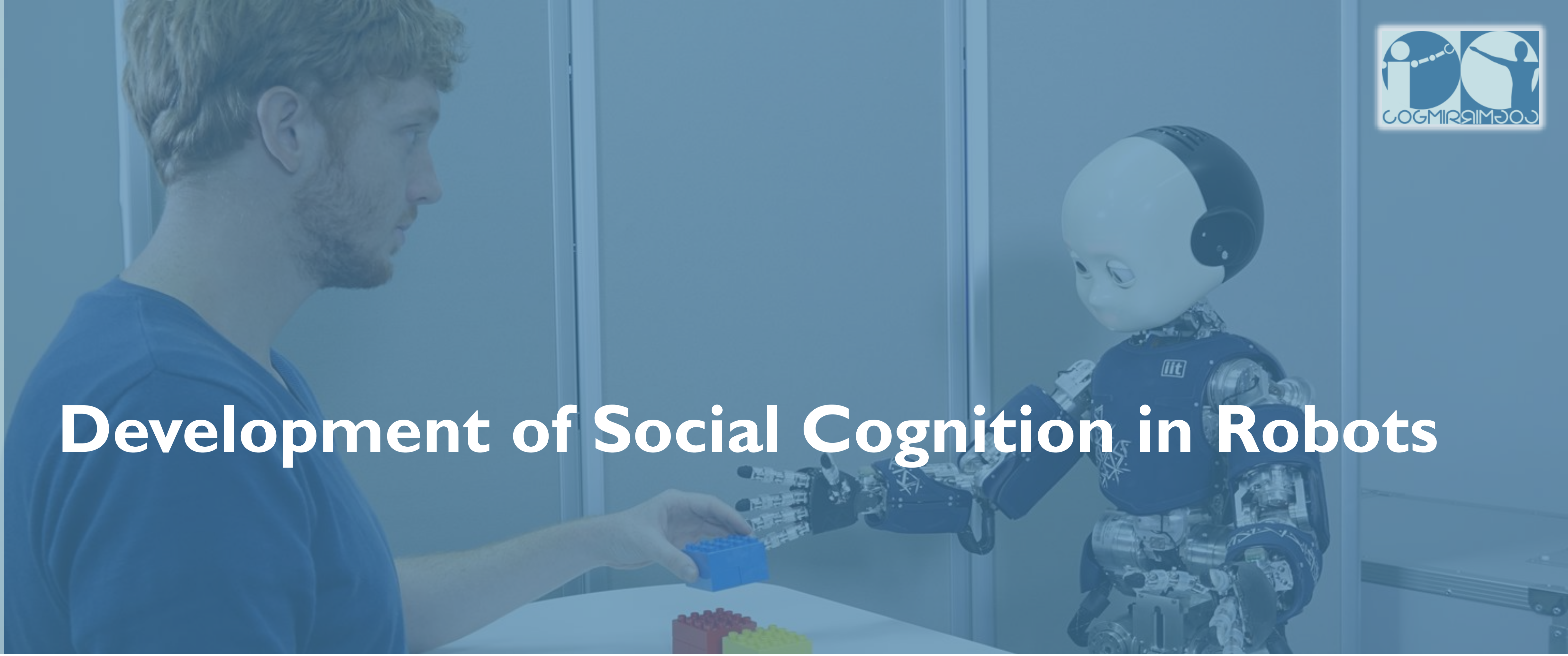


Development of Social Cognition in Robots

Yukie Nagai

NICT / Osaka University

JST-CREST / IEEE-RAS Spring School on "Social and Artificial Intelligence for User-Friendly Robots" @ Shonan Village, Japan, March 17-24, 2019

Mystery in Social Cognitive Development

Self recognition in mirror (24 mo)

[Amsterdam, 1972; Povinelli et al., 1996]

Helping **others** (14 mo)

[Warneken & Tomasello, 2006]

Imitation (0 mo)

[Meltzoff & Moore, 1977]
[Heyes, 2001]

Reading others' intention (6 mo)

[Woodward, 1998; Gergely et al., 1995]

Joint attention (12 mo)

[Butterworth & Jarrett, 1991]
[Moore et al., 1996; Brooks & Meltzoff, 2002]

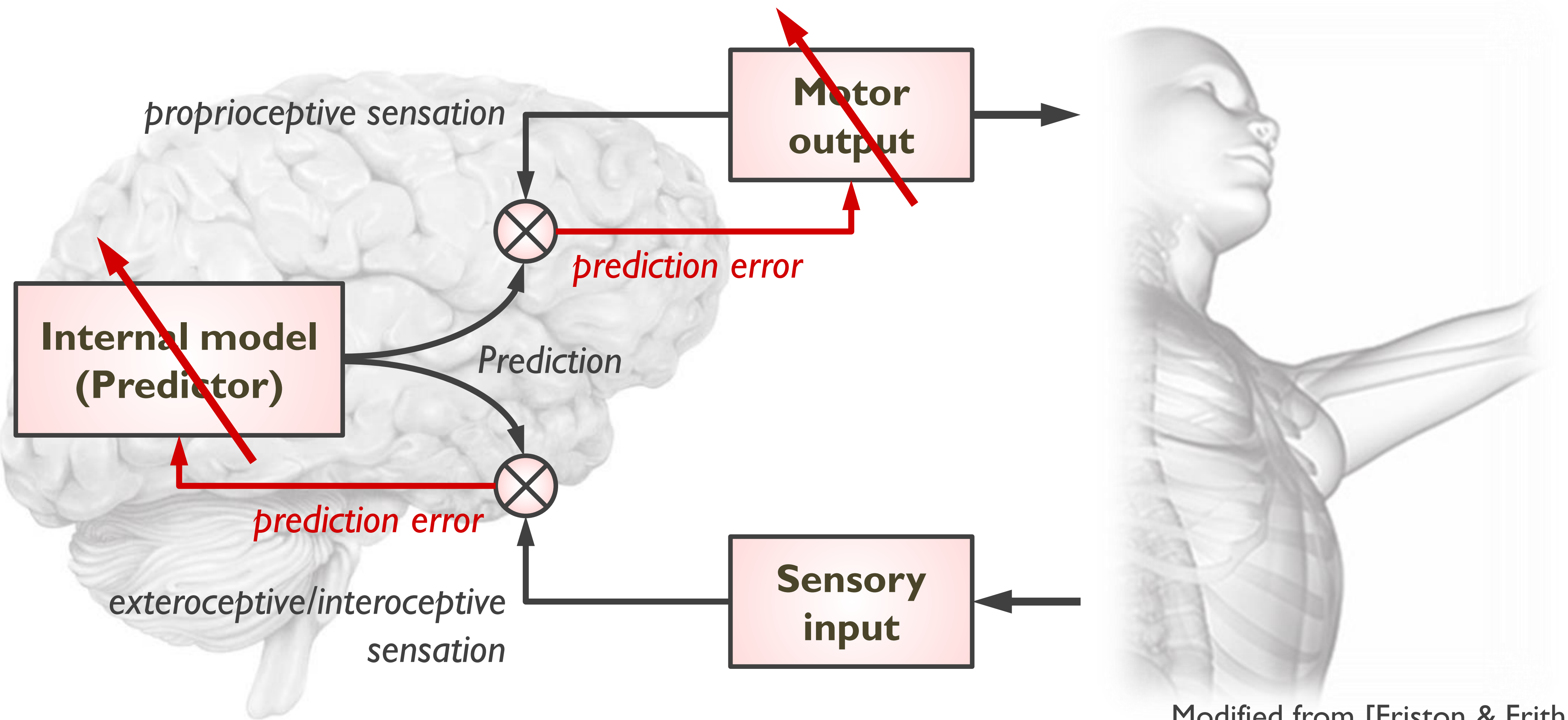
Emotion recognition/expression (6 mo)

[Bridges 1930; Lewis, 2007]

Predictive Coding: Brain as Predictive Machine

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

- The human brain tries to minimize prediction errors, which are calculated as difference between top-down prediction and bottom-up sensation.

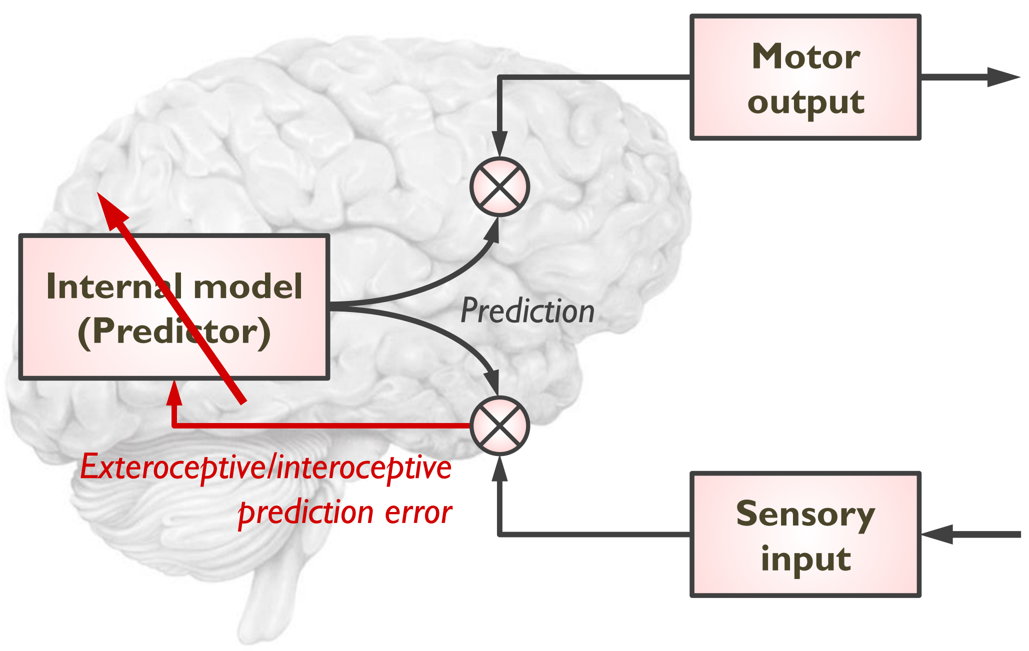


Modified from [Friston & Frith, 2015]

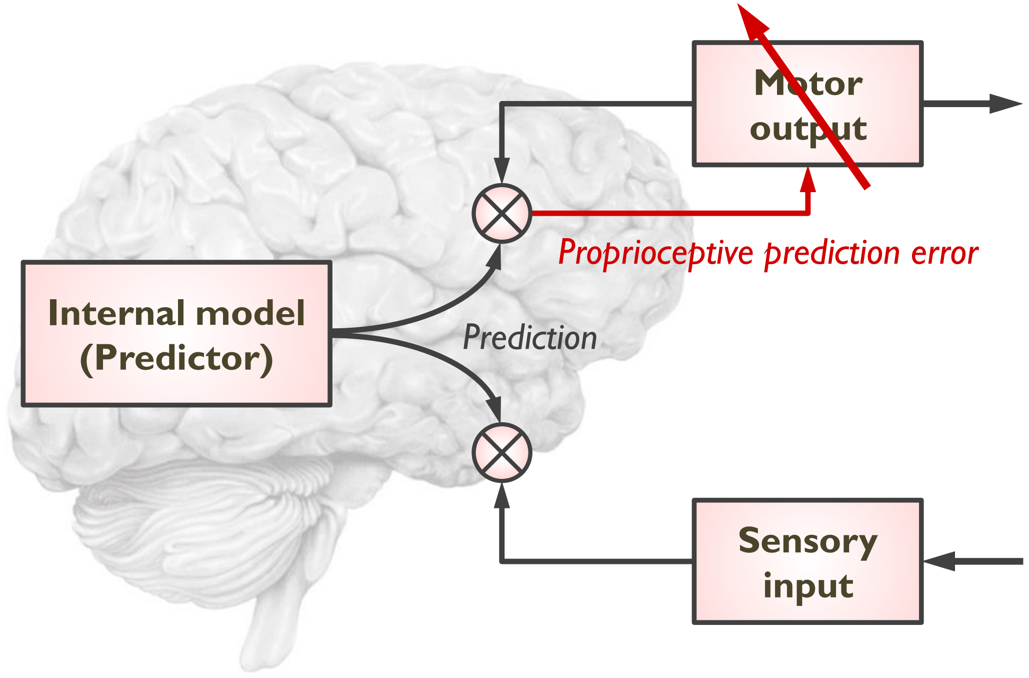
Our Hypothesis: Cognitive Development Based on Predictive Learning [Nagai, Phil Trans B 2019]

- Infants acquire various cognitive abilities ranging from non-social to social cognition through learning to minimize prediction errors:

(a) *Updating the internal model* through own sensorimotor experiences
  – Development of *self-relevant* abilities



(b) *Executing an action* to alter sensory signals
  – Development of *social* abilities



PHILOSOPHICAL TRANSACTIONS B

royalsocietypublishing.org/journal/rstb

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'.

Predictive learning: its key role in early cognitive development

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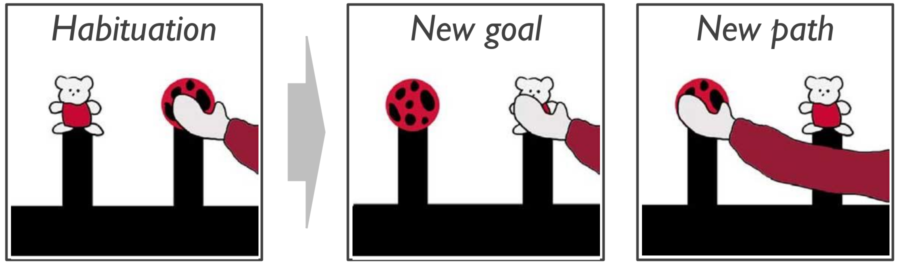
What is a fundamental ability for cognitive development? Although many researchers have been addressing this question, no shared understanding has been acquired yet. We propose that predictive learning of sensorimotor signals plays a key role in early cognitive development. The human brain is known to 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

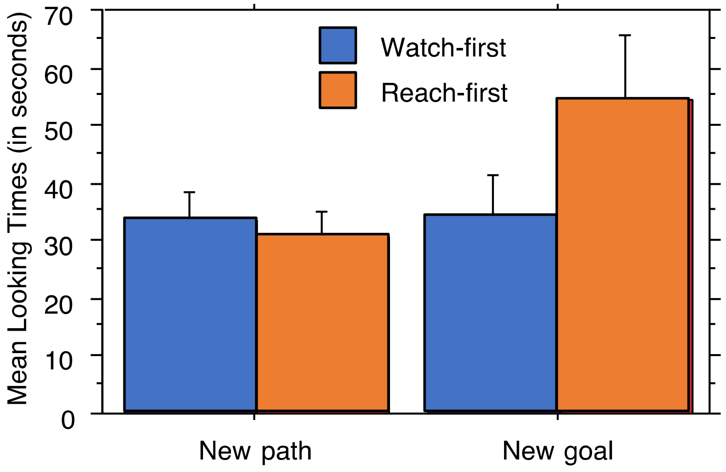
Part 1:

Social Cognitive Development Based on Predictive Learning

Estimation of Others' Action Goal by Infants

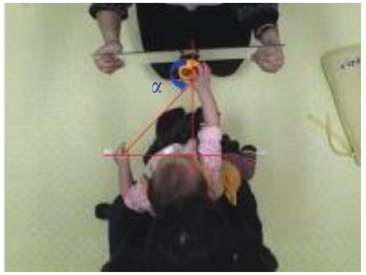
- 3-month-old infants can detect the goal-directed structure in others' action only *when they were given own action experiences.*
  [Sommerville et al., 2005; Gerson & Woodward, 2014]

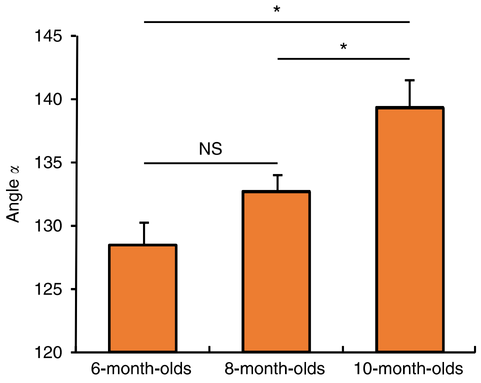




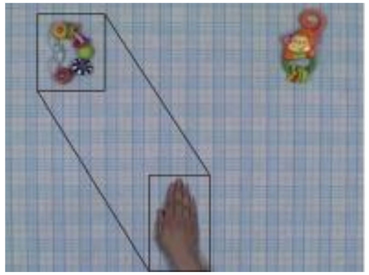
- Infants' ability to predict the goal of others' action develops *in synchrony with the improvement in their action production.*
  [Kanakogi & Itakura, 2011]

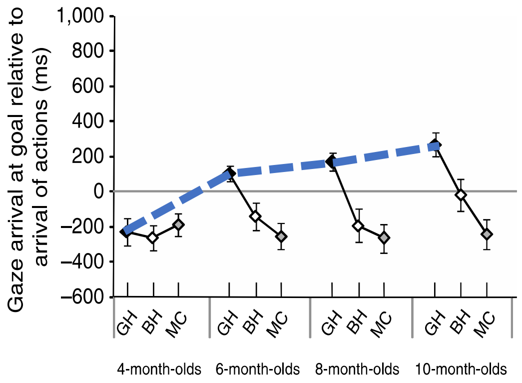
Action production



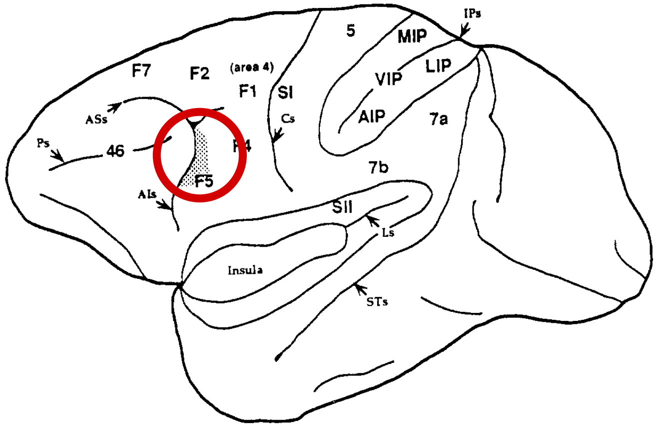


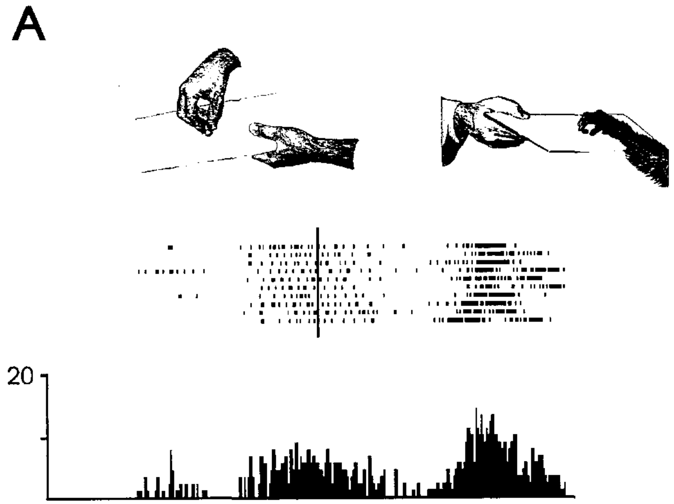
Action perception



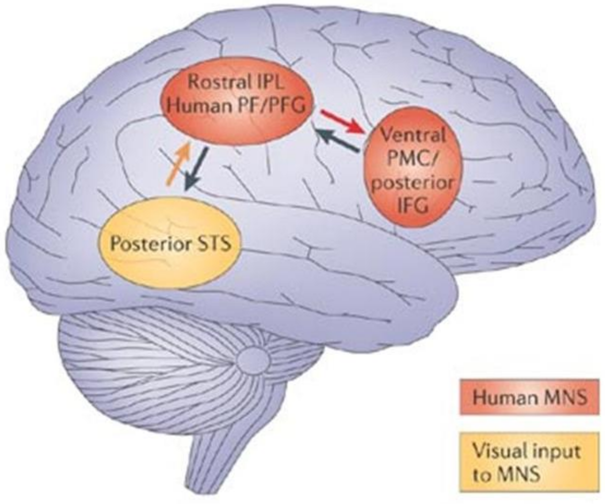


Mirror Neuron (MN) and Mirror Neuron System (MNS)





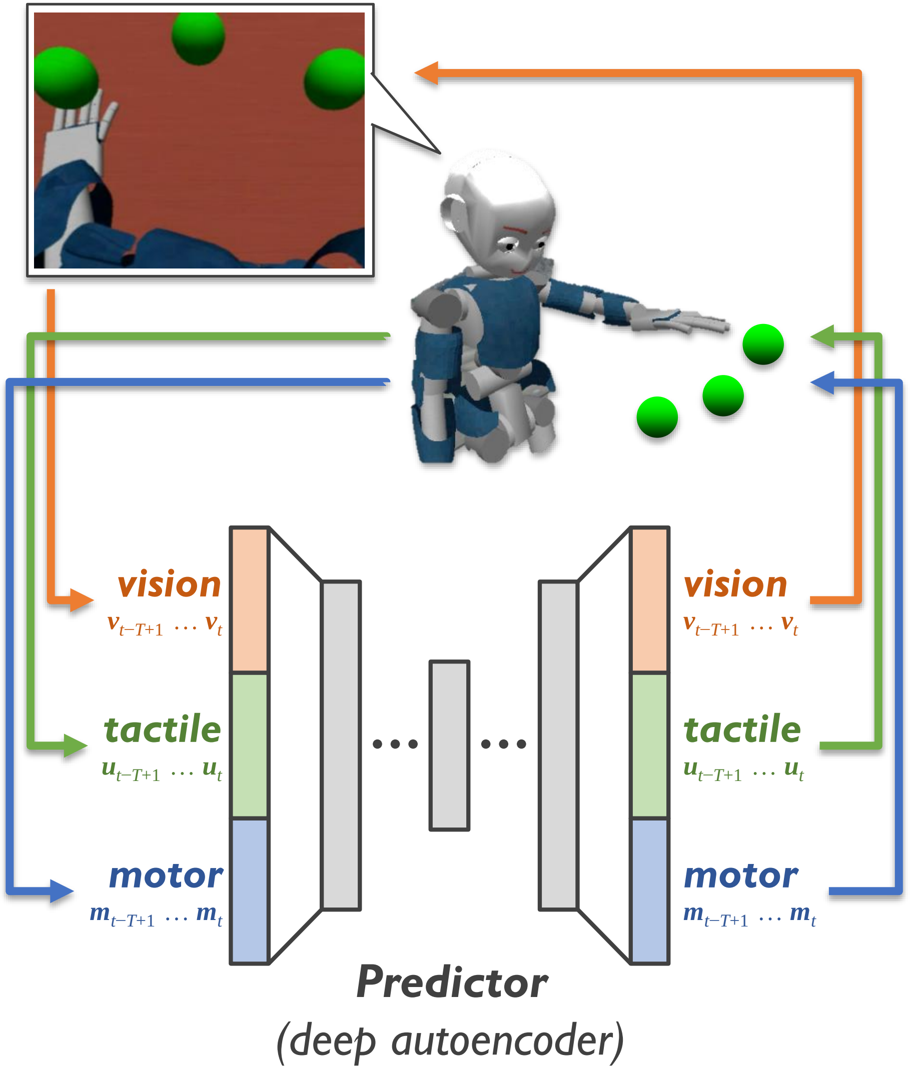
[Rizzolatti et al., 1996]



[Iacoboni & Dapretto, 2006]

- Originally found in monkey's premotor cortex [Rizzolatti et al., 1996, 2001]
- Discharge both:
  - when *executing* an action
  - when *observing* the same action performed by other individuals
- Understand others' action and intention based on self's motor representation

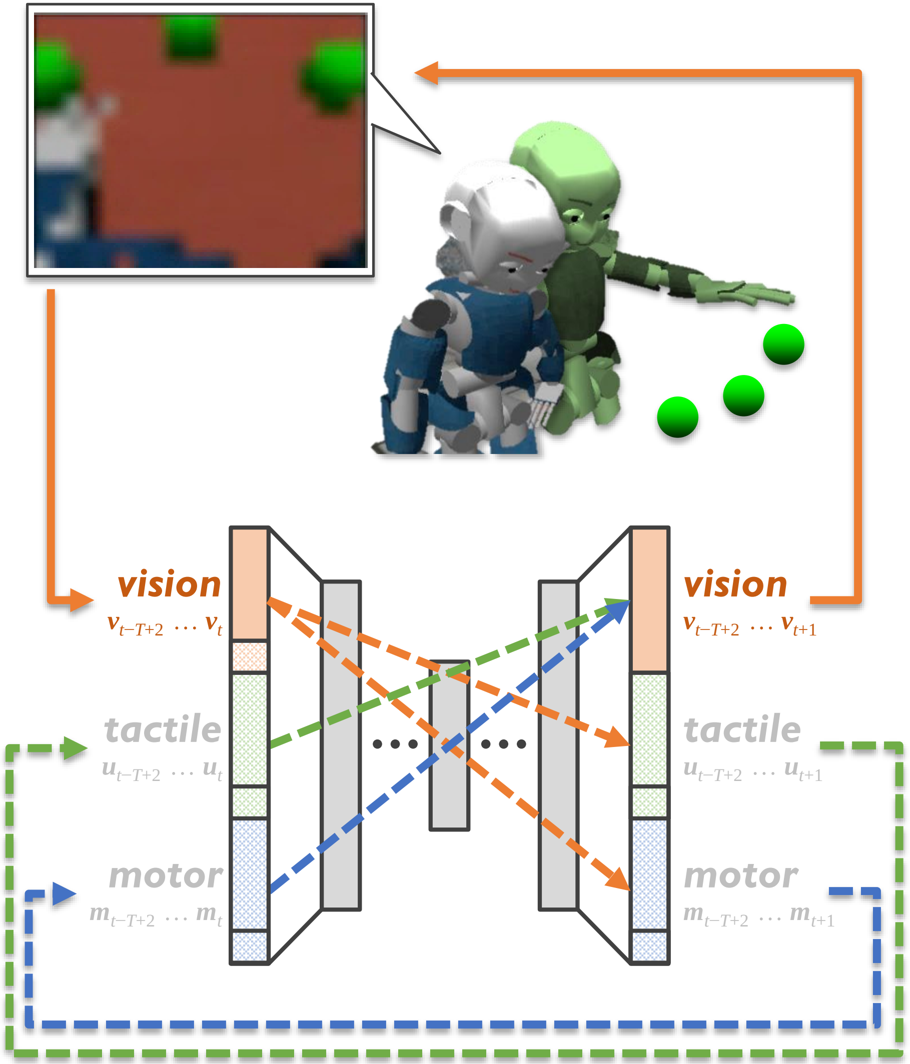
Predictive Learning for Development of MNS



- Predictive learning to integrate sensorimotor signals enables a robot to *recall own motor experiences* while observing others' action as well as to produce the action.
  → *Mirror neuron system*
- Predictor using a deep autoencoder:
  – Action production: learns to reconstruct visual $\boldsymbol{v}$, tactile $\boldsymbol{u}$, and motor signals $\boldsymbol{m}$.

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

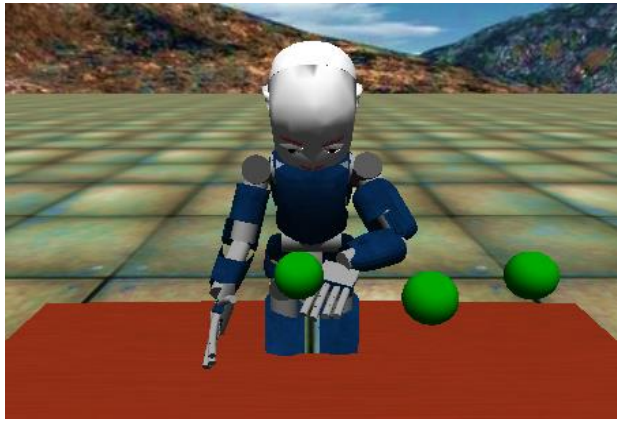
Predictive Learning for Development of MNS



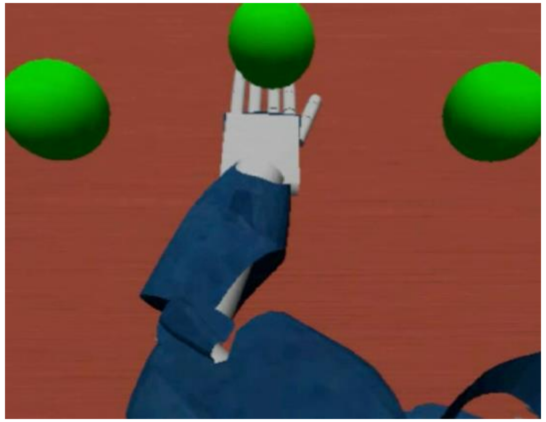
- Predictive learning to integrate sensorimotor signals enables a robot to *recall own motor experiences* while observing others' action as well as to produce the action.
  → *Mirror neuron system*
- Predictor using a deep autoencoder:
  – Action production: learns to reconstruct visual ***v***, tactile ***u***, and motor signals ***m***.
  – Action observation: predicts ***v*** using imaginary ***u*** and ***m*** as well as actual ***v***
  →More accurate prediction of ***v***

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

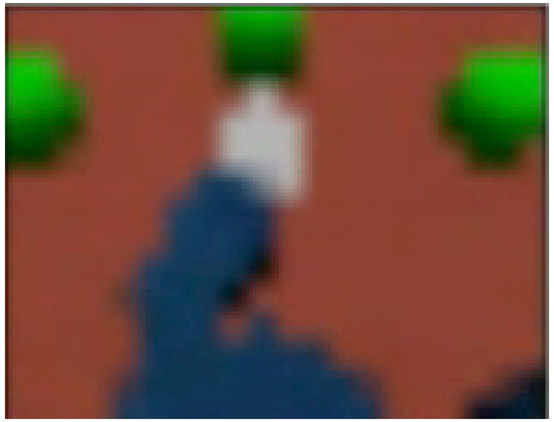
Result 1: Prediction of Observed Action



Actual image



Predicted image



Input/output signals

- Vision: camera image (30 dim)
- Tactile: on/off (3 dim)
- Motor: joint angles of shoulder and elbow (4 dim)

… for 30 steps

Assumption

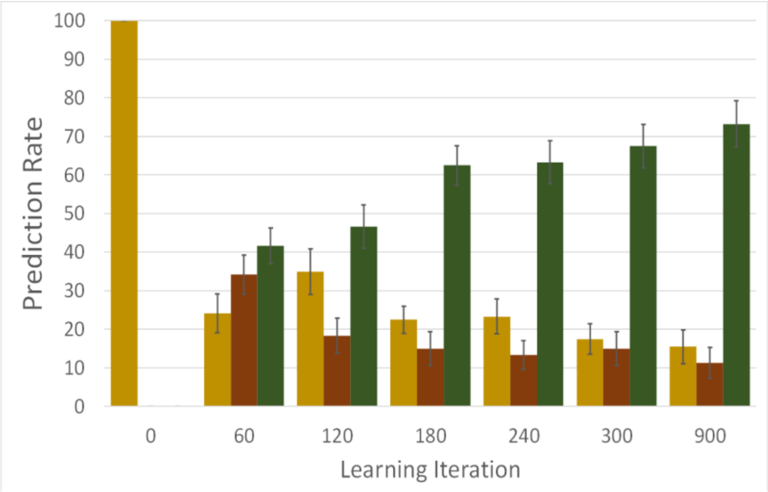
- Shared viewpoint between self and other

Predicted image	Classification of prediction
	Correct goal
	Incorrect goal
	No goal

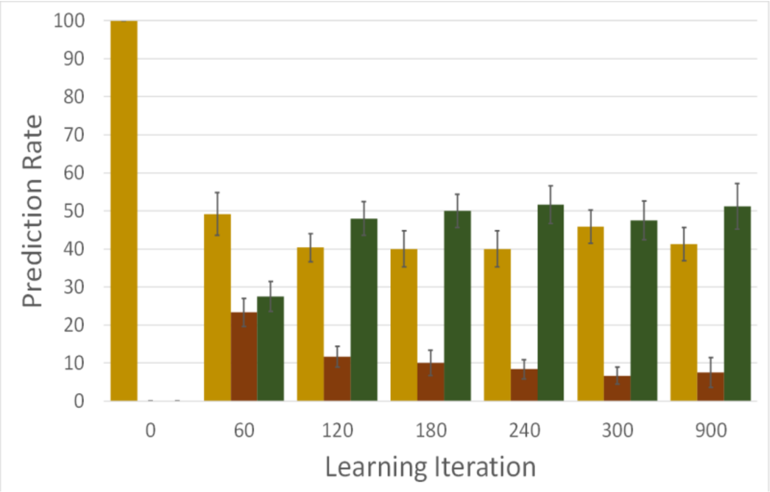
[Copete, Nagai, & Asada, ICDL-EpiRob 2016]

Result 2: Prediction Accuracy Improved by Motor Experience

With motor experience



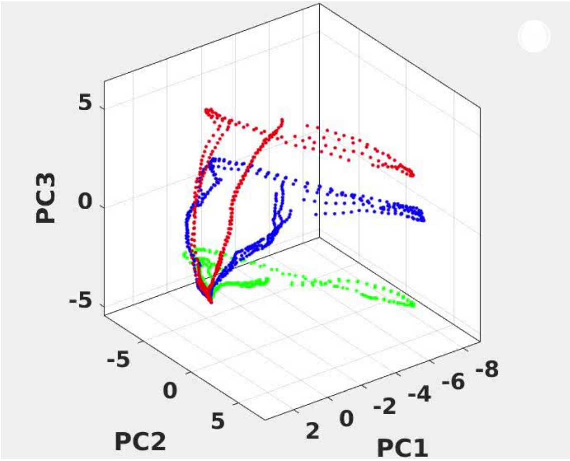
Without motor experience (only observation)

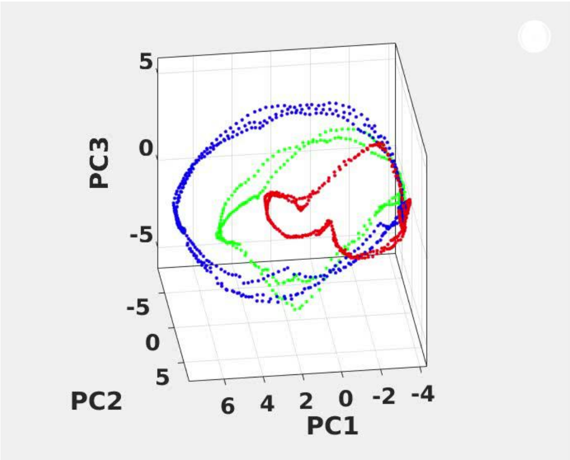


Correct goal

Incorrect goal

No goal





Reaching for left

Reaching for center

Reaching for right

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

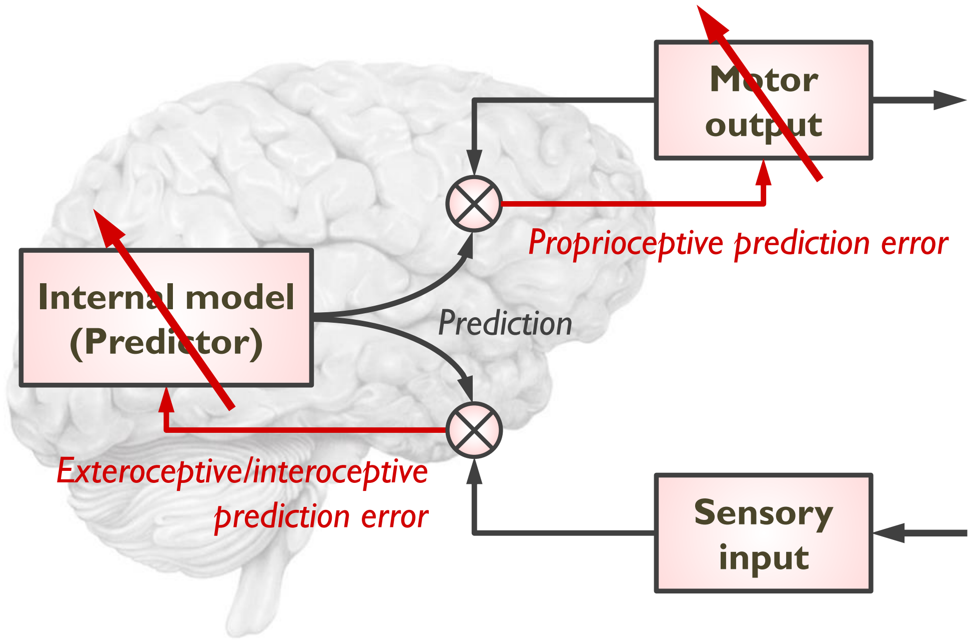
Two Theories for Helping Behaviors [Paulus, 2014]

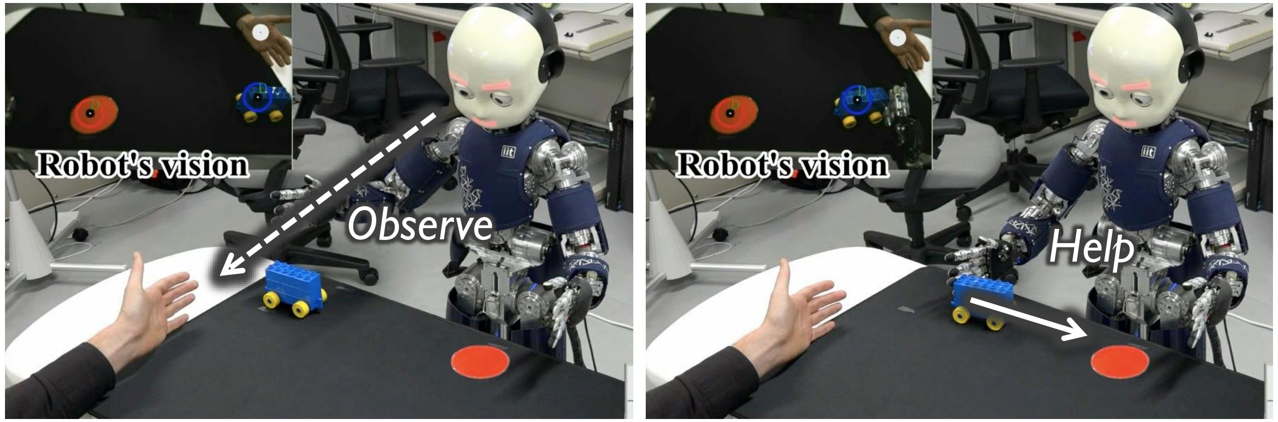
[Warneken & Tomasello, 2006]

- Emotion-sharing theory
  - Recognize other persons as intentional agents [Batson, 1991]
  - Be motivated to help others based on empathic concern for others' needs [Davidov et al., 2013]
  - Self-other *differentiation*
- Goal-alignment theory
  - Estimate others' goal, but not their intention [Barresi & Moore, 1996]
  - Take over others' goal as if it were the infant's own
  - *Undifferentiated* self-other

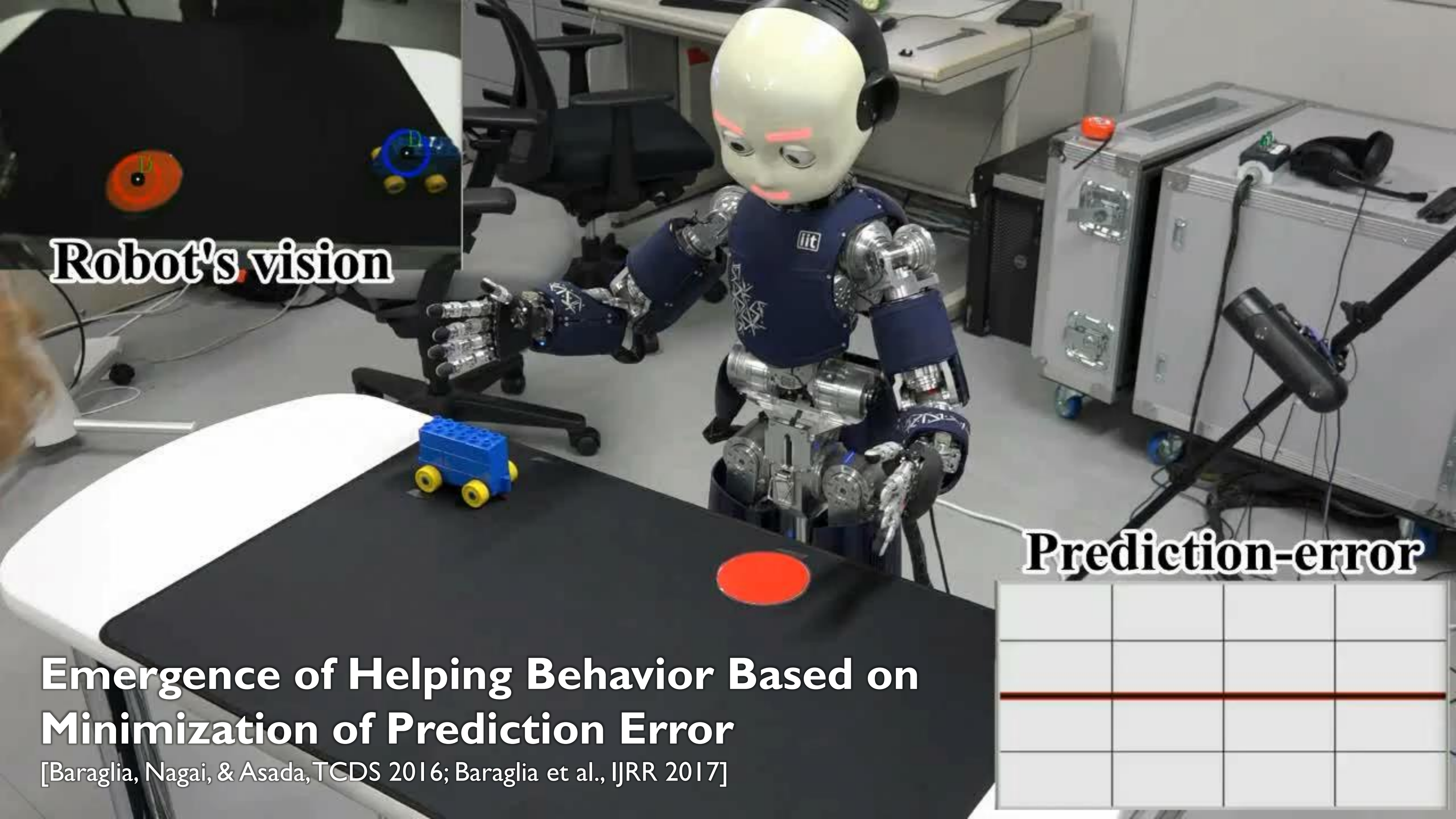
Computational Model for Emergence of Helping Behavior

- Helping behaviors emerge though the minimization of prediction error.
- The robot:
  1) learns to acquire the predictor through own motor experiences,
  2) calculates a *prediction error* while observing others' action, and
  3) executes a motor command to minimize *the prediction error.*



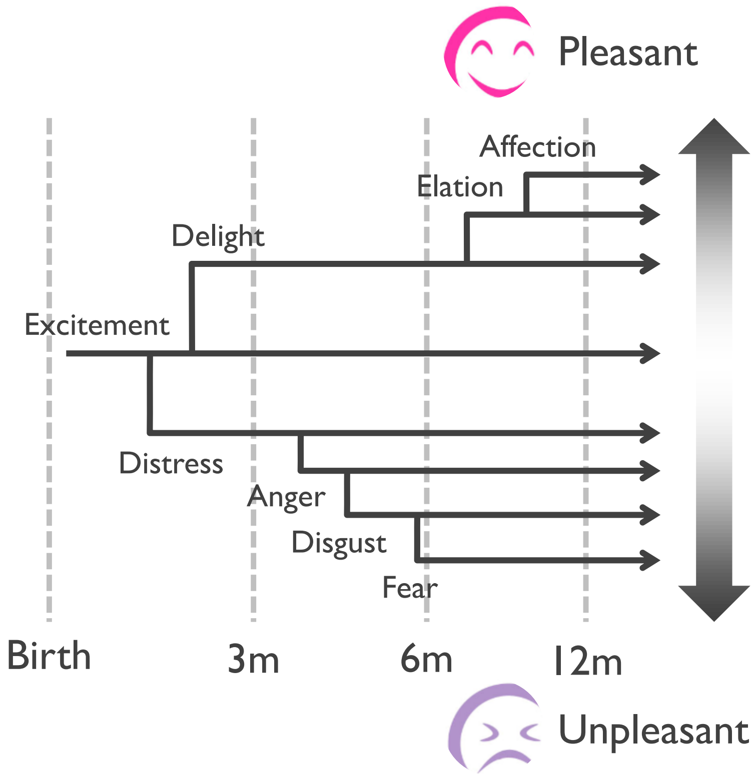


[Baraglia, Nagai, & Asada, TCDS 2016; Baraglia et al., IJRR 2017]

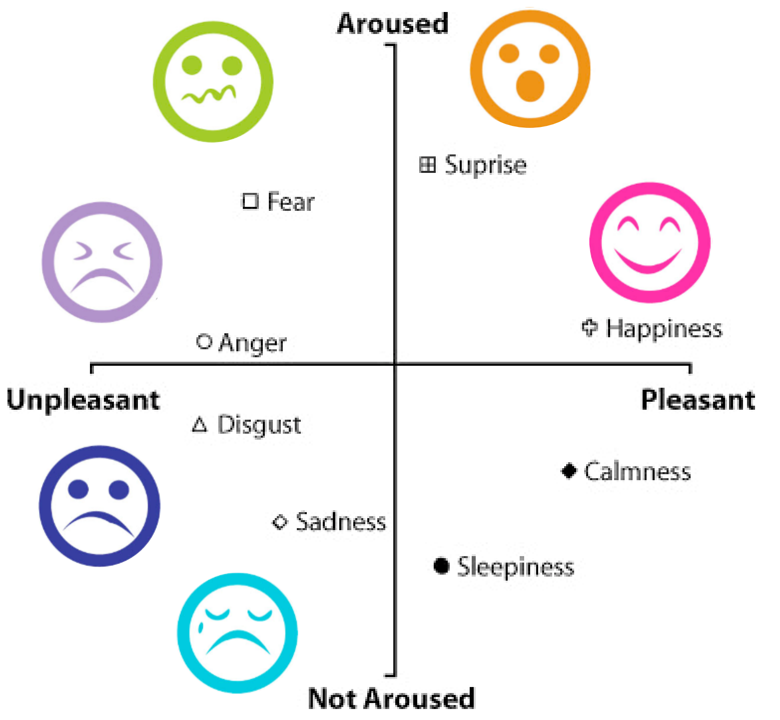

Robot's vision
iit
Prediction-error
Emergence of Helping Behavior Based on Minimization of Prediction Error
[Baraglia, Nagai, & Asada, TCDS 2016; Baraglia et al., IJRR 2017]

Developmental Differentiation of Emotion in Infants

- Infants at birth have *only excitation*, which is later differentiated into *pleasant and unpleasant* [Bridges, 1930].
- *Six basic emotions* as in adults appear only at about 12 months old [Sroufe, 1979; Lewis, 1997].



[Bridges, 1980]

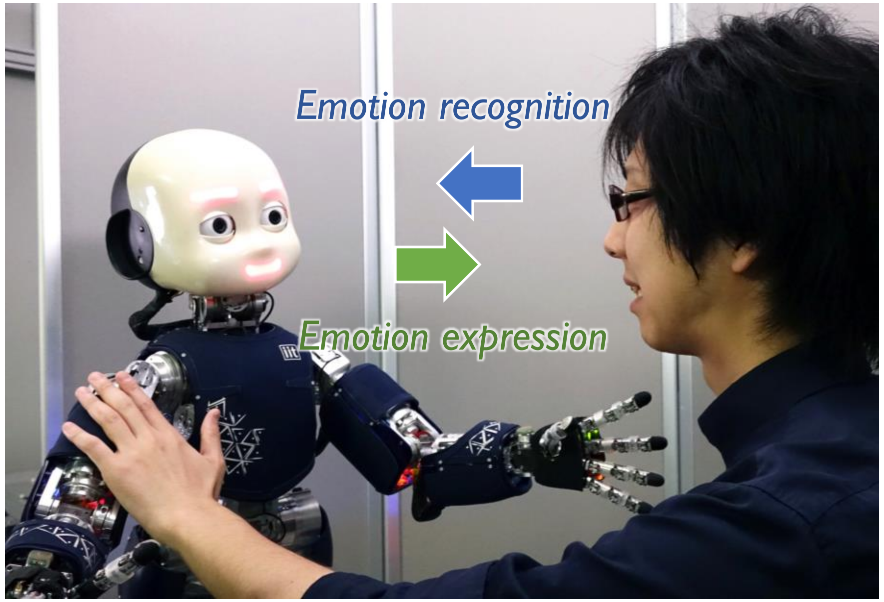


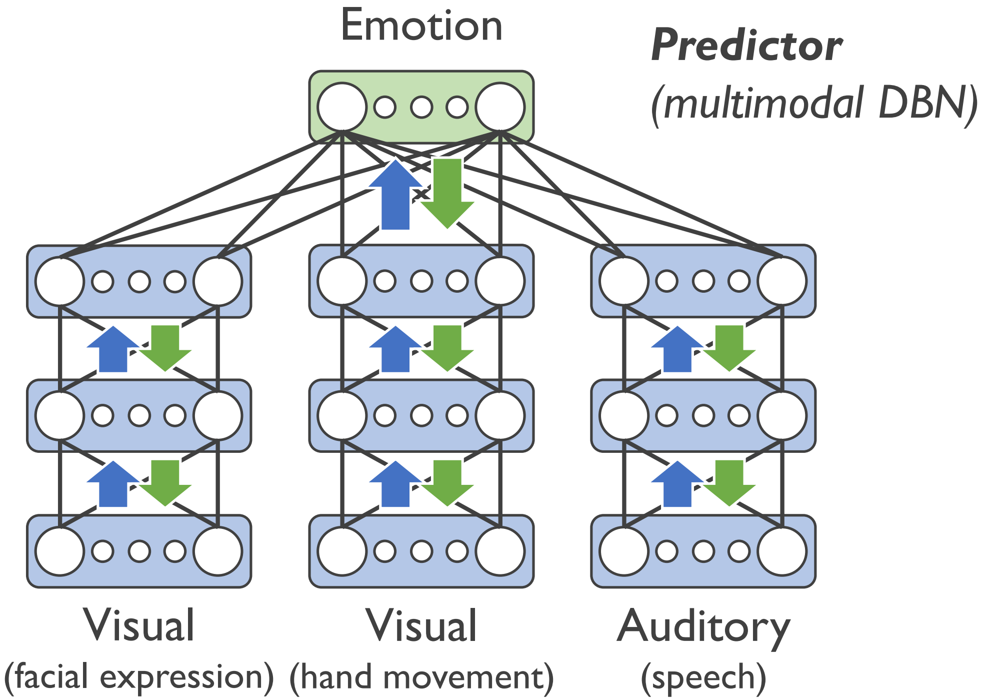
[Russell, 1980]

Predictive Learning for Emotion Development

- Emotion is perceived through inference of interoceptive and exteroceptive signals [Seth et al., 2012].
- Predictive learning of multimodal signals enables a robot to estimate and imitate others' emotion by *putting themselves in others' shoes*.

  → *Mirror neuron system*





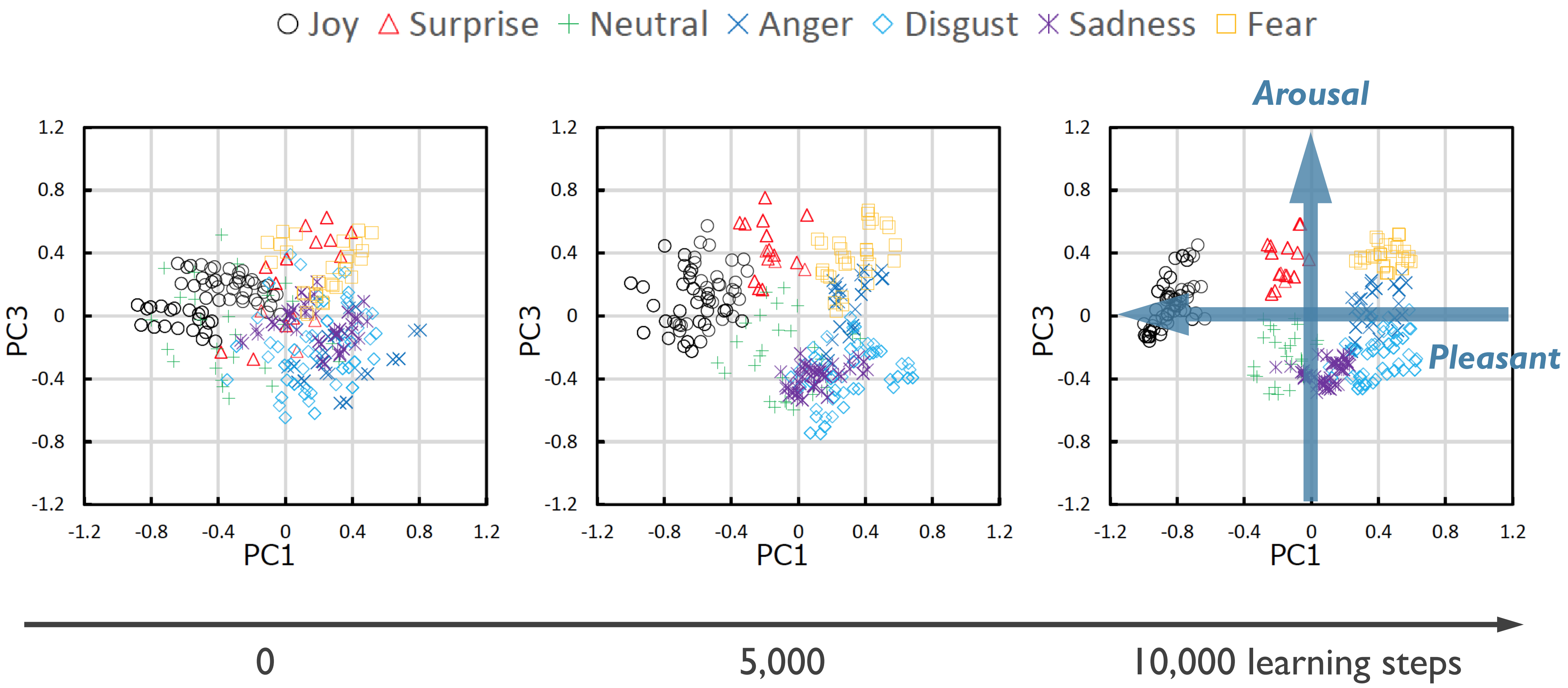
[Horii, Nagai, & Asada, Paladyn 2016; TCDS 2018]

Robot that Learns to Imitate Human Emotion

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

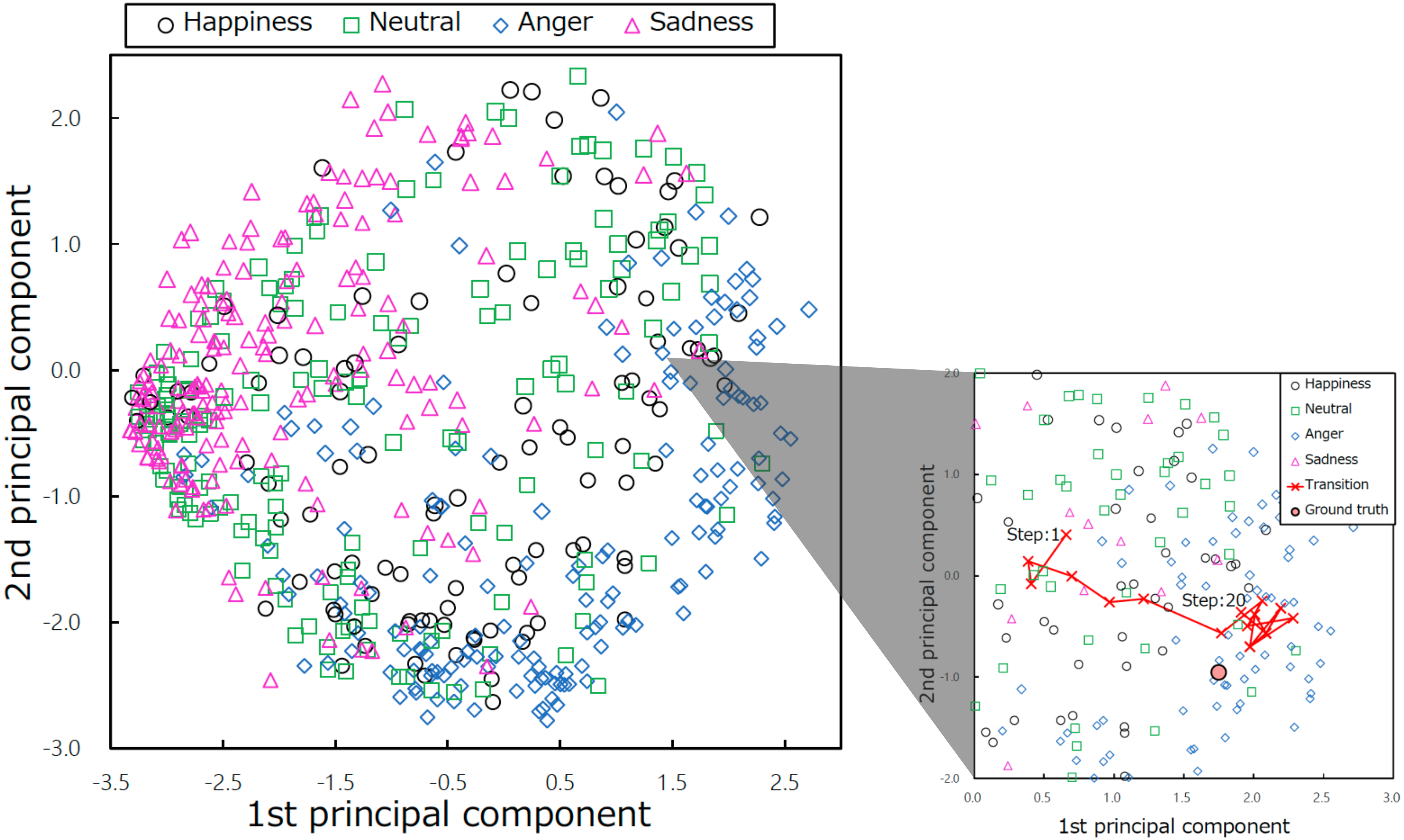
(NHK, 2016.08.23)

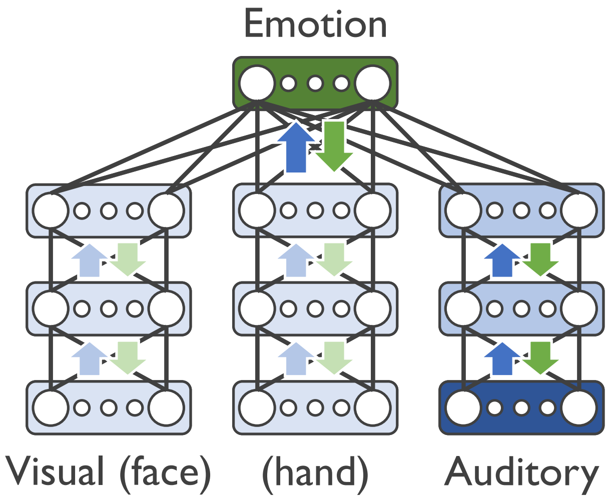
Result 1: Developmental Differentiation of Emotion



[Horii, Nagai, & Asada, TCDS 2018]

Result 2: Emotion Estimation through Mental Simulation





Only auditory input is given.

→ *Imaginary* visual signals improved the accuracy of emotion estimation.

[Horii, Nagai, & Asada, Paladyn 2016]

Part 2:

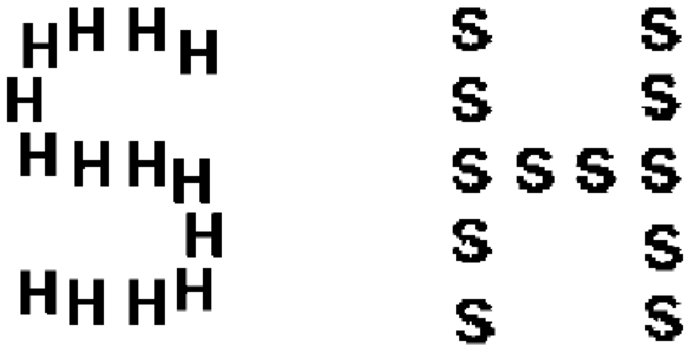
What Cause Developmental Disorders?

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]

Tojisha-Kenkyu on ASD [Kumagaya, 2014; Ayaya & Kumagaya, 2008]

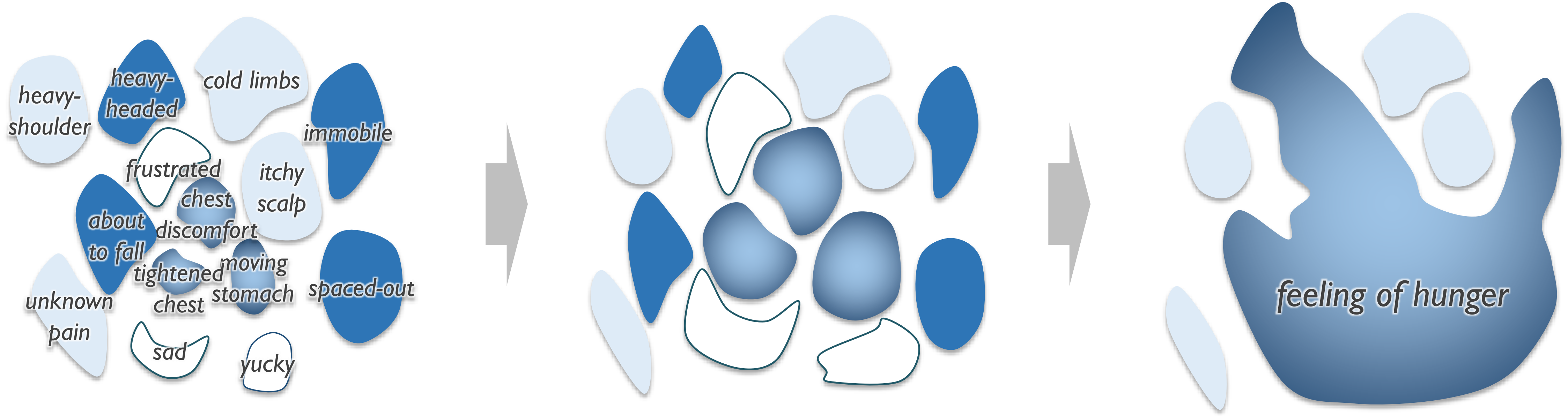
- A research method by which people with ASD investigates themselves from the first-person's perspective
  - Heterogeneity of ASD
  - Subjective experiences

Ms. Satsuki Ayaya (Researcher, University of Tokyo)

- Diagnosed as Asperger syndrome in 2006
- Has been organizing regular meetings to conduct Tojisha-kenkyu since 2011
- Member of my CREST project since 2016

Difficulty in Feeling Hunger in ASD

- Feeling of hunger is hard to be recognized and requires conscious process of selecting and integrating proper sensory signals in ASD [Ayaya & Kumagaya, 2008].



1. Equally perceive multimodal sensations
2. Enhance hunger-relevant signals while diminishing irrelevant signals
3. Recognize hunger by integrating relevant signals

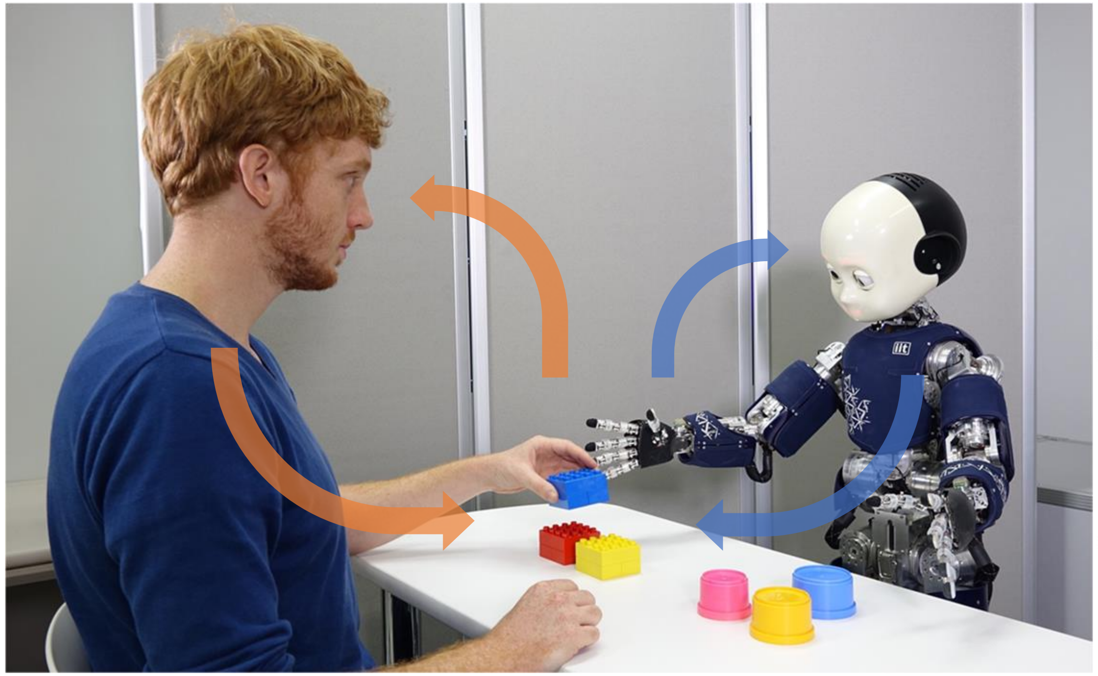
: *limited to hunger* : *relevant to hunger* : *irrelevant to hunger* : *psychological*

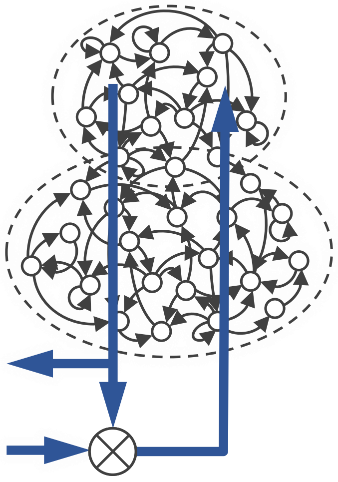
"Cognitive Mirroring" as New Approach to Understanding ASD

- Artificial intelligent systems that make human cognitive processes observable
- Self-understanding and social-sharing as an important first step for assistance

Human cognition = **System's cognition**

Unobservable & qualitative *Observable & quantitative*





Computational models

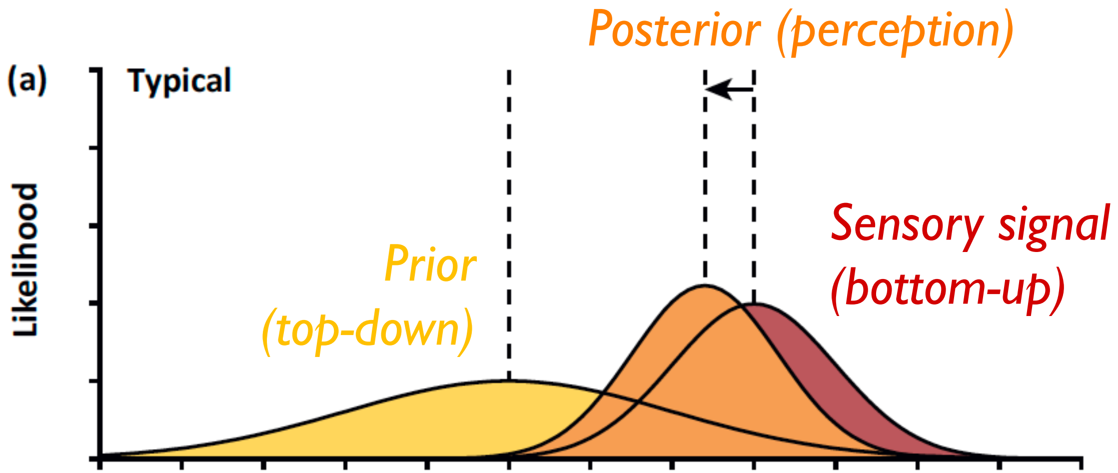
Neural networks, Bayesian models, etc.

[Nagai, Seitai no Kagaku 2018]

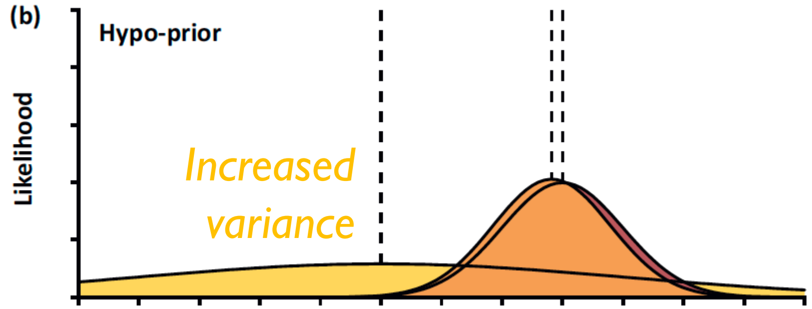
Bayesian Account for ASD Based on Predictive Coding

- Perception based on Bayesian inference
  (a) Perception $p(\boldsymbol{x}|\boldsymbol{u})$ is determined by the integration of sensory observation $p(\boldsymbol{u}|\boldsymbol{x})$ and prior expectation $p(\boldsymbol{x})$

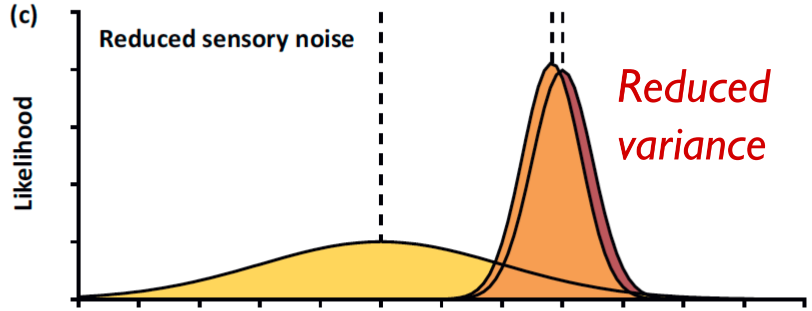
$$p(\boldsymbol{x}|\boldsymbol{u}) \propto p(\boldsymbol{u}|\boldsymbol{x})\, p(\boldsymbol{x})$$



- Hypotheses about ASD
  (b) Hypo-prior hypothesis [Pellicano & Burr, 2012]

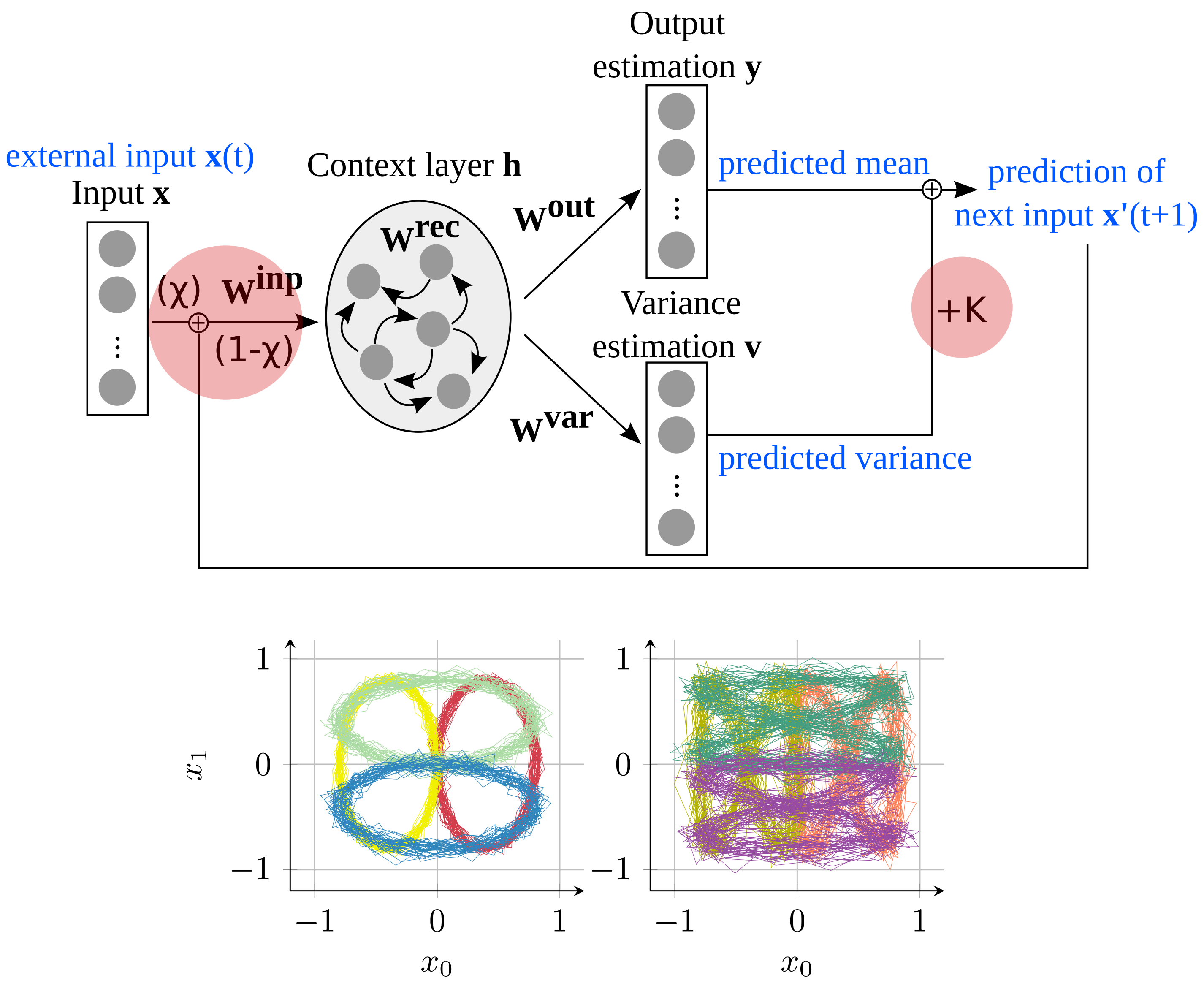


  (c) Reduced sensory noise hypothesis [Brock, 2012; Van de Cruys et al., 2014; Davis & Plaisted-Grant, 2015]



  (d) Imbalance between (b) and (c) [Lawson et al., 2014]

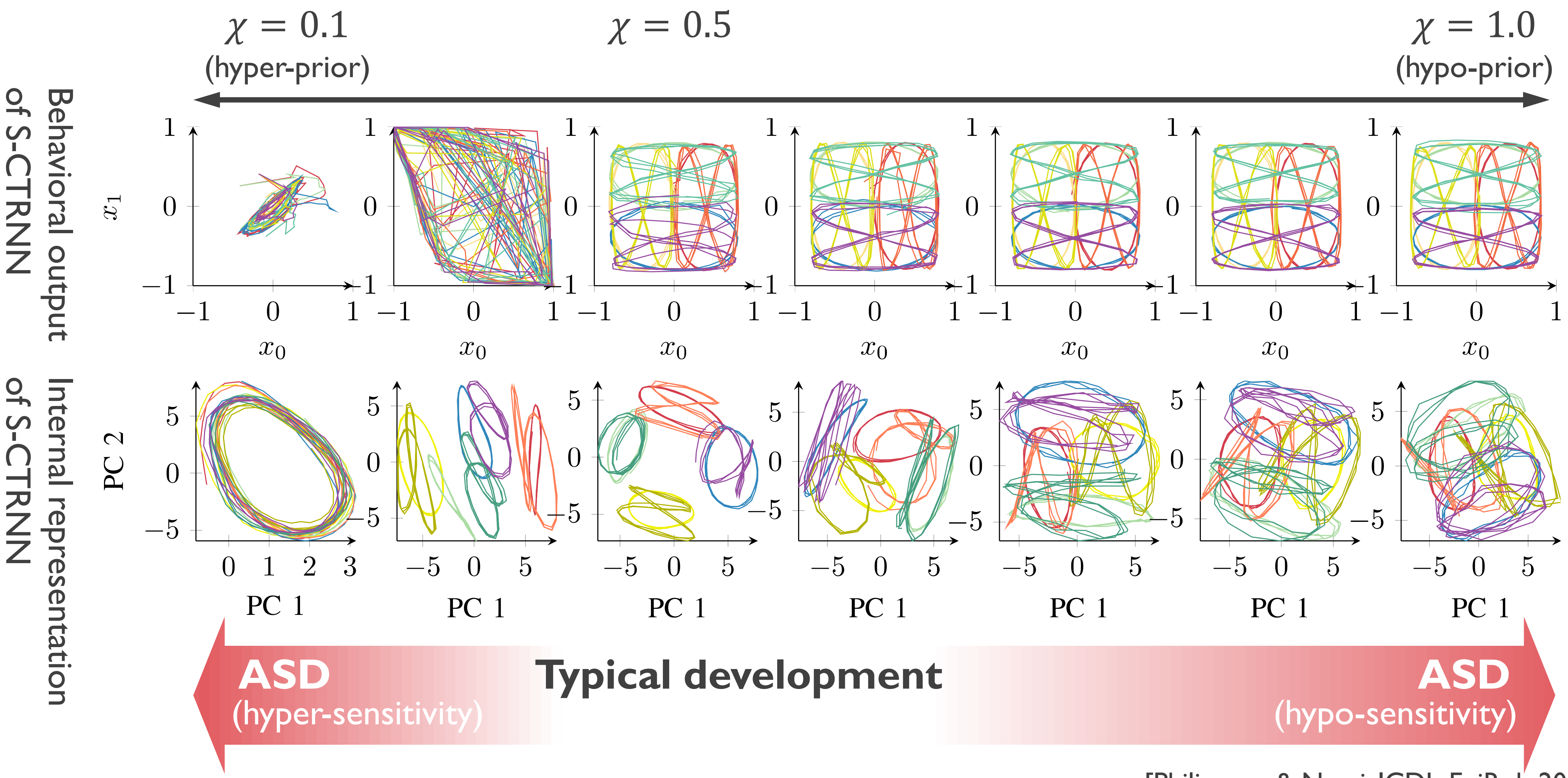
Bayesian-Based Predictive Coding



- S-CTRNN: Learn to estimate a signal $\boldsymbol{x}_{t+1}$ and its variance $\boldsymbol{v}_{t+1}$ at the next time step $t+1$ based on the current signal $\boldsymbol{x}_t$ [Murata et al., 2013]
- Parameters that characterize individual differences in cognitive capabilities:
  - Sensitivity χ to external signal $\boldsymbol{x}_{t+1}$
  - Precision K of predicted variance $\boldsymbol{v}_t$
  - etc.

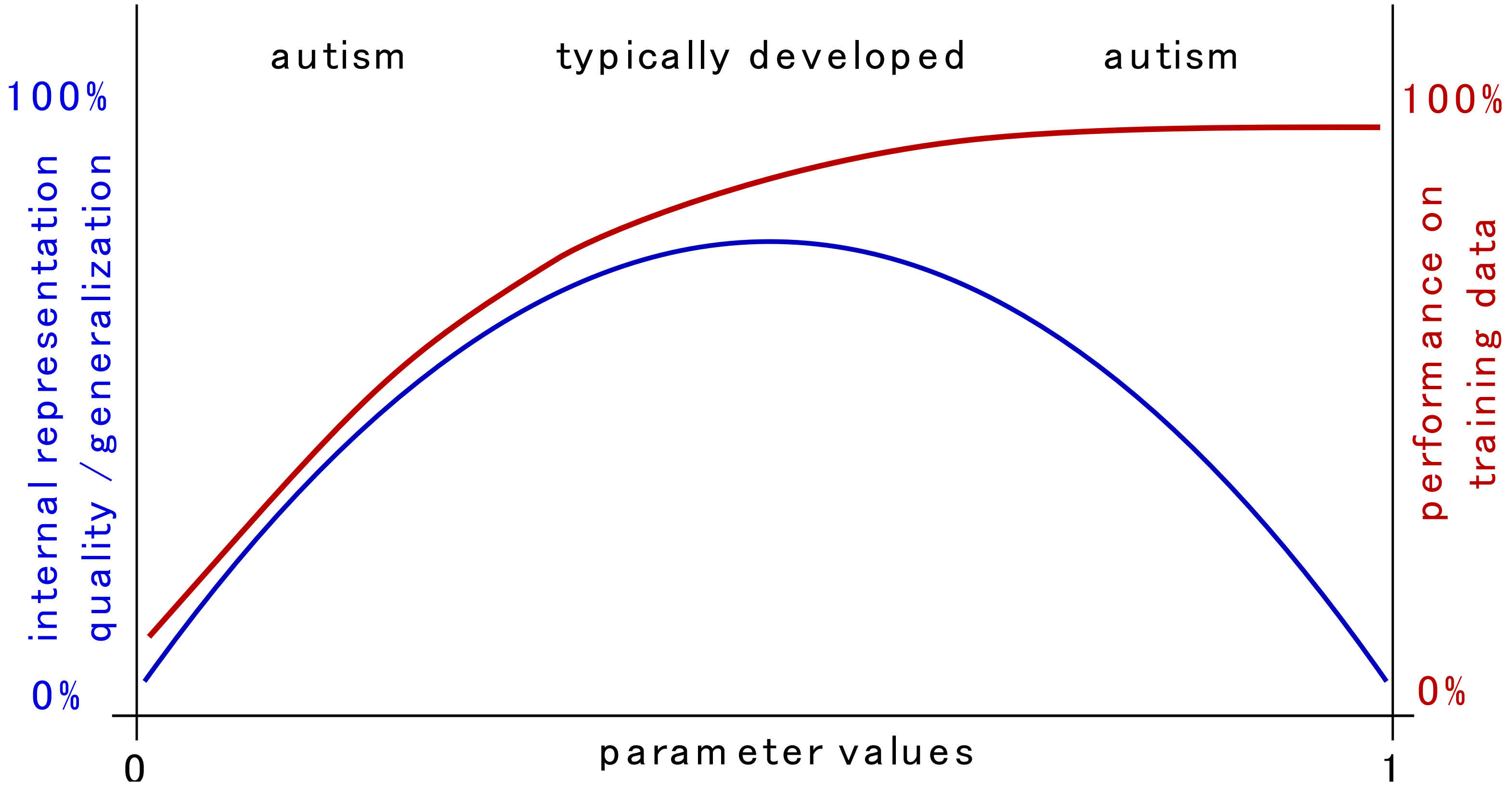
[Philippsen & Nagai, ICDL-EpiRob 2018]

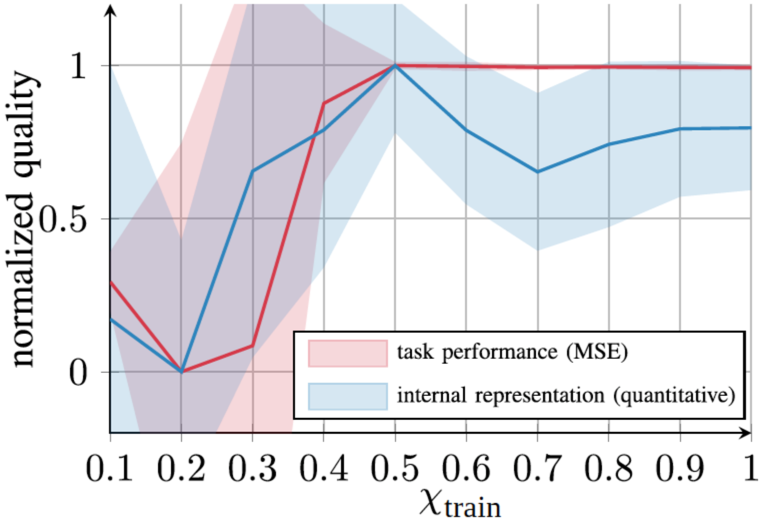
Result 1: Influence of External Sensory Sensitivity χ on Learning



[Philippsen & Nagai, ICDL-EpiRob 2018]

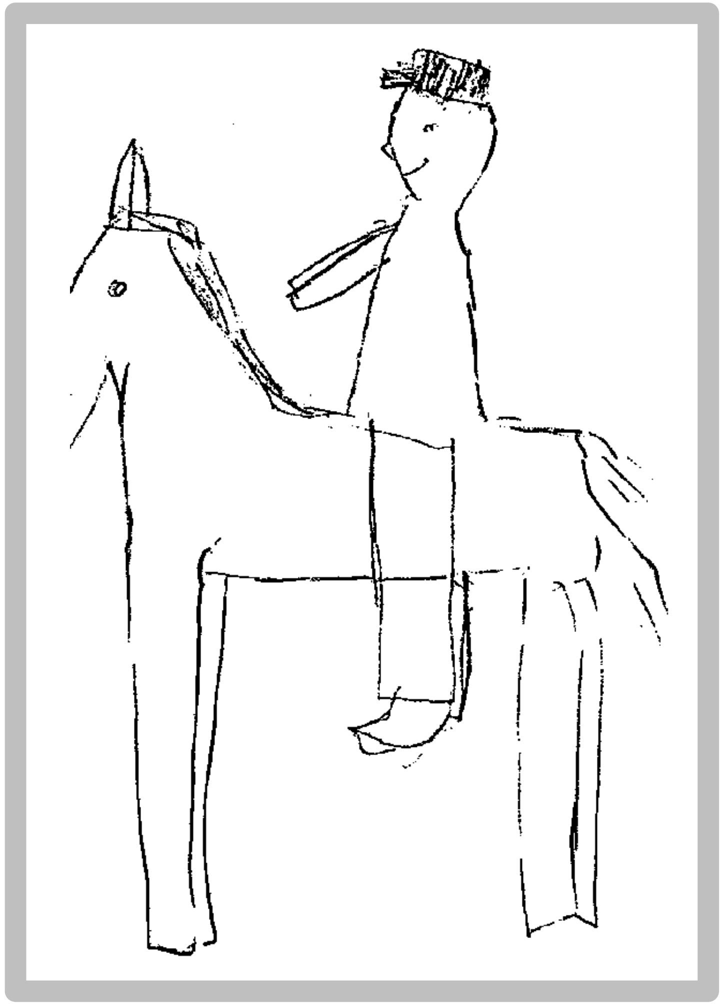
Result 2: ASD Caused by Two Extremes in Predictive Learning



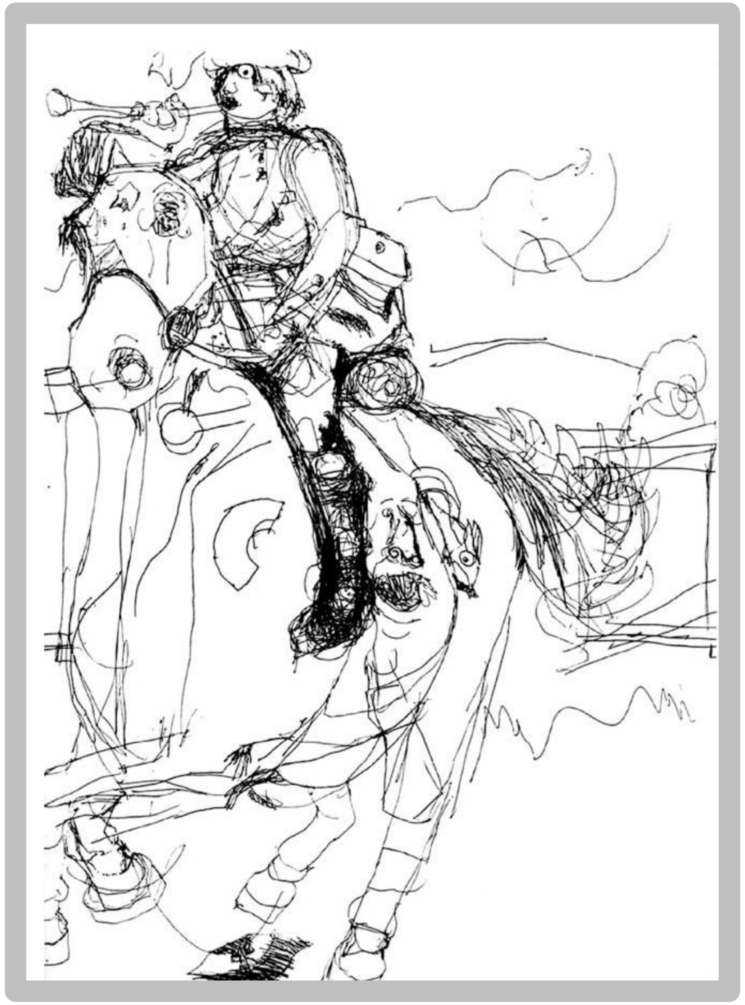


[Philippsen & Nagai, ICDL-EpiRob 2018]

Ability of Representational Drawing in Children

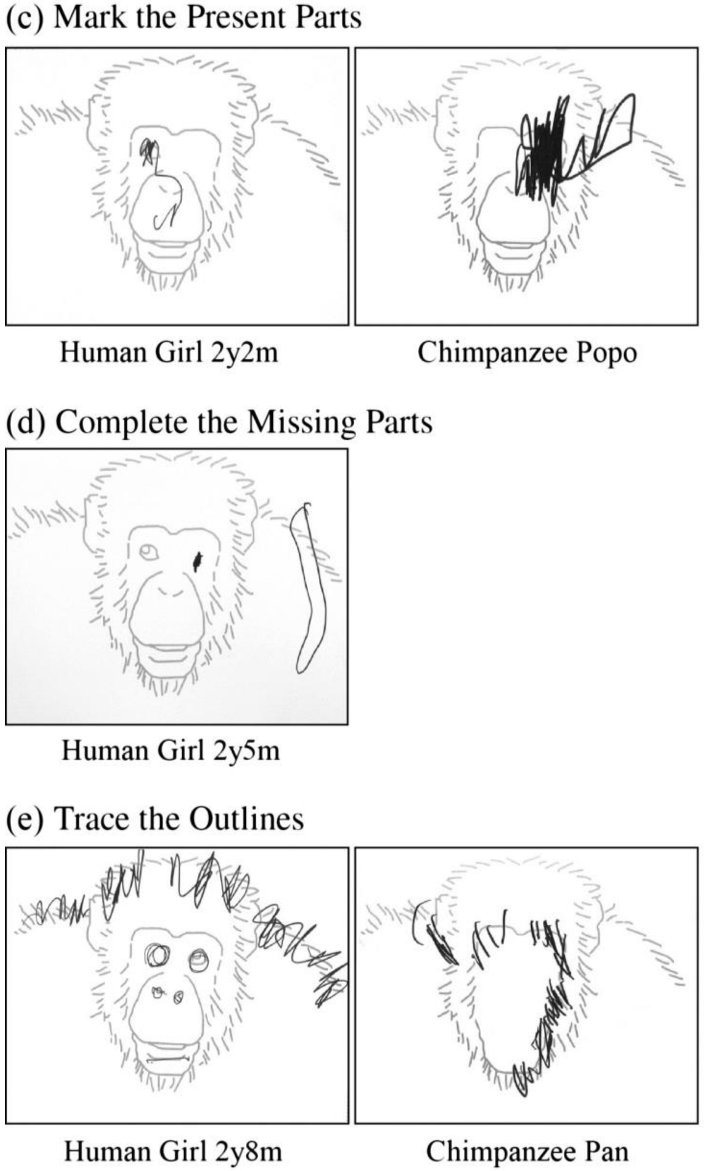


by 6-years-old child

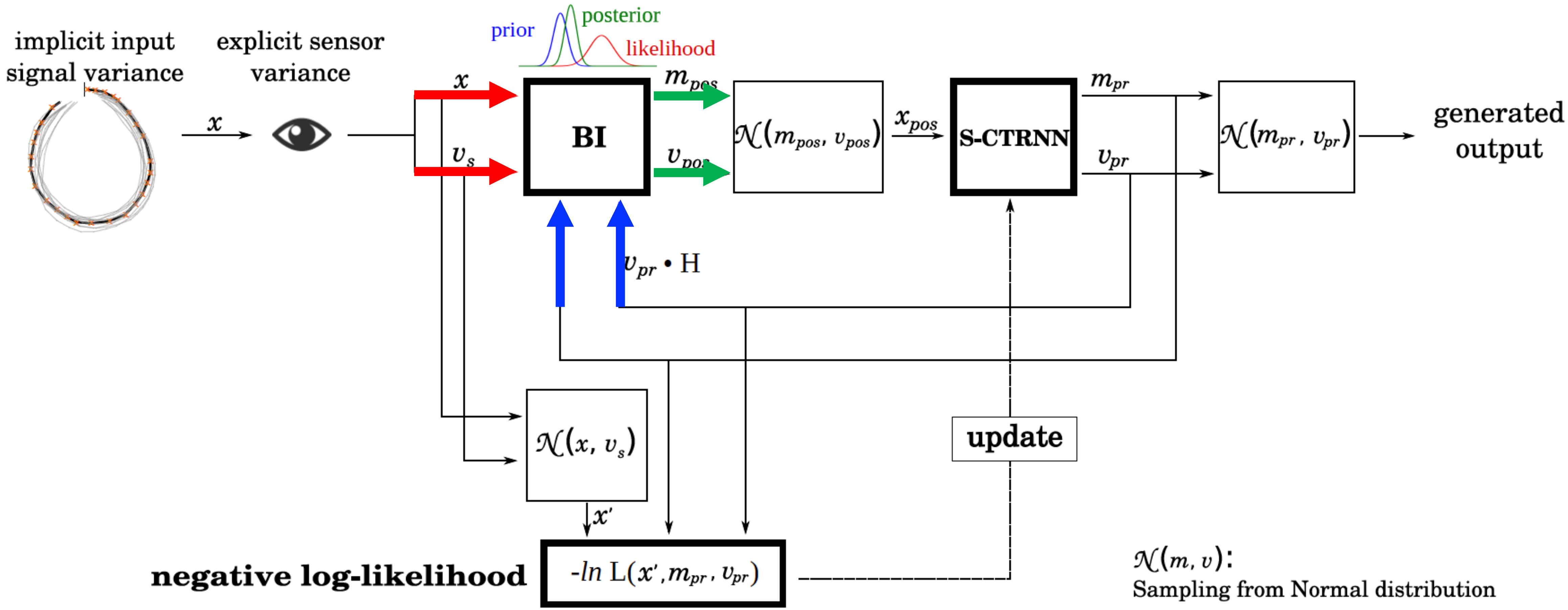


by Nadia, autistic savant at age 5

Drawing by Human Children and Chimpanzees [Saito et al., 2014]

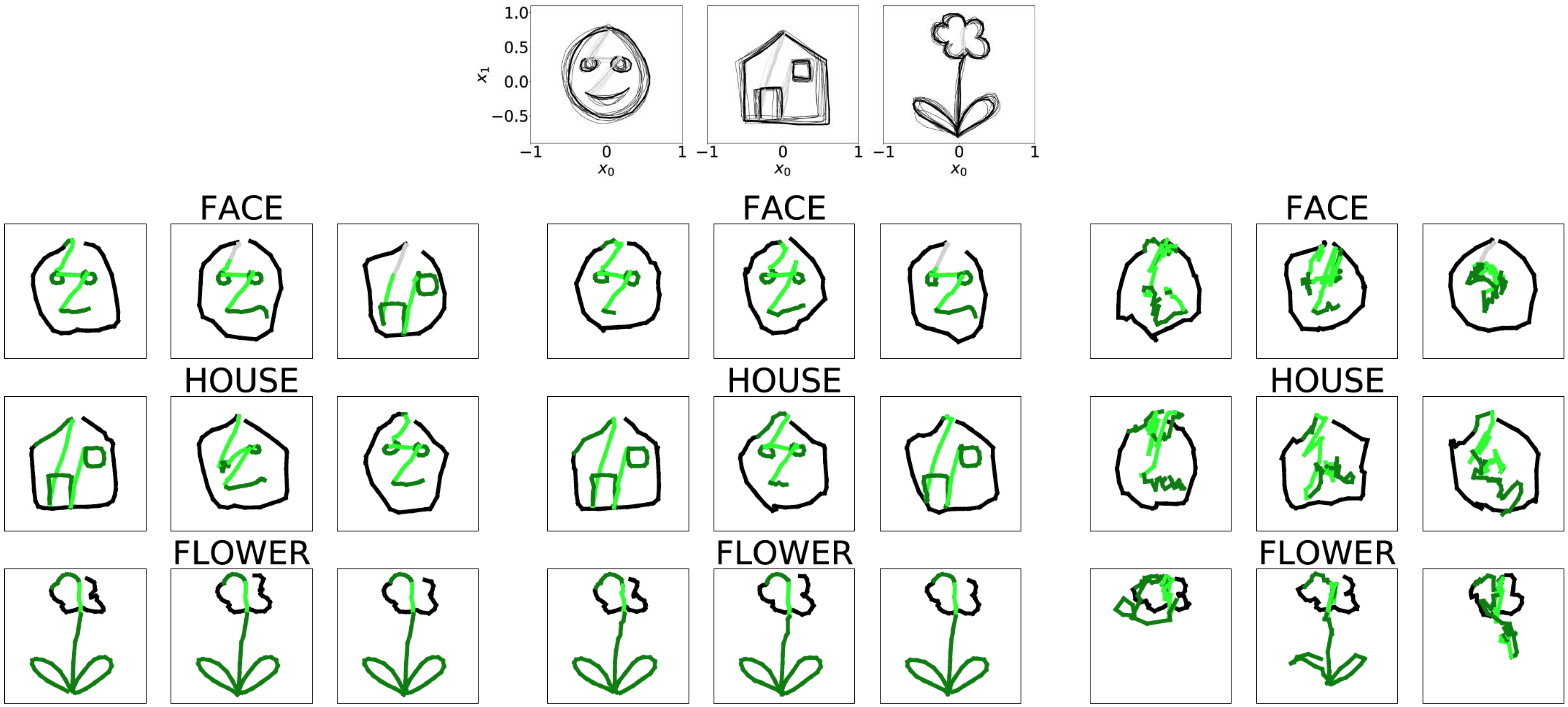


S-CTRNN with Bayesian Inference



[Oliva, Philippsen & Nagai, under review; Philippsen & Nagai, under review]

Result: Influence of Hyper-/Hypo-prior on Predictive Drawing



(a) Hyper-prior (b) Normal prior (c) Hypo-prior

[Philippsen & Nagai, under review]

Simulator of Atypical Visual Perception in ASD

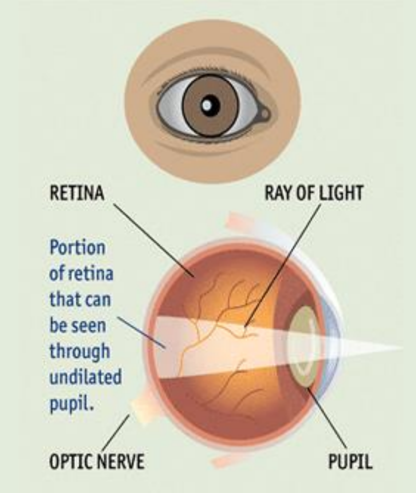
[Qin et al., ICDL-EpiRob 2014; Nagai et al., JCSS 2015]

(NHK, 2017.05.21)

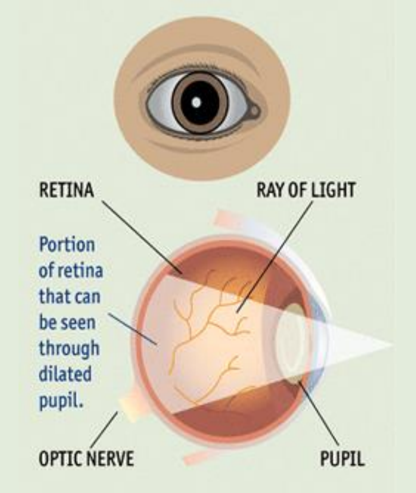
Result I: High Contrast & Intensity Induced by Brightness

- Potential physiological causes
  - Larger pupil size in ASD [Anderson & Colombo, 2009]
  - Longer latency and reduced constriction amplitude in pupillary light reflex [Daluwatte et al., 2013]

Bright → small pupil



Dark → large pupil

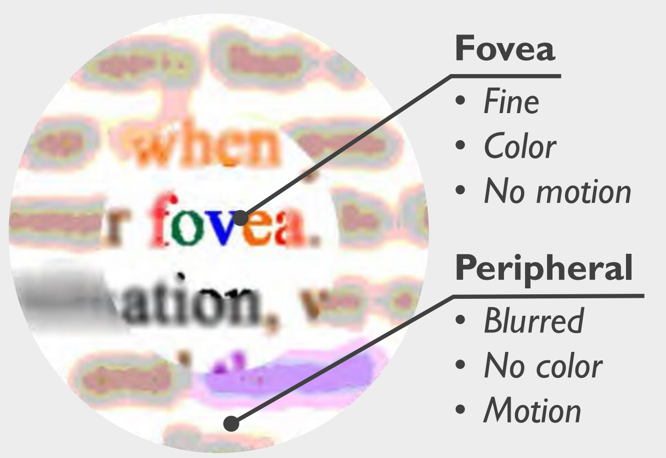


[Qin et al., ICDL-EpiRob 2014; Nagai et al., JCSS 2015]

Result 2: No Color & Blurring Induced by Motion

- Potential physiological/neural causes
  - Reliance on peripheral vision, high amplitude of visual evoked potentials in response to peripheral stimuli [Mottron et al., 2007; Noris et al., 2012; Frey et al., 2013]
  - Difficulty in integrating the foveal and peripheral information? (cf. [Behrmann et al., 2006; Nakano et al., 2010])

Retinal view

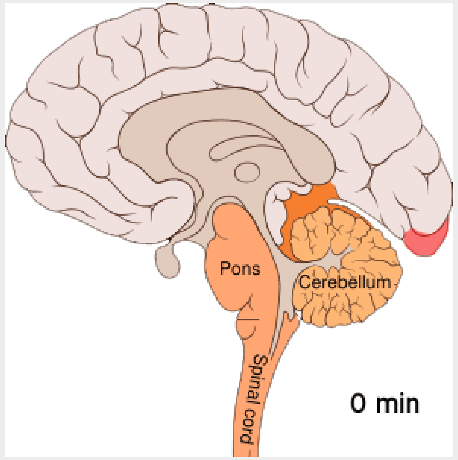


[Qin et al., ICDL-EpiRob 2014; Nagai et al., JCSS 2015]

Result 3: Dotted Noise Induced by Change in Motion & Sound

- Potential physiological/neural causes
  - Visual snow observed in migraine patients [Schankin et al., 2014]
  - Atypical brain activities correlated with visual snow (e.g., cortical spreading depression in visual cortex [Hadjikhani et al., 2001], hyper-metabolism in lingual gyrus [Schankin et al., 2014])
  - Similar brain activities in ASD?

Cortical spreading depression



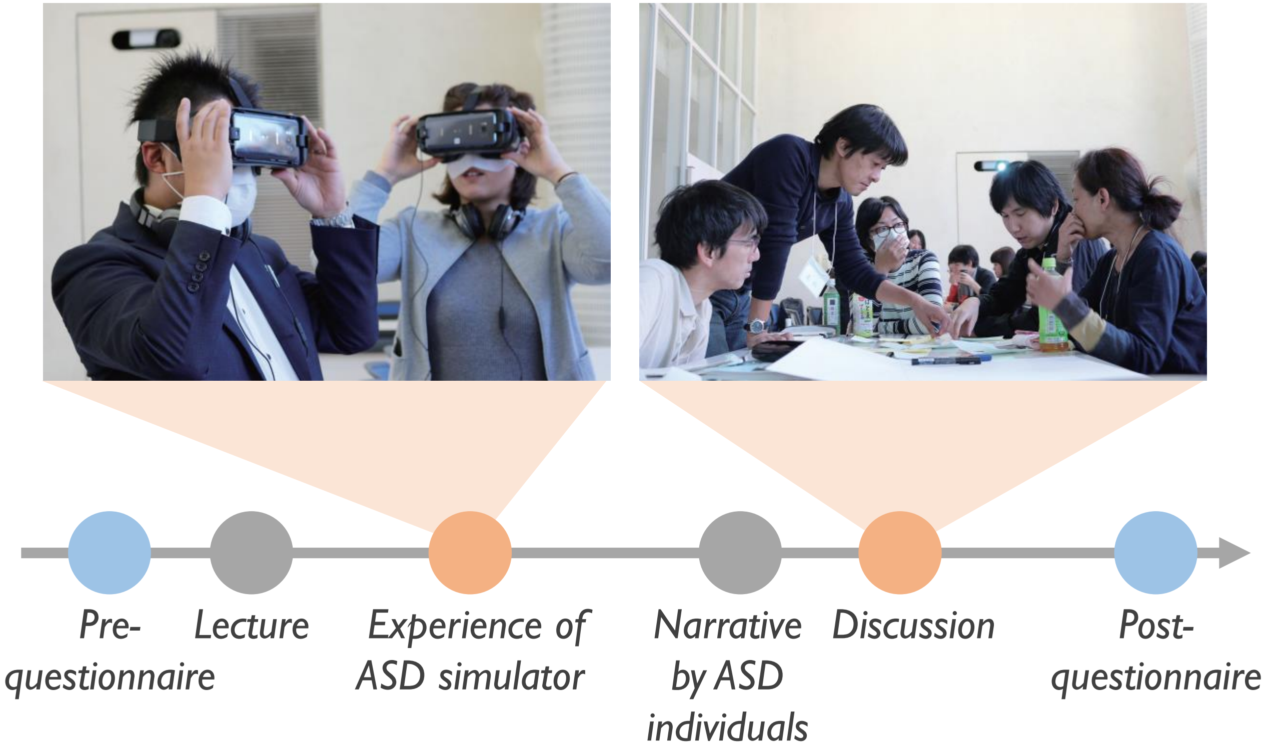
[Qin et al., ICDL-EpiRob 2014; Nagai et al., JCSS 2015]

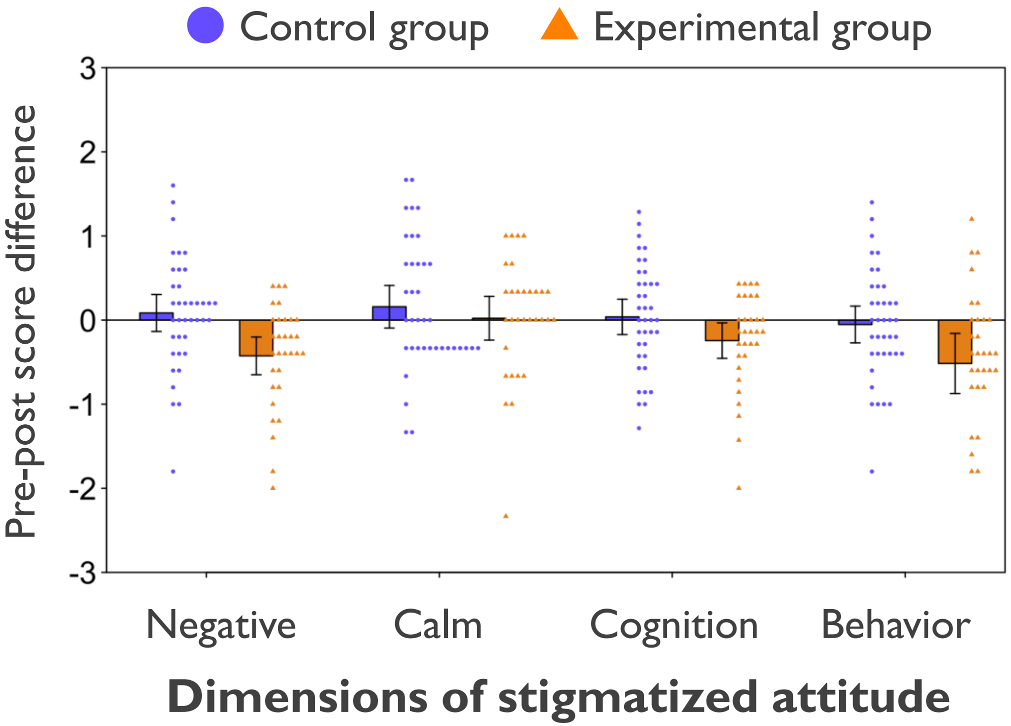
Improvement of Self-Understanding Using ASD Simulator

Reduction of Stigma Through Experience of ASD's Perception

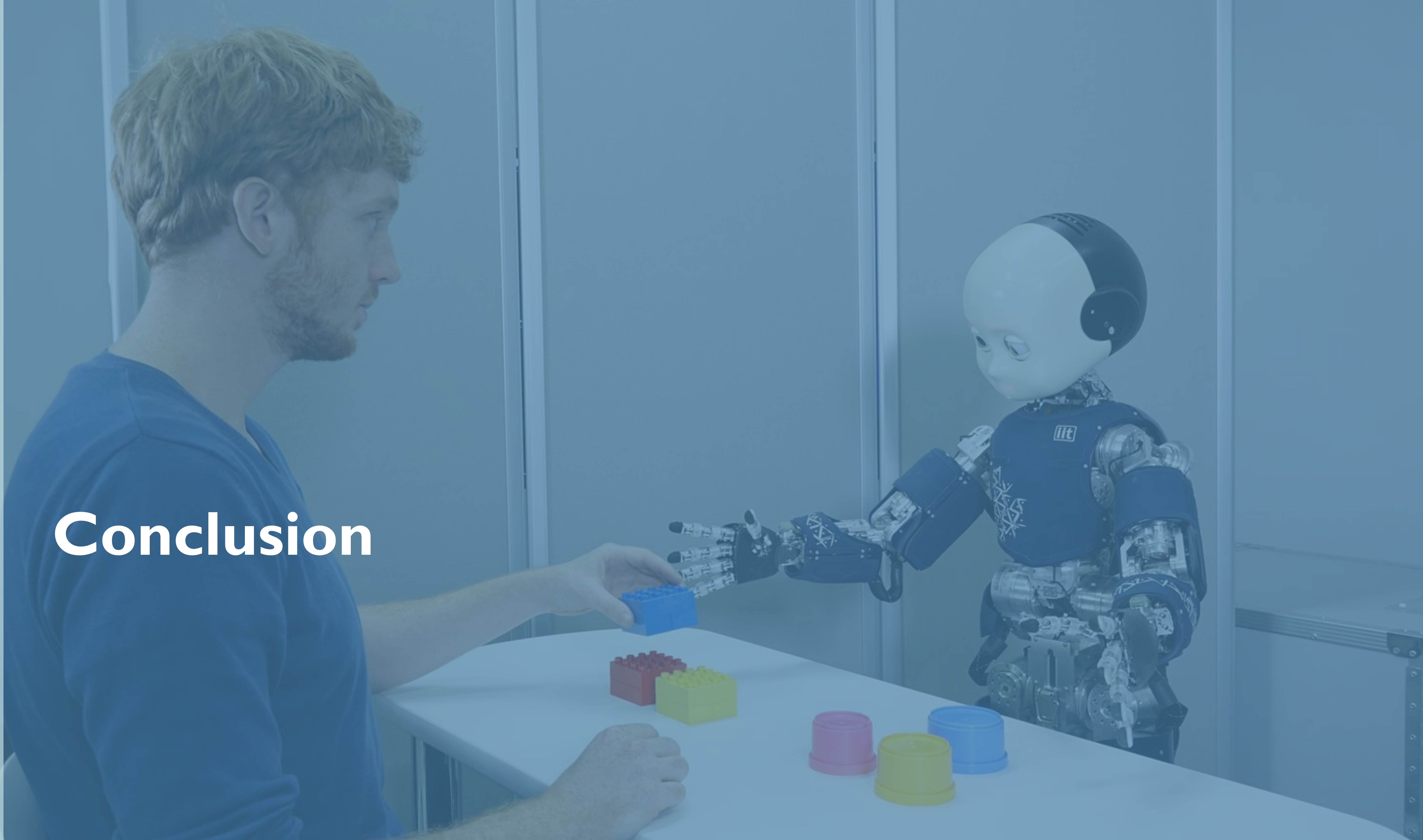
[Suzuki et al., 2017; Tsujita et al., 2017]

- ASD simulator workshops for families with and caretakers of individuals with ASD (50-200 participants x 20 times since Dec. 2016)
  - To promote mutual understanding between people with and without ASD
  - To mitigate social stigma by experiencing ASD simulators



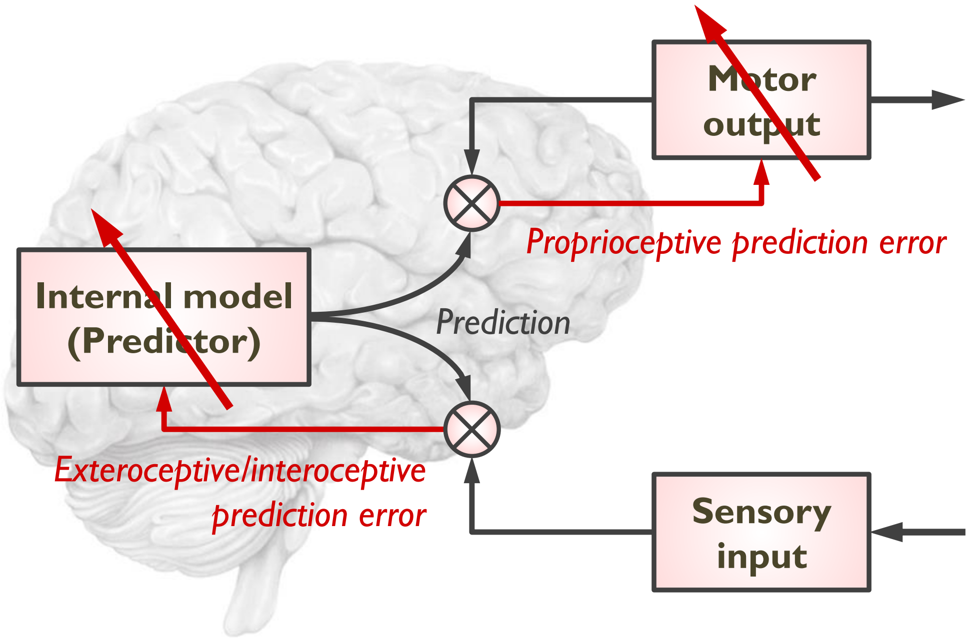


Conclusion

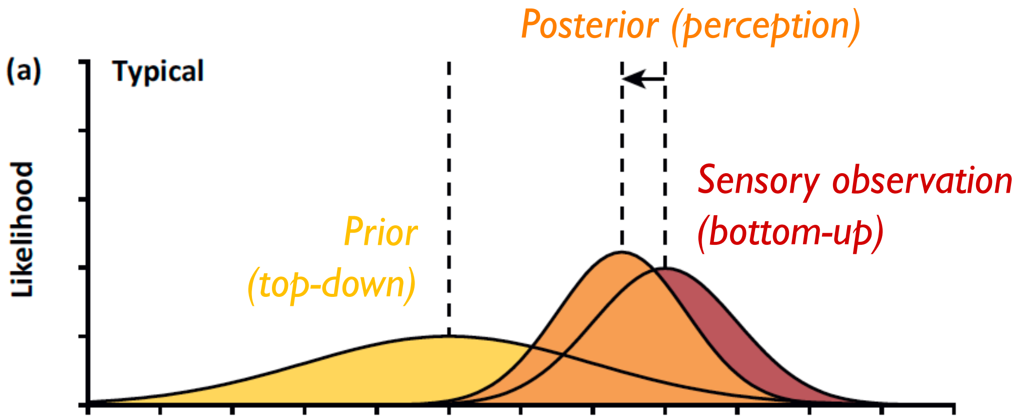


Cognitive Development Based on Predictive Coding

- Development of social cognition through **prediction error minimization**
  - *Updating the predictor* through own sensorimotor experiences
  - *Executing an action* to alter sensory signals



- **Hypo- and hyper-prior** might cause behavioral and cognitive characteristics in ASD
  - Hypo-prior: stronger sensitivity to sensory input
  - Hyper-prior: poorer sensitivity to sensory input

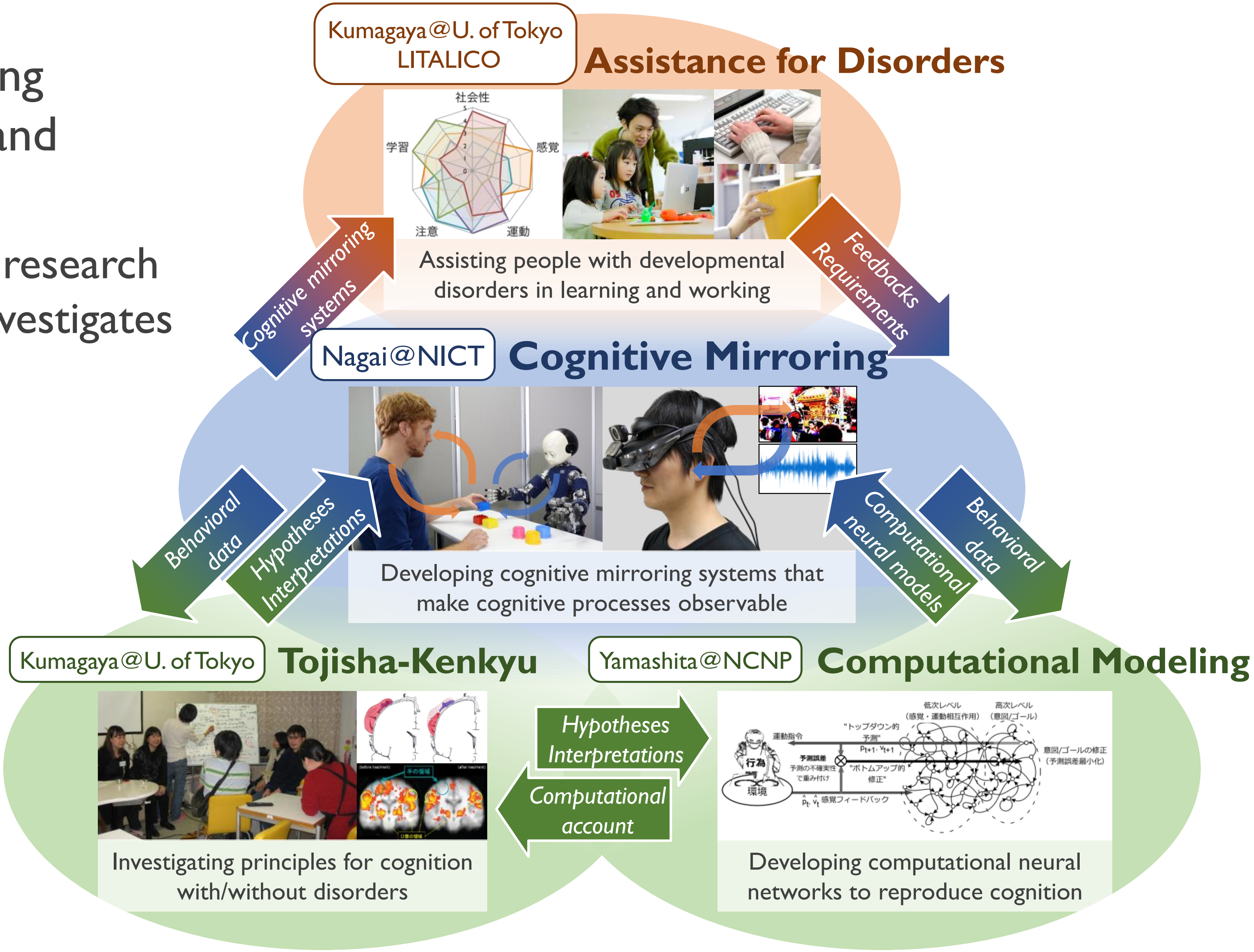


JST CREST "Cognitive Mirroring"

- Interdisciplinary team involving robotics, computer science, and tojisha-kenkyu
  - Tojisha-kenkyu: first person's research by which people with ASD investigates their own cognition

(Period: 2016.12-2022.03)

(Director: Yukie Nagai)



Postdoctoral Fellow (Project Researcher) (Nagai Laboratory)

Submission deadline: March 31, 2019

Yukie Nagai (IRCN Principal Investigator) lab ,which will be established in April 2019, has been investi[illegible] infants acquire various cognitive abilities by means of computational approach and designing assistant systems for people with developmental disorders. T[illegible]docs who will work in the fields of cognitive developmental robotics, human-robot interaction, machine learning, neural network, and relevant topics. The la[illegible] intelligent systems for understanding and assisting cognitive development. Visit the lab homepage (http://developmental-robotics.jp/en/) for more details. Postd[illegible]k on the project: JST CREST "Cognitive Mirroring: Assisting people with developmental disorders by means of self-understanding and social sharing of cognitive proce[illegible]://cognitive-mirroring.org/en/; Nagai, Phil. Trans. R. Soc. B, 2019, doi: 10.1098/rstb.2018.0030).

募集要項

Job title	IRCN Postdoctoral Fellow (Project Researcher)
Starting Date	June 1, 2019 or later (Negotiable)
Term	The first contract will be ended on March 31, 2020. The contract is renewable on a fiscal year basis (from April 1 to March 31; every year) according to research budget, research activity, and research achievements. Contract duration is until March 31, 2022. Probationary period is 6 months from the date of arrival.

Thank you!

NICT
- Anja Philippsen
- Konstantinos Theofilis

Osaka University
- Minoru Asada
- Jimmy Baraglia (-2016.11)
- Takato Horii (-2017.09)
- Shibo Qin (-2015.03)
- Jorge L. Copete
- Jyh-Jong Hsieh
- Kyoichiro Kobayashi

University of Tokyo
- Shinichiro Kumagaya
- Satsuki Ayaya

Bogazici University
- Emre Ugur

Ozyegin University
- Erhan Oztop

devsci
Constructive Developmental Science

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

yukie@nict.go.jp | http://developmental-robotics.jp