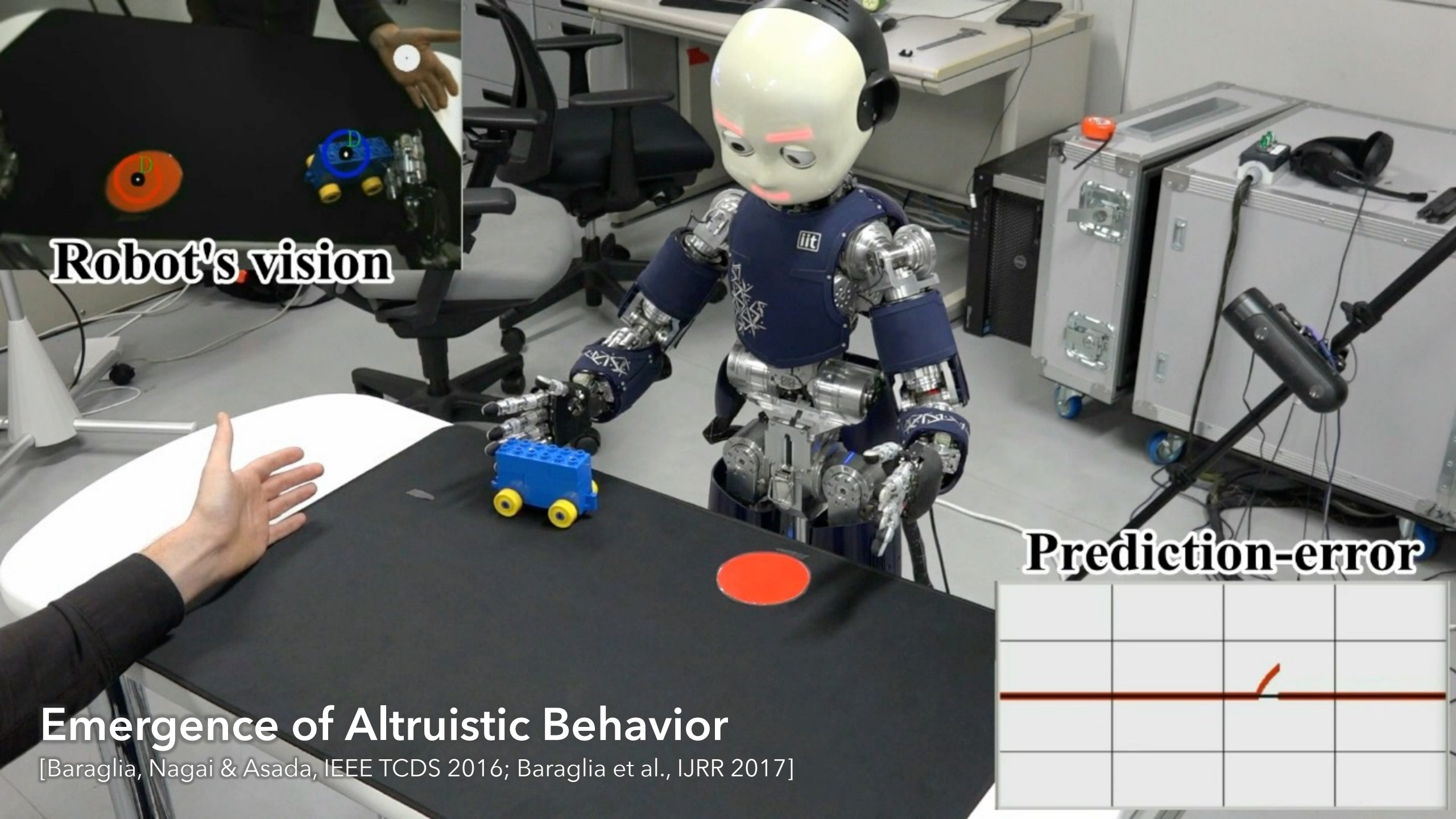




Reaching for left

Reaching for center

Reaching for right



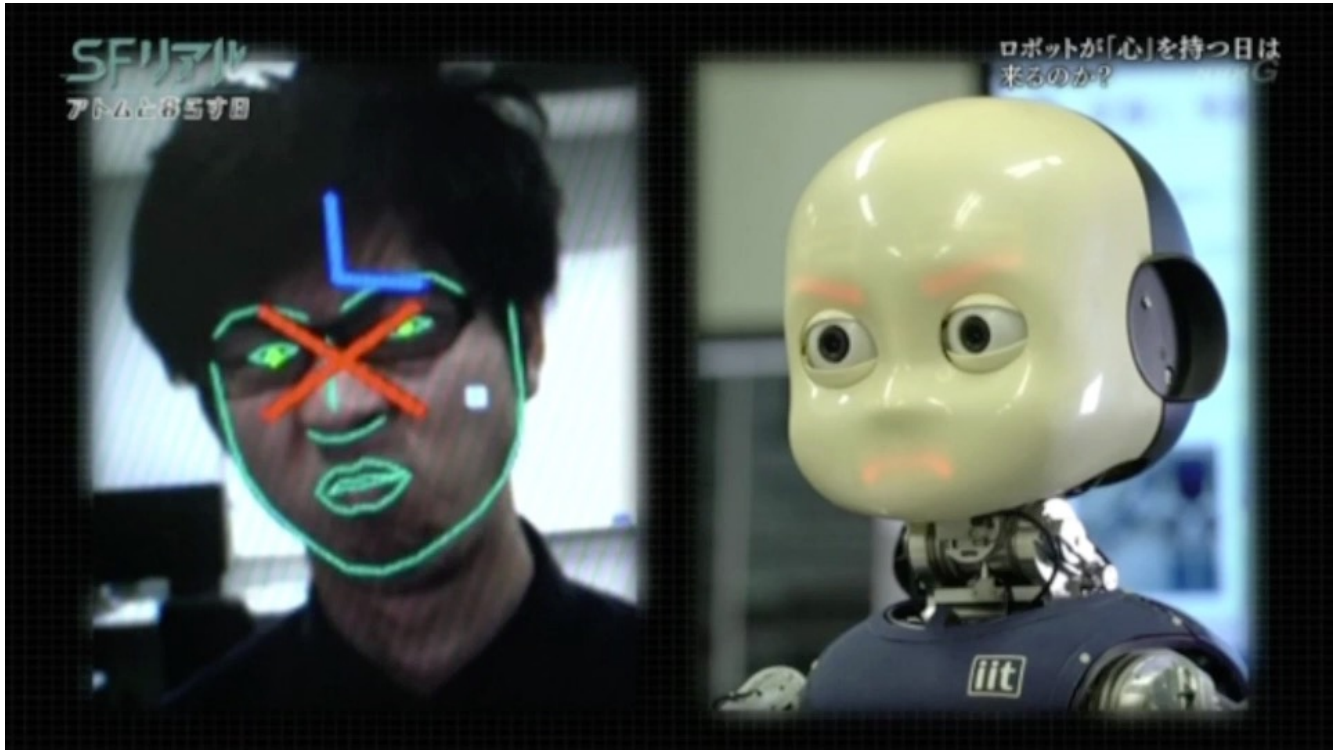
Emergence of Altruistic Behavior

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

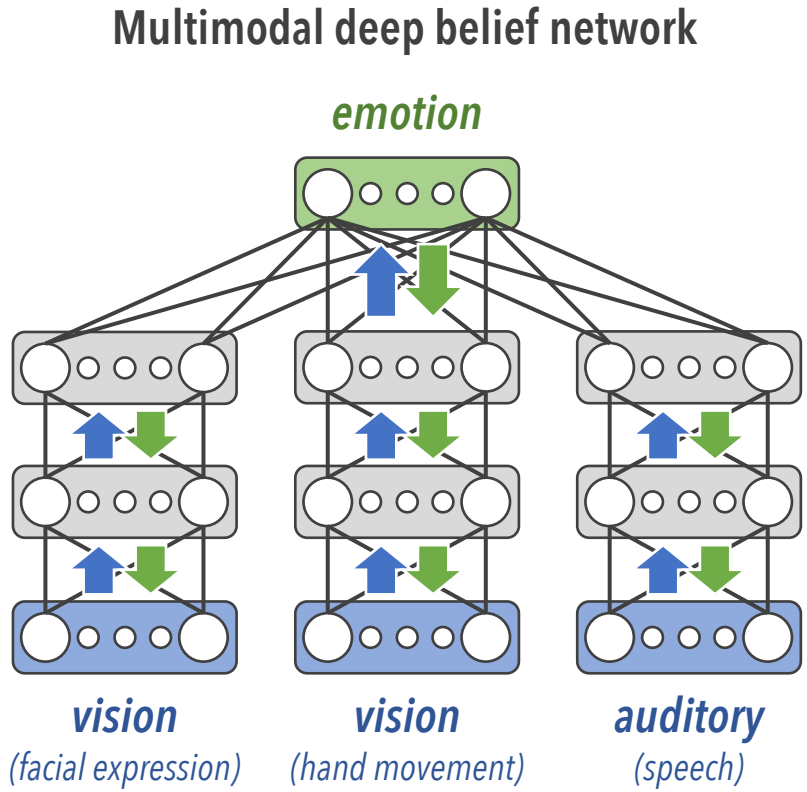
Development of Emotion and Its Inference

[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.

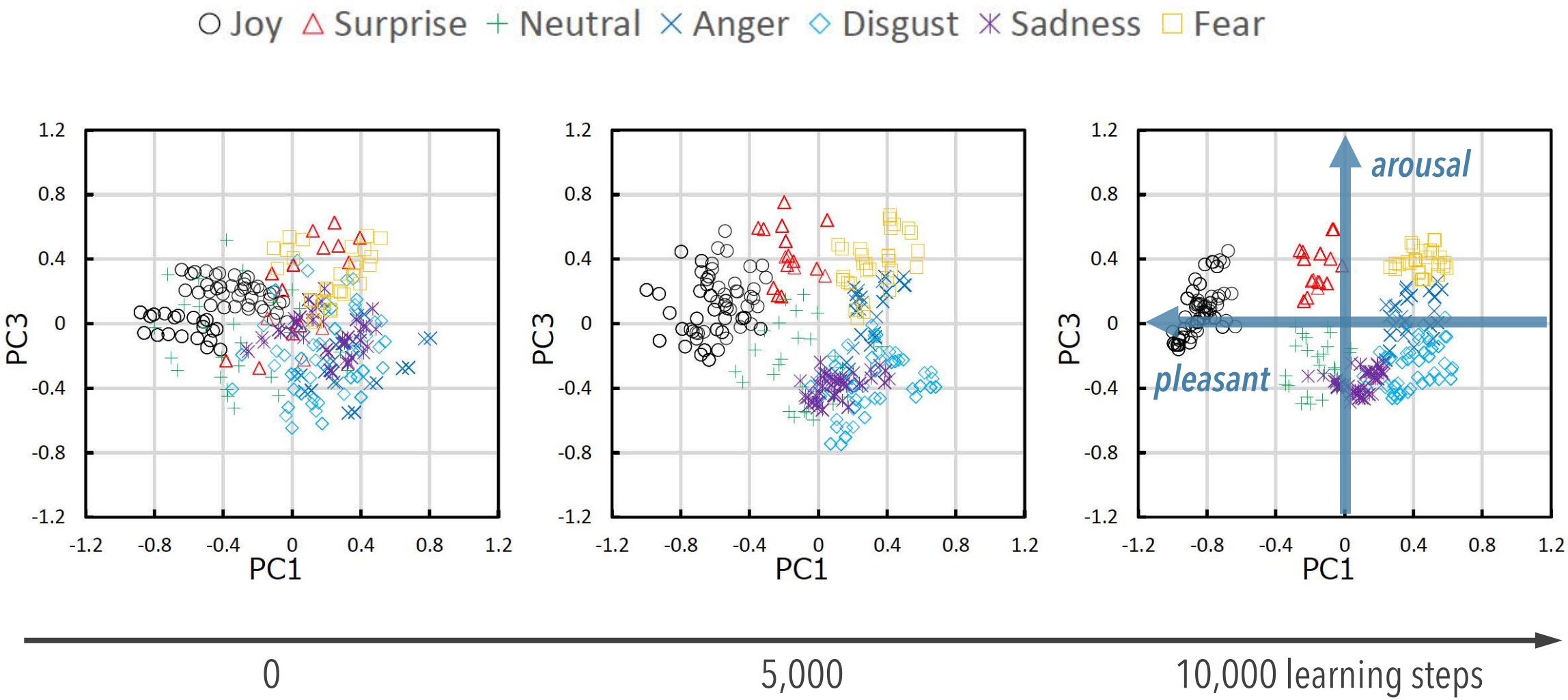


(NHK, 2016.08.23)



Exp 1: Developmental Differentiation of Emotion

[Horii, Nagai & Asada, IEEE TCDS 2018]



Exp 2: Emotion Estimation Facilitated by Mental Simulation

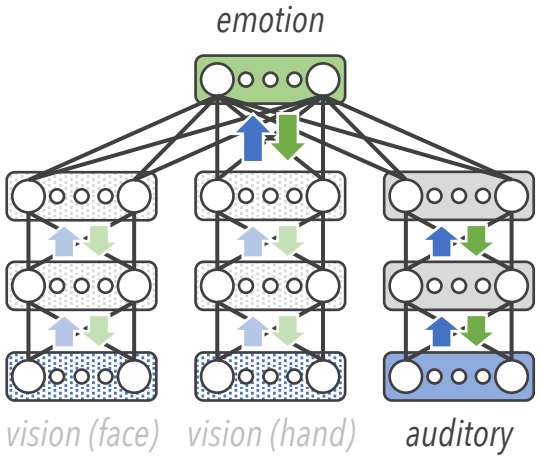
[Horii, Nagai & Asada, Paladyn 2016]

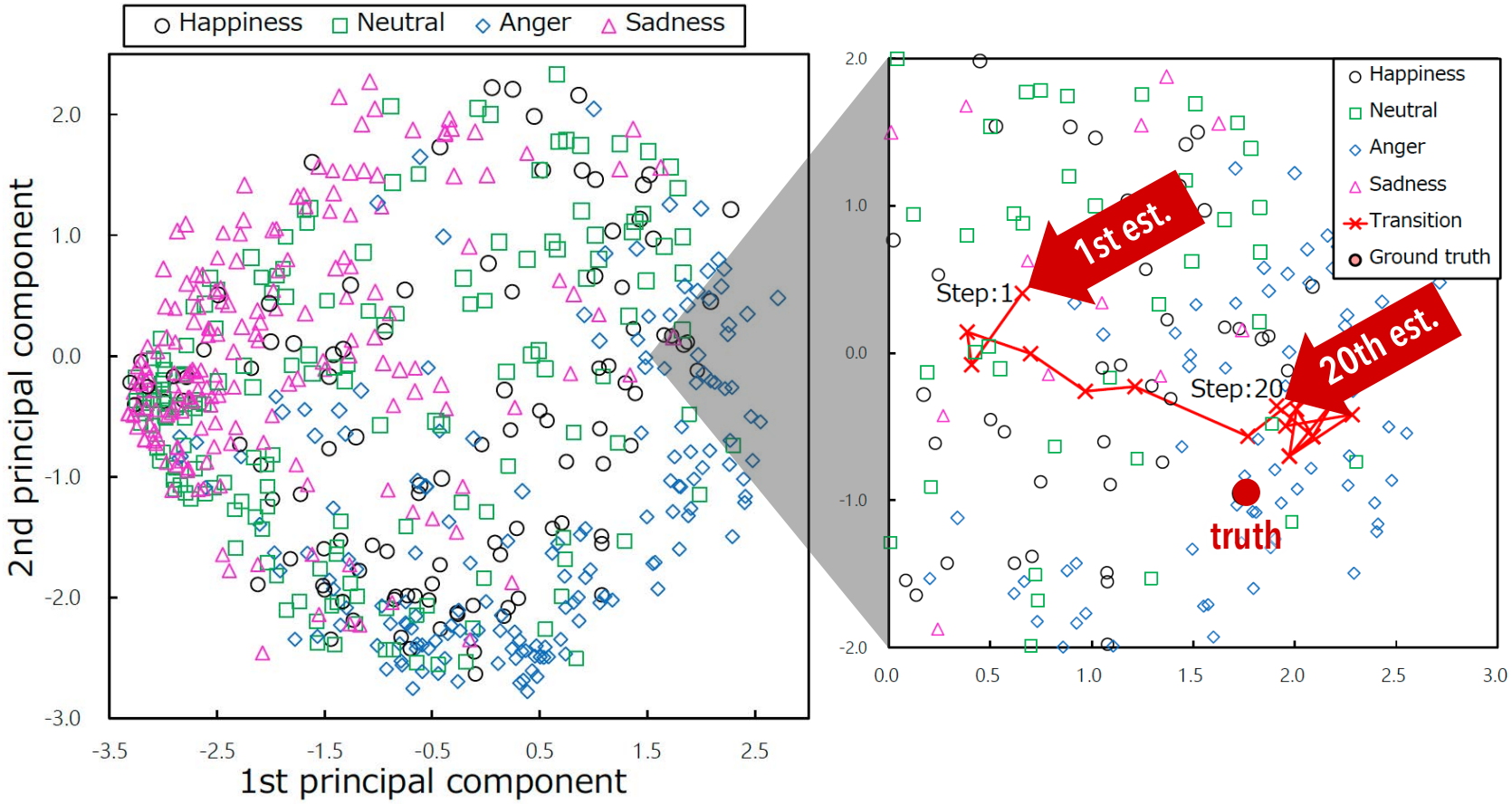
Training

- Given all modality signals

Testing:

- Given only auditory signal
  → prediction of imaginary visual signals



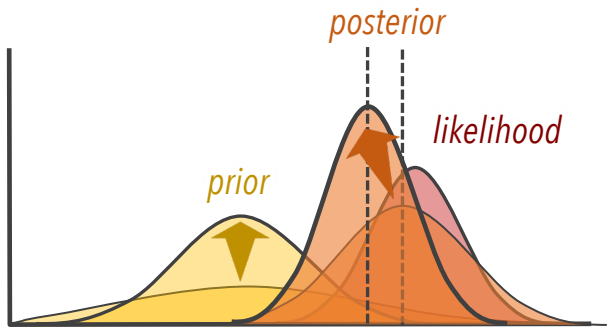


Interim Summary 1

Social Development Based on Predictive Coding

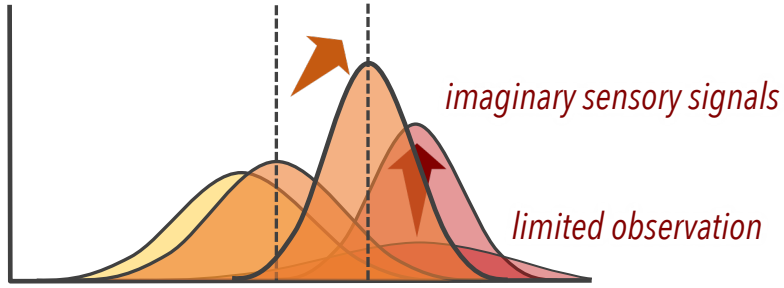
Development of sensorimotor abilities

To acquire precise priors through sensorimotor experiences



Emergence of social abilities

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



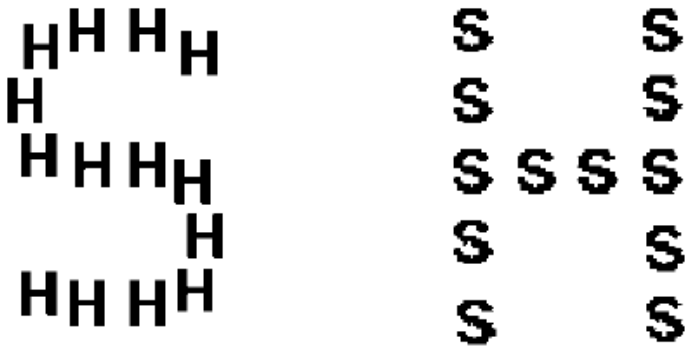
Individual Diversity in Cognitive Development

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]

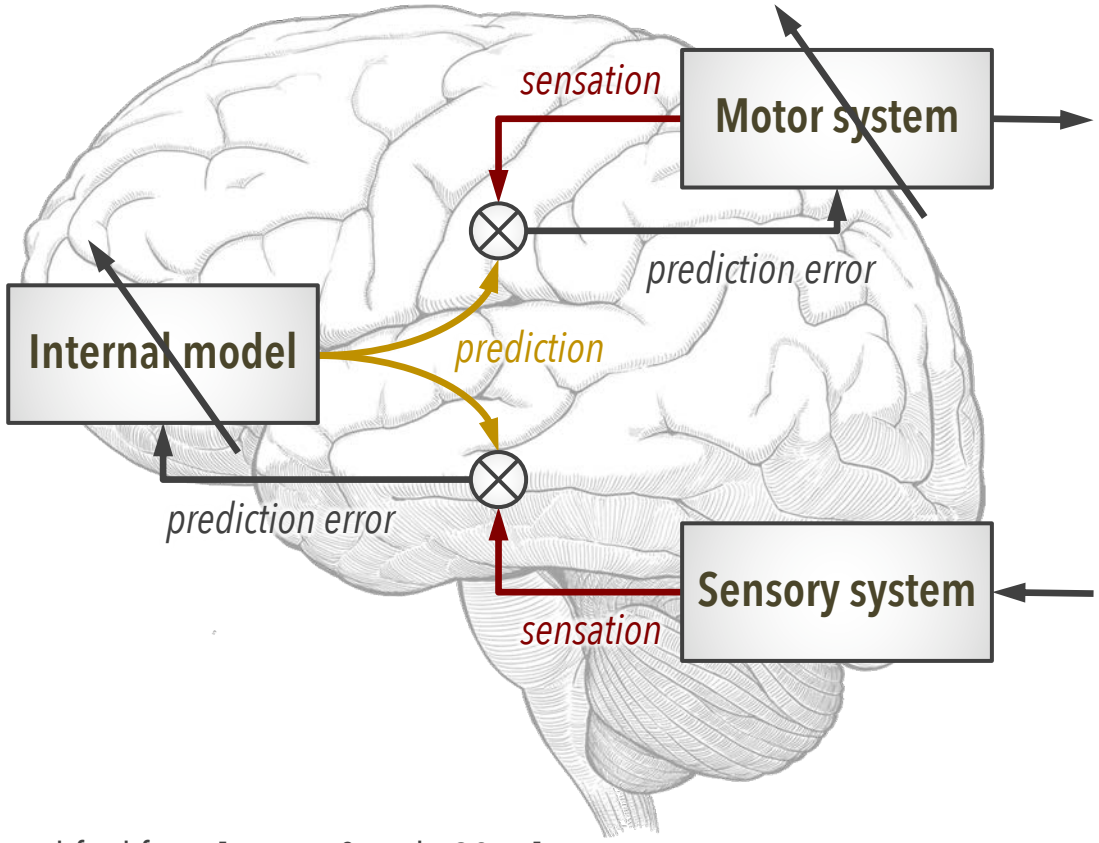
- Specific perceptual-cognitive style described as a limited ability to understand global context
  - Weak central coherence [Happé & Frith, 2006]
  - Local information processing bias
    [Behrmann et al., 2006; Jolliffe & Baron-Cohen, 1997]



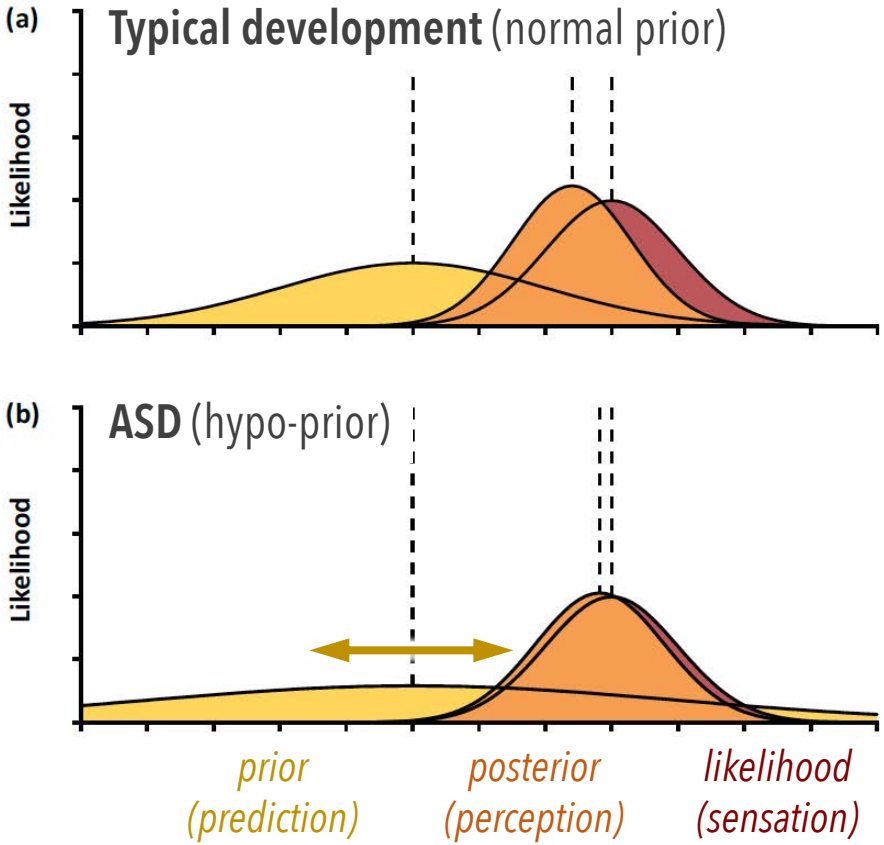
[Behrmann et al., 2006]

Predictive Coding Account for ASD

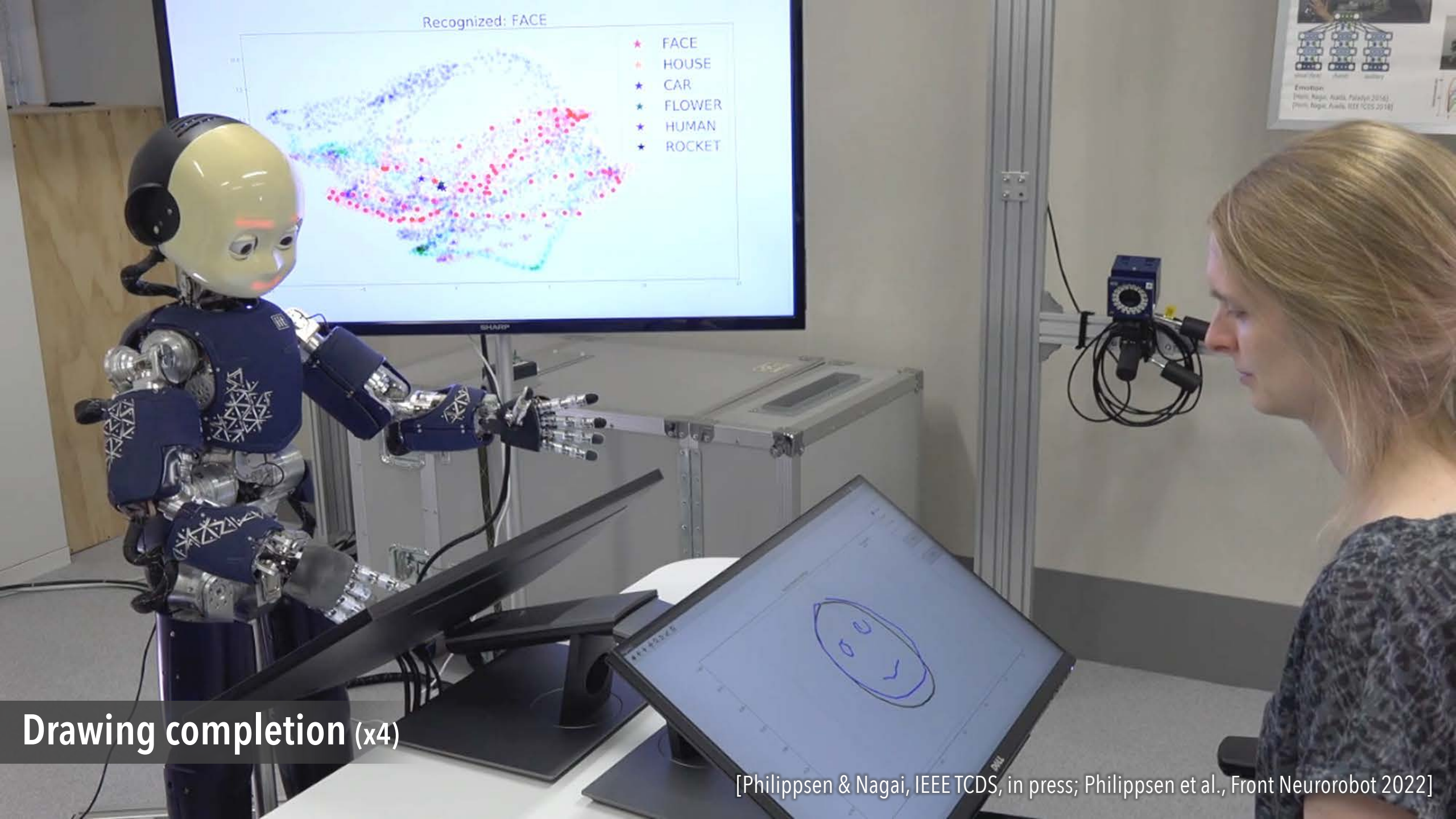
- Aberrant precision of top-down predictions may cause atypical cognitive abilities in ASD. [Brock, 2012]



Modified from [Friston & Frith, 2015]



[Brock, 2012]

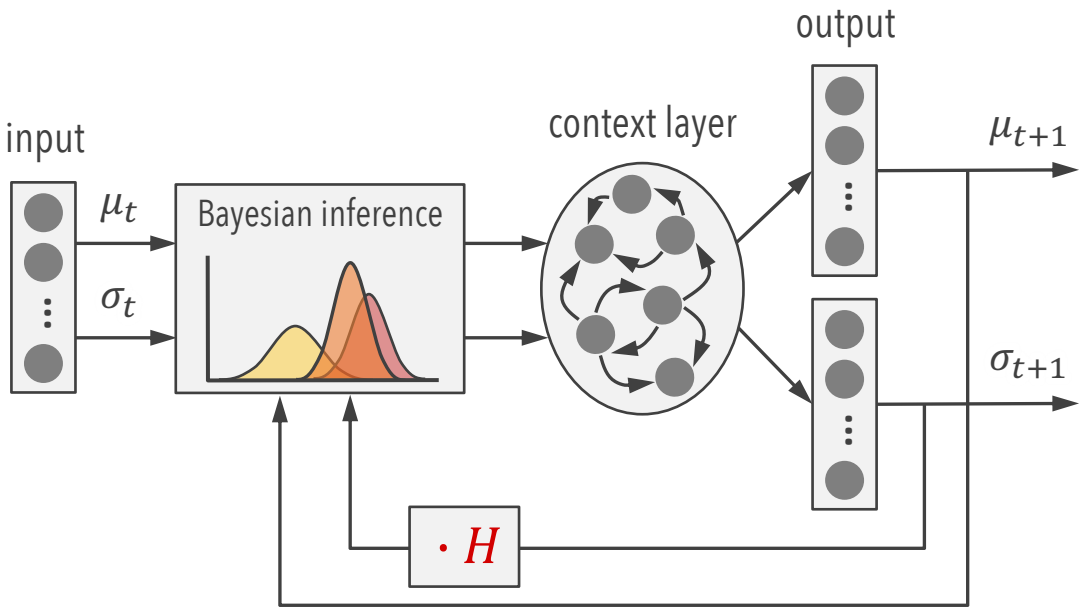


Drawing completion (x4)

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

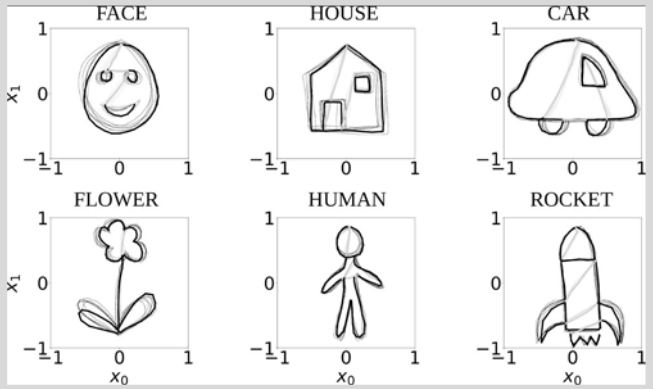
Learning of Representational Drawing with RNN

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

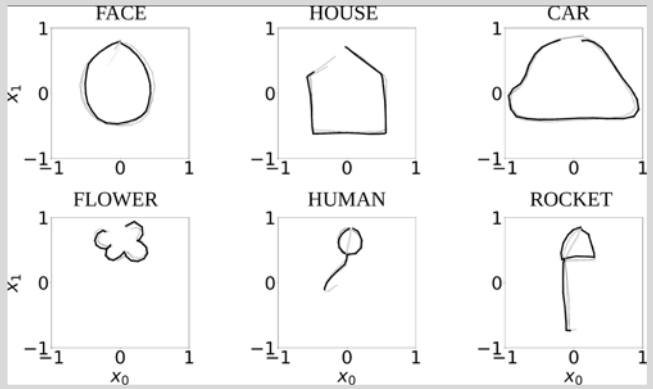


- How aberrant precision of predictions H affects the drawing ability of a neural network
  - Training: learn to draw six types of objects
  - Testing: infer the intended objects from the first 33% of trajectories and complete missing parts

Training data

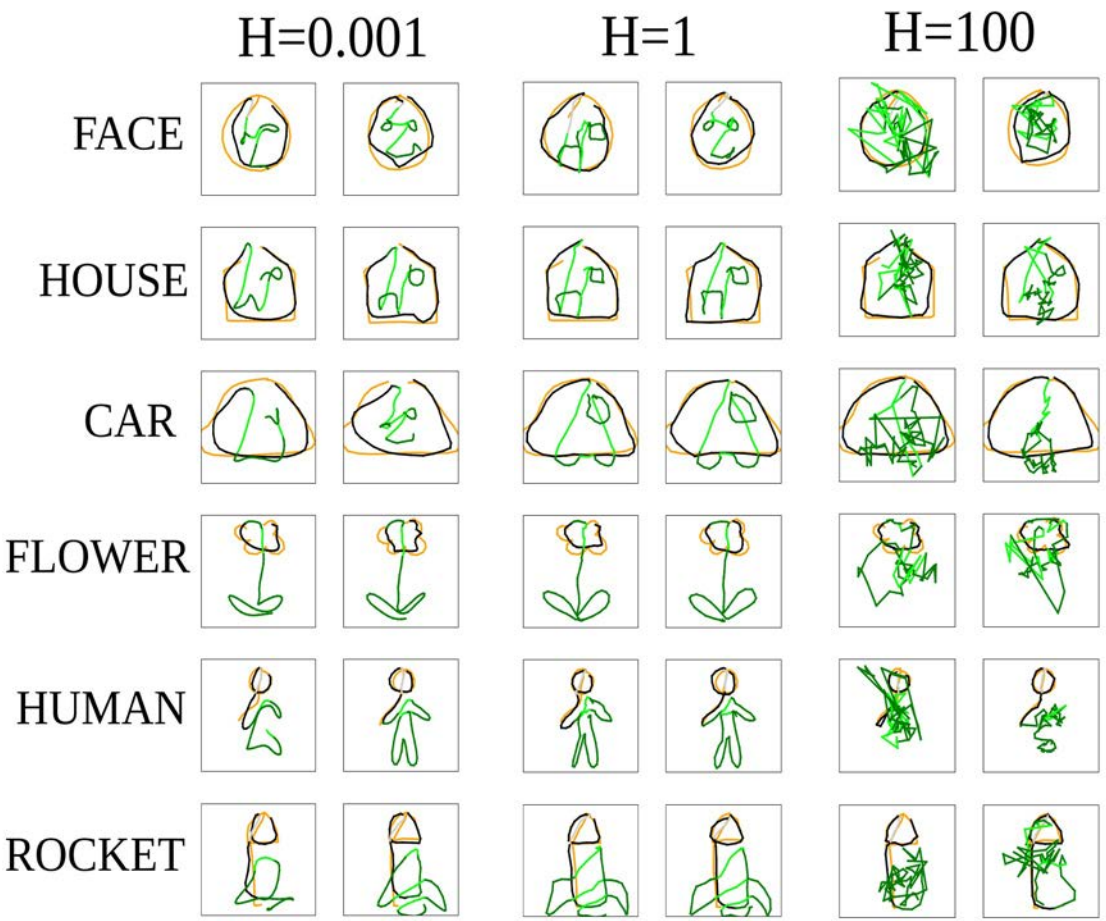


Testing data

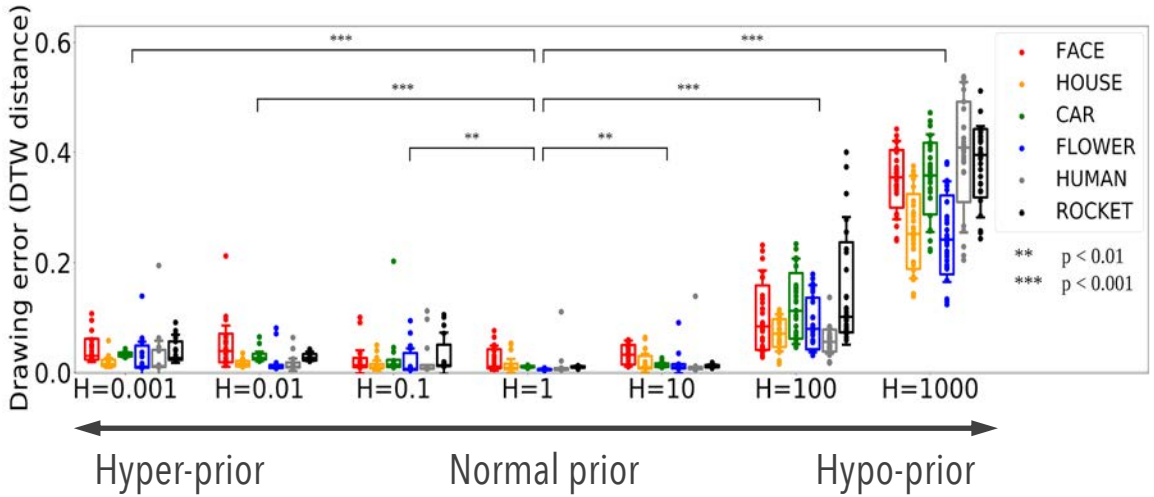


Exp 1: Influence of Aberrant Prediction on Drawing

[Philippsen & Nagai, IEEE TCDS, in press]

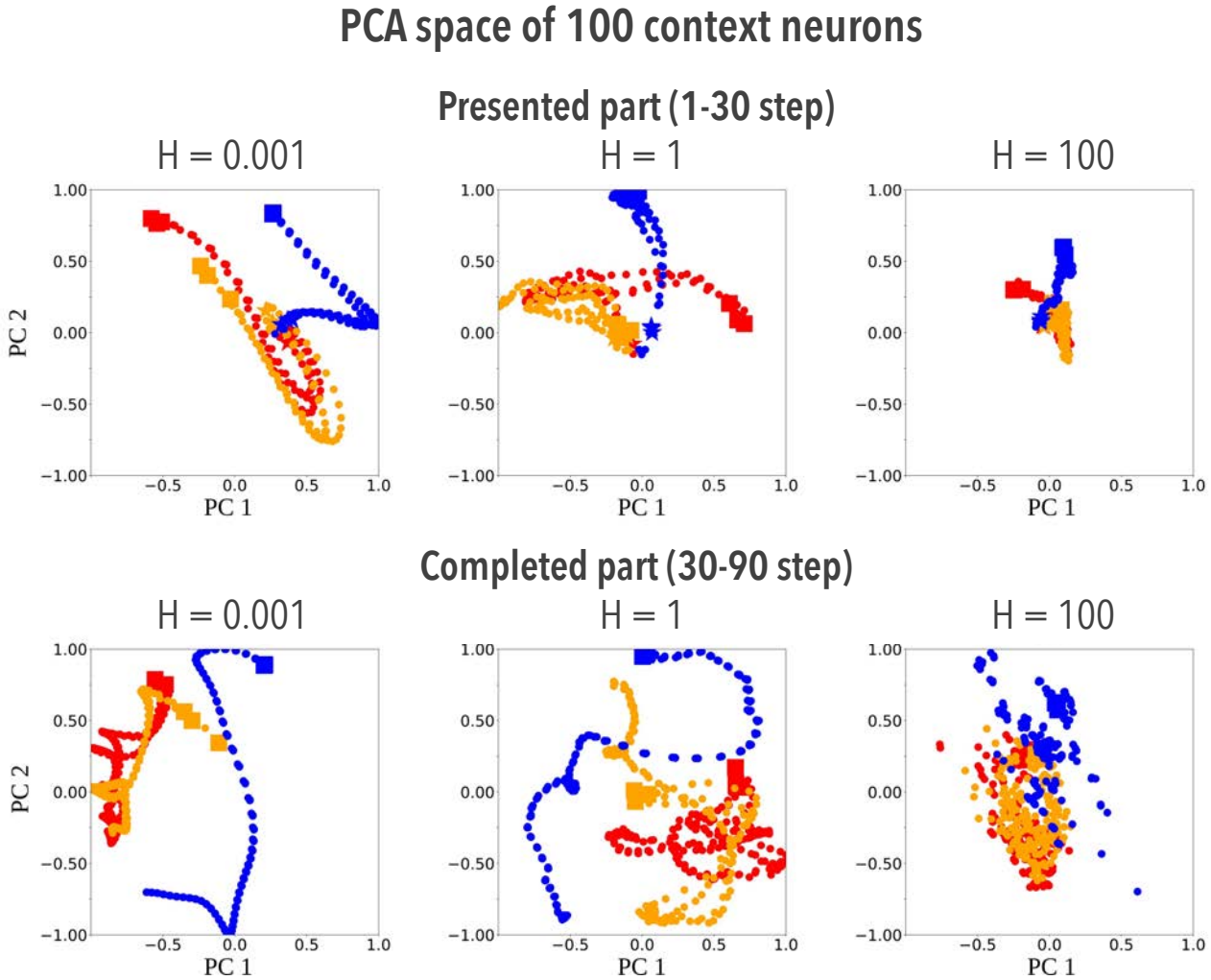


- Influences of precision H
  - Hyper-priors ($H \ll 1$): misinterpretation of intended patterns, abstract drawing
  - Normal priors ($H \approx 1$): successful completion
  - Hypo-priors ($H \gg 1$): tracing, scribbling

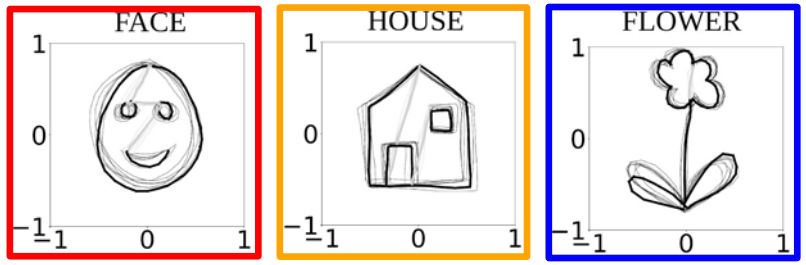


Exp 2: Influence of Aberrant Prediction on Internal Model

[Philippsen & Nagai, IEEE TCDS, in press]



- 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

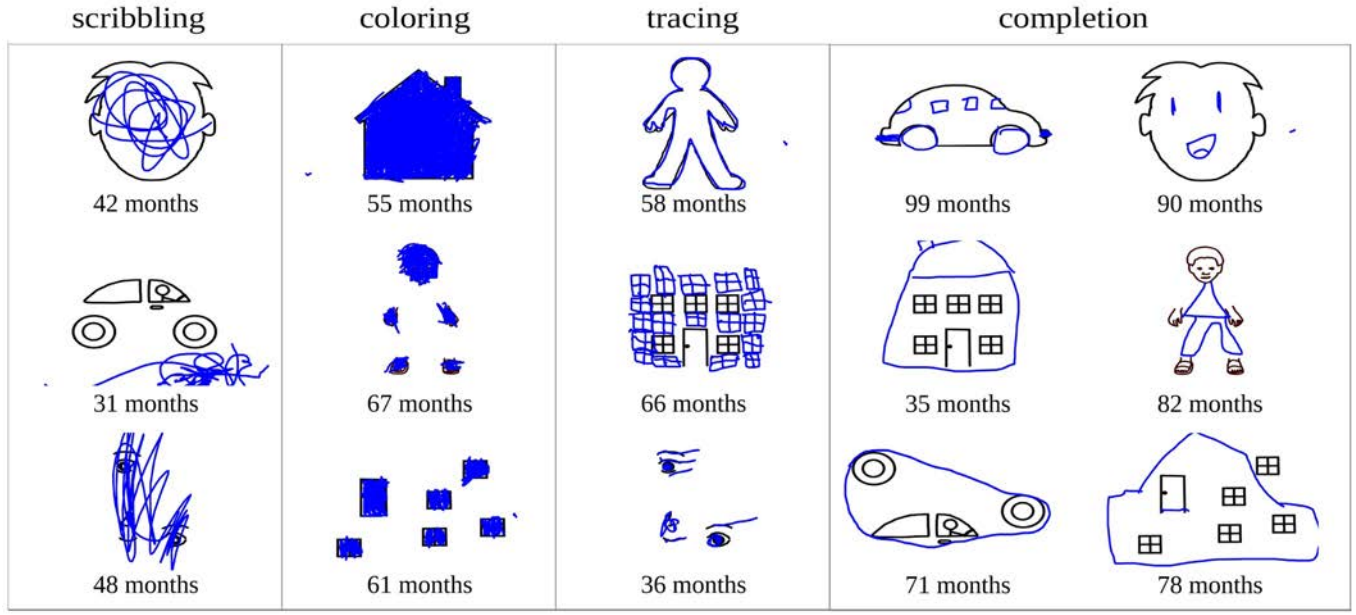


[Philippsen, Tsuji & Nagai, Front Psychology 2022]

Development of Representational Drawing in Children

[Philippsen, Tsuji & Nagai, Front Psychology 2022]

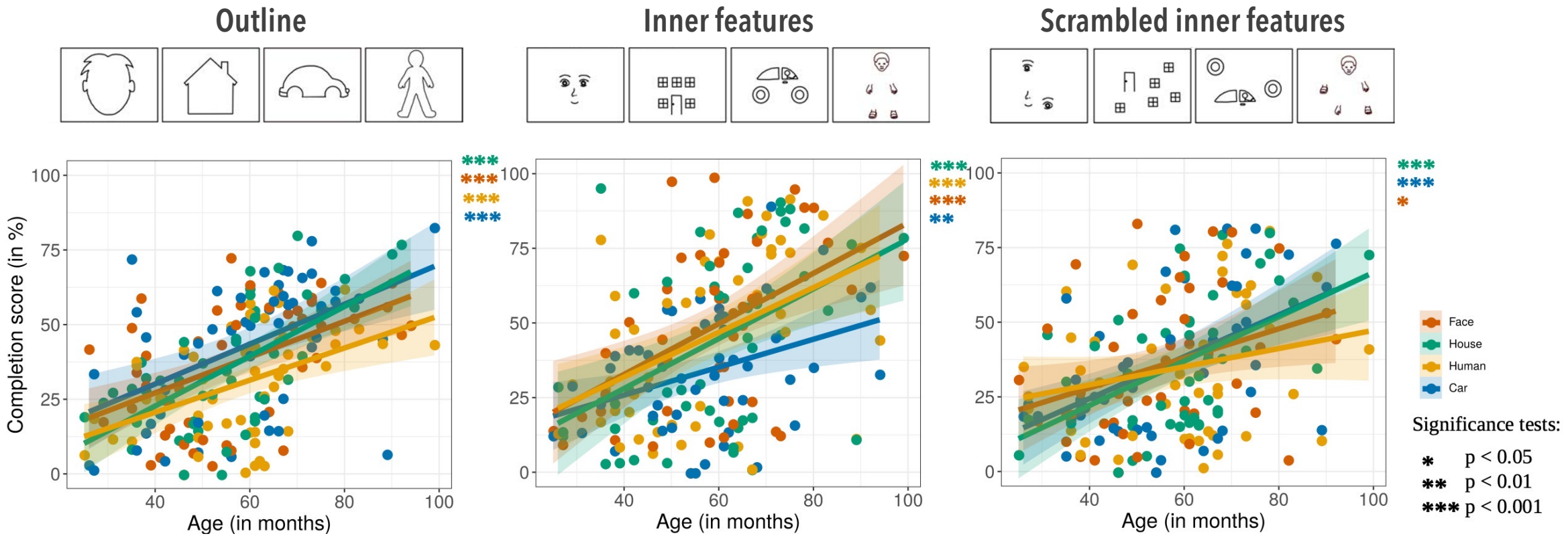
- How the drawing ability based on predictive processing develops with age
  - 104 typically-developing children (2-8 years old, 62M+42F)
  - 621 drawing data (given only outer/inner features)
  - AQ scores assessed by parents



Adults

Exp 1: Subjective Evaluation by Adult Rating

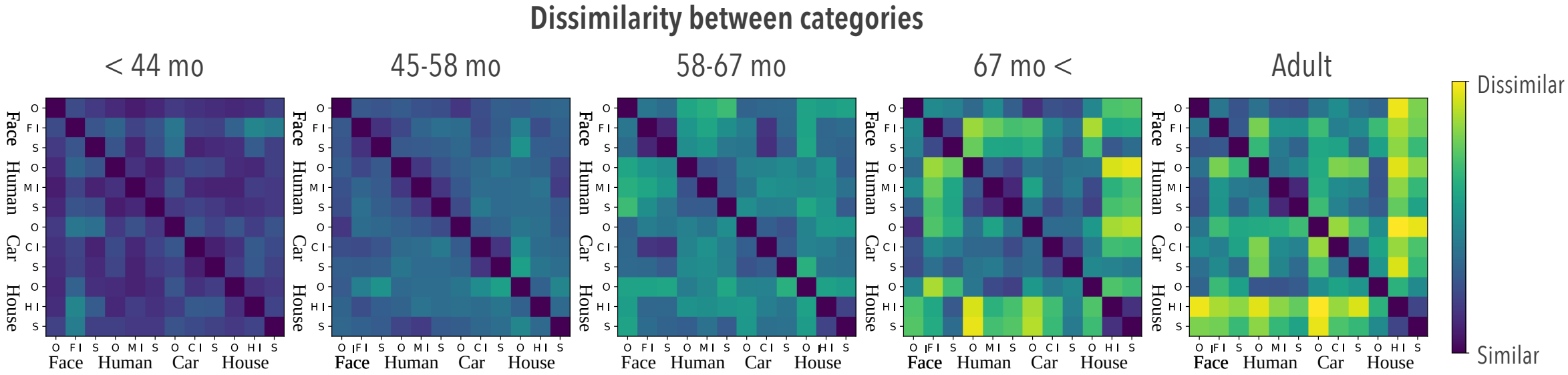
[Philippsen, Tsuji & Nagai, Front Psychology 2022]



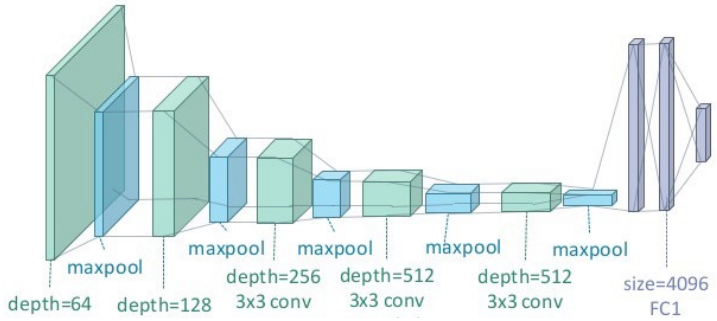
- Linear improvement in prediction and completion abilities with age
- More significant improvement in outline/inner features conditions

Exp 2: Categorical Drawings Evaluated by Convolutional NN

[Philippsen, Tsuji & Nagai, Front Psychology 2022]



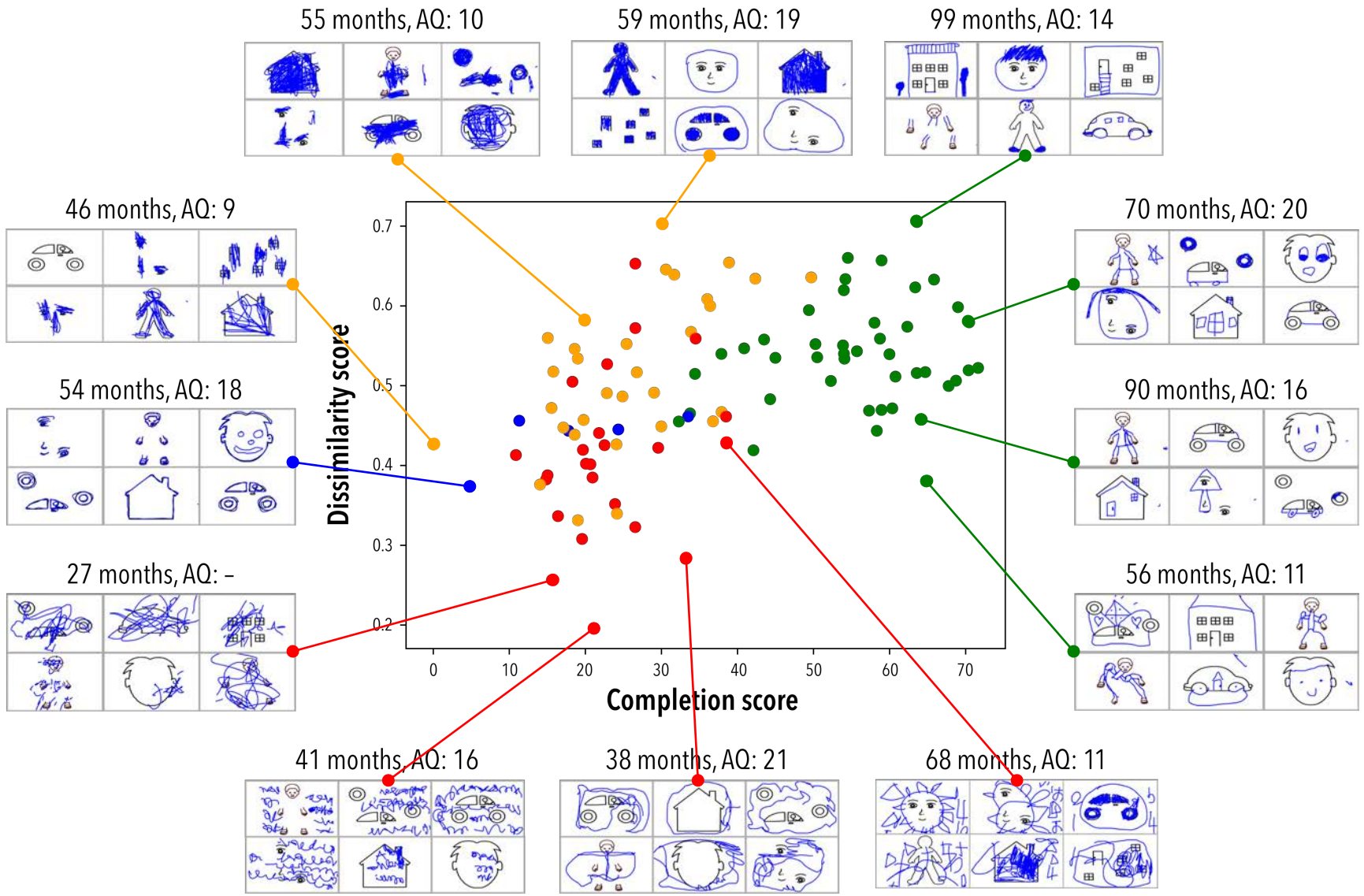
- Development of categorical representations with age
  - Younger childres: undifferentiated categories
  - Older children and adults: properly differentiated categories



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

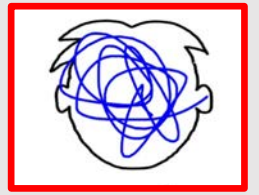
Exp 3: Developmental Diversity in Drawing

[Philippsen, Tsuji & Nagai, Front Psychology 2022]



Drawing style

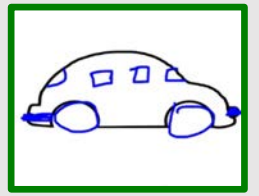
Scribbling



Coloring

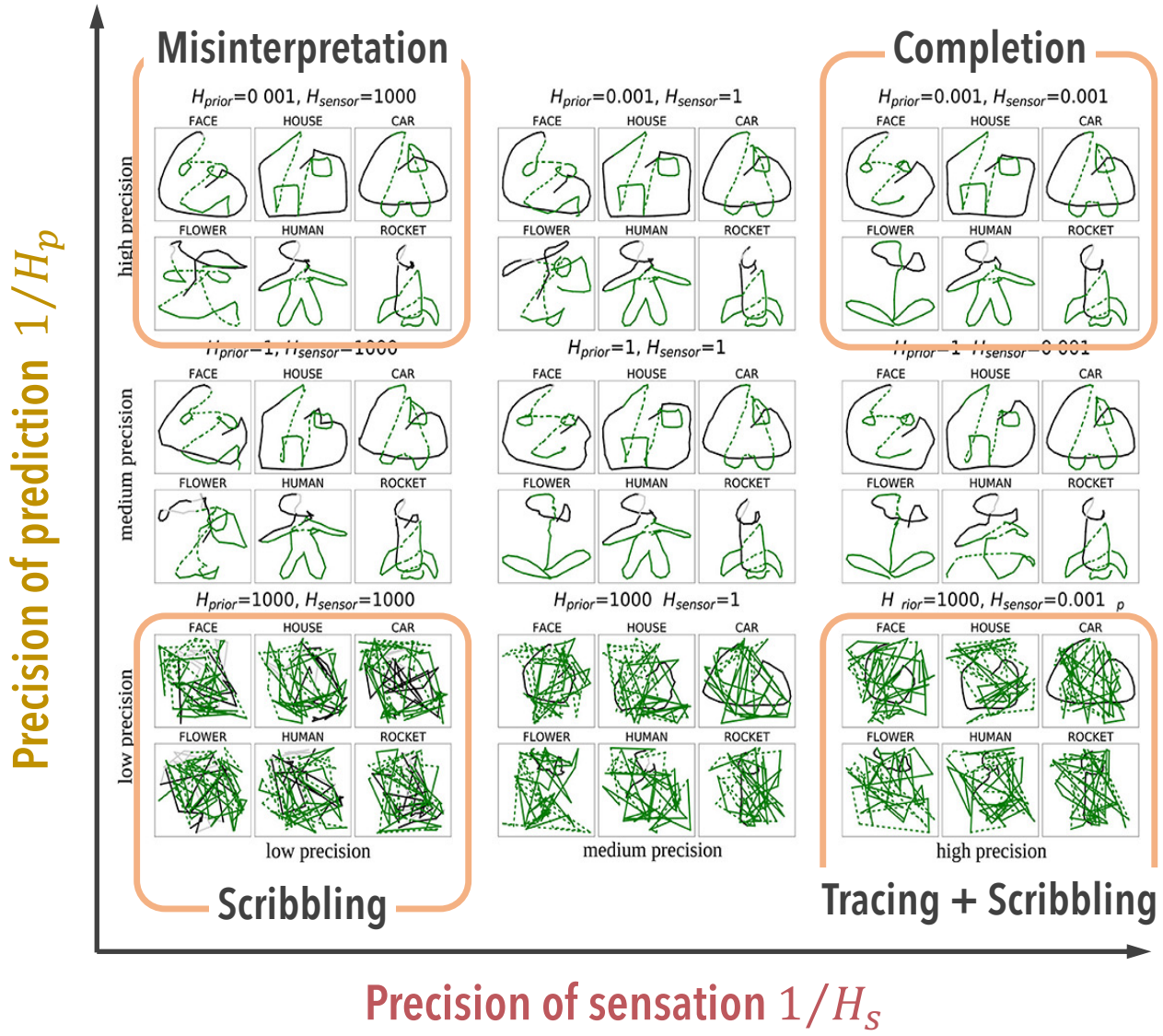
Tracing

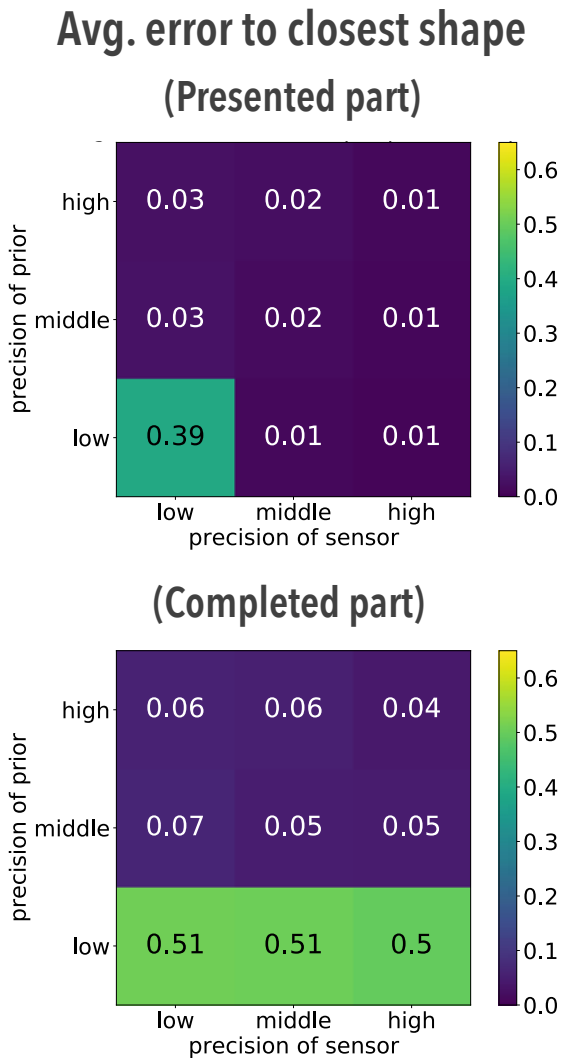
Completion



Exp 3: Influence of Aberrant Prediction and Sensation on Drawing

[Philippsen, Tsuji & Nagai, Front Neurorobot 2022]

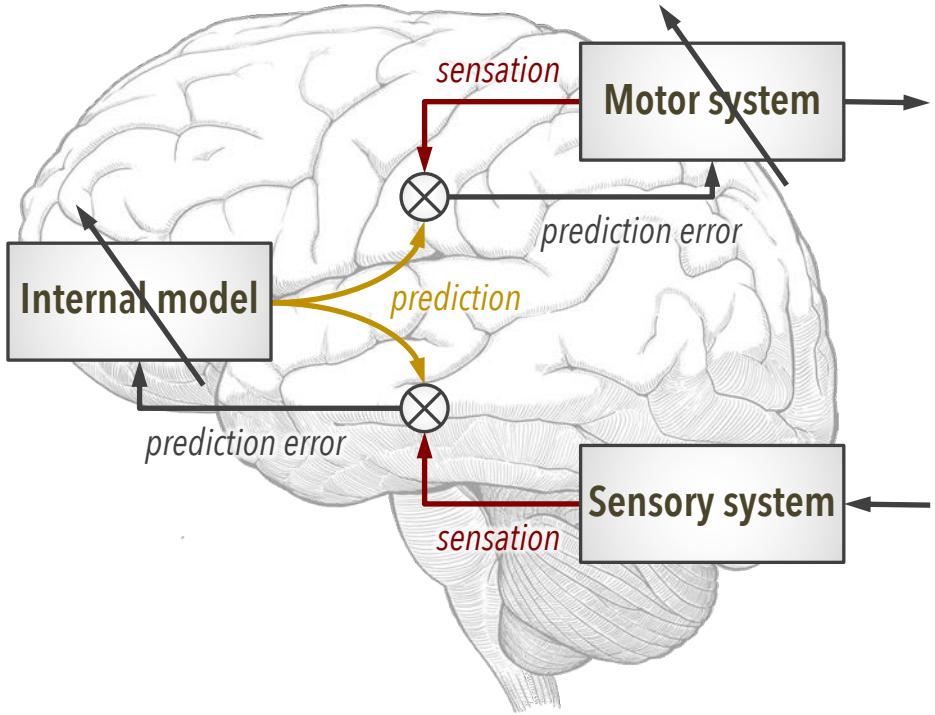


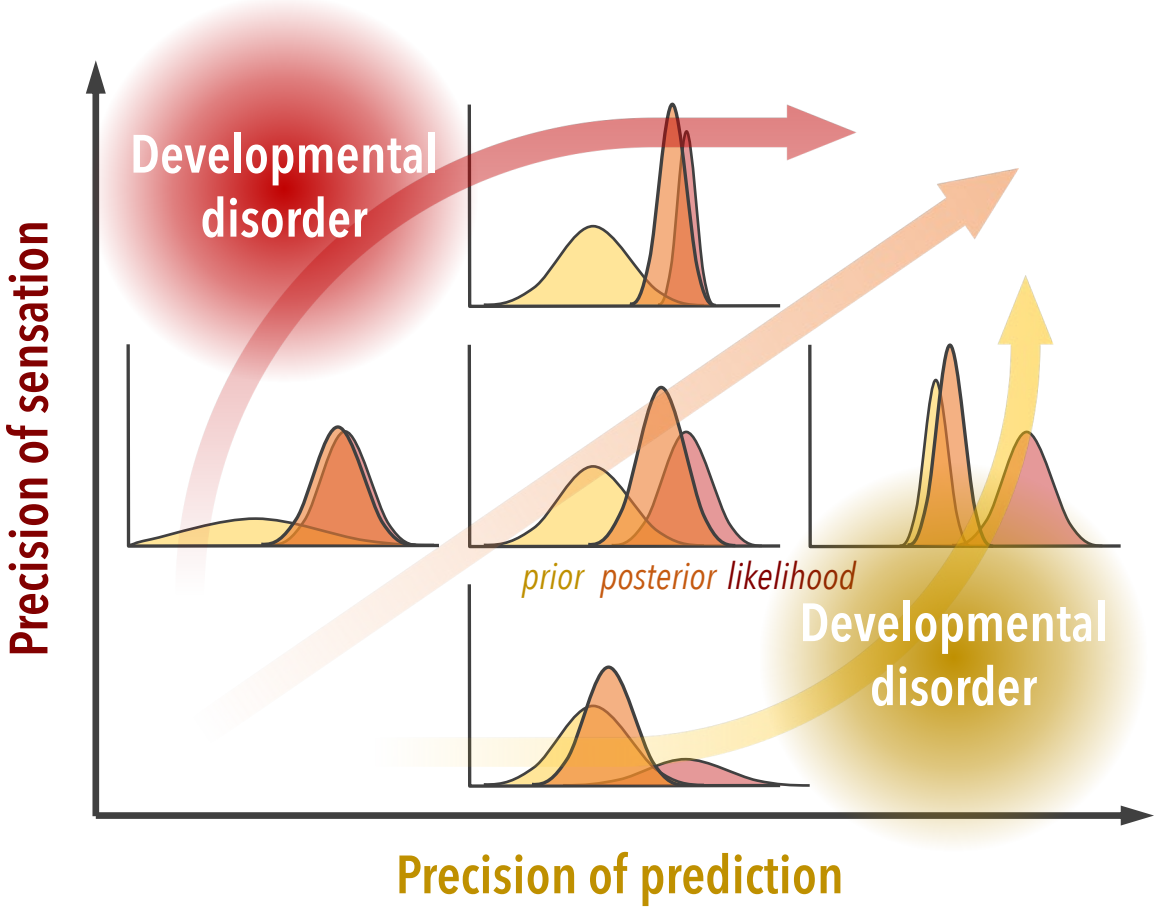


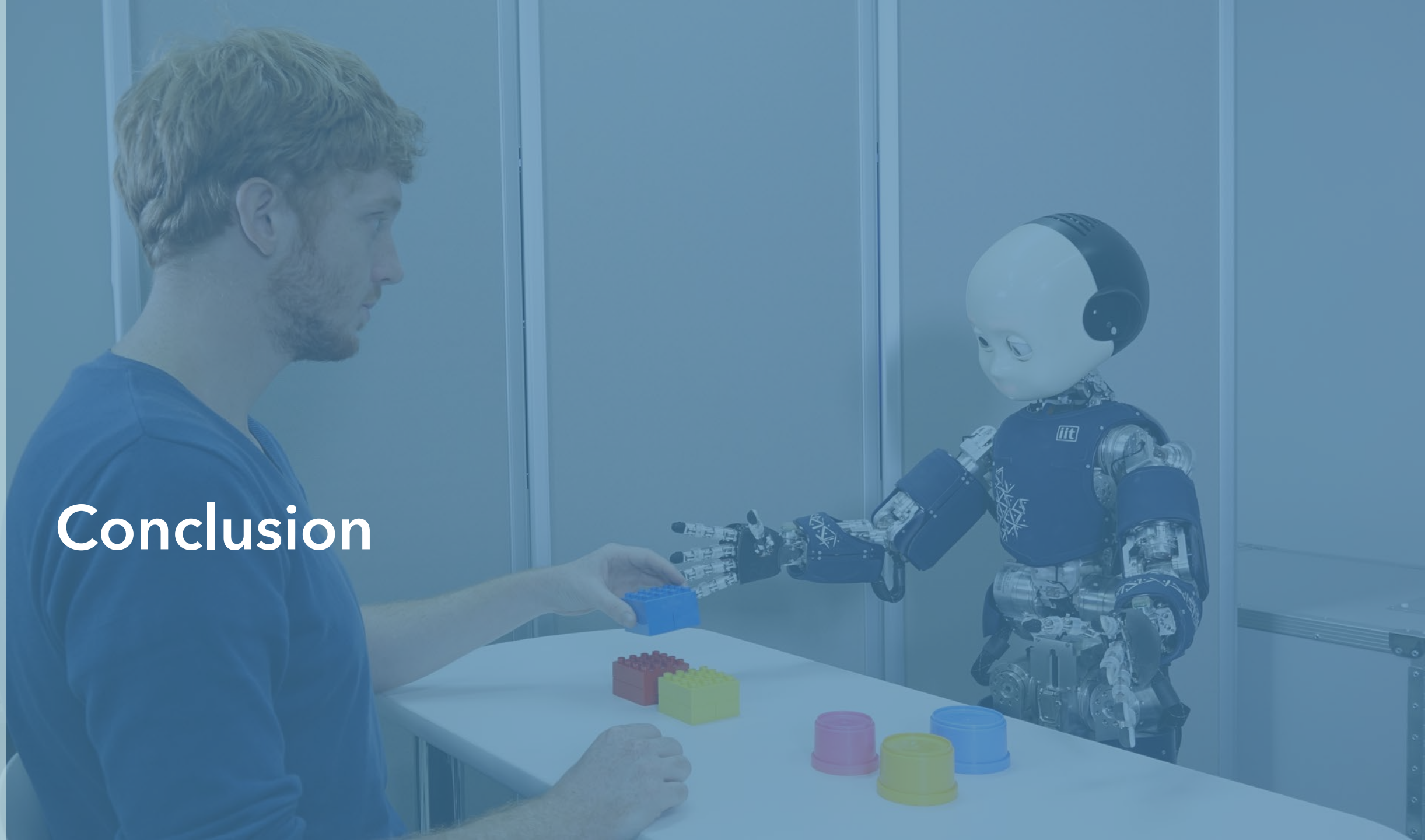
Interim Summary 2

Indivisual Diversity Based on Predictive Coding

- Improvement in prediction and sensory precision leads to cognitive development.
- Imbalance between prediction and sensation produces individual diversity.

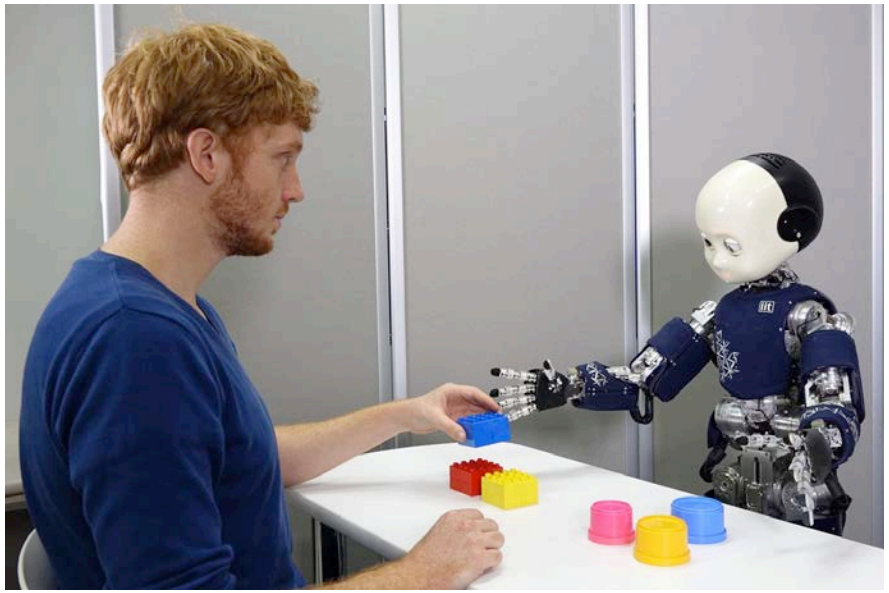






Conclusion

Cognitive Developmental Robotics



- Robotic approach to elucidate human intelligence
  - To bridge the gap between neuroscience and psychology
  - To gain new insights into neural, bodily, and social mechanisms
- Predictive coding as a unified princple for cognitive development and neurodiersity
  - Typical development as a result of balanced precision of sensation and prediction
  - Developmental disorders as a result of immbalanced precision

Thank You!

nagai.yukie@mail.u-tokyo.ac.jp | http://developmental-robotics.jp

CREST
Cognitive Feeling (2021-2026)
Cognitive Mirroring (2016-2021)

科研費 KAKENHI
KIBAN(S) Cognitive Individuality (2021-2025)
KIBAN(S) Mother-Infant Interaction (2021-2025)

Institute for AI and Beyond
AI x Tojisha-Kenkyu (2020-2022)

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JIZAI Translators (2022-2026)

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