

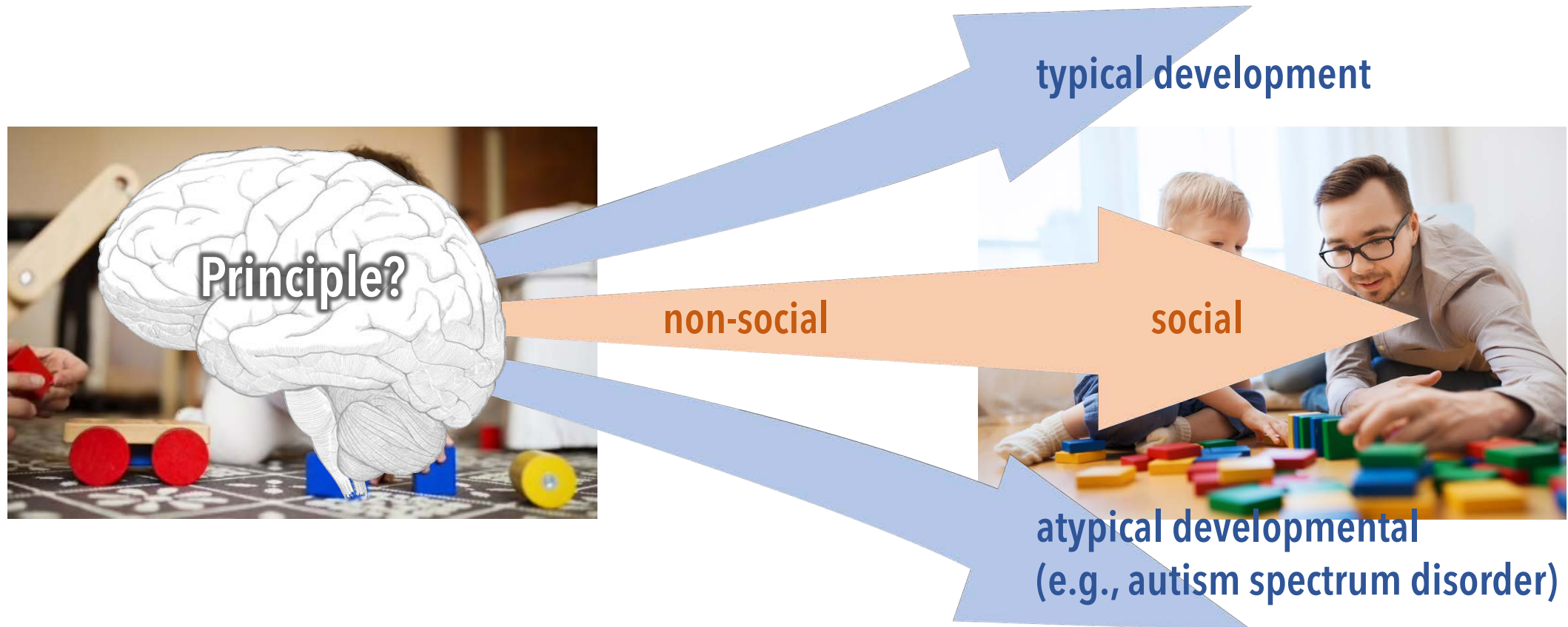
**Cognitive Development Based on
Predictive Coding**

Yukie Nagai

IRCN, The University of Tokyo

Open Question: Unified Principle of Cognitive Development?

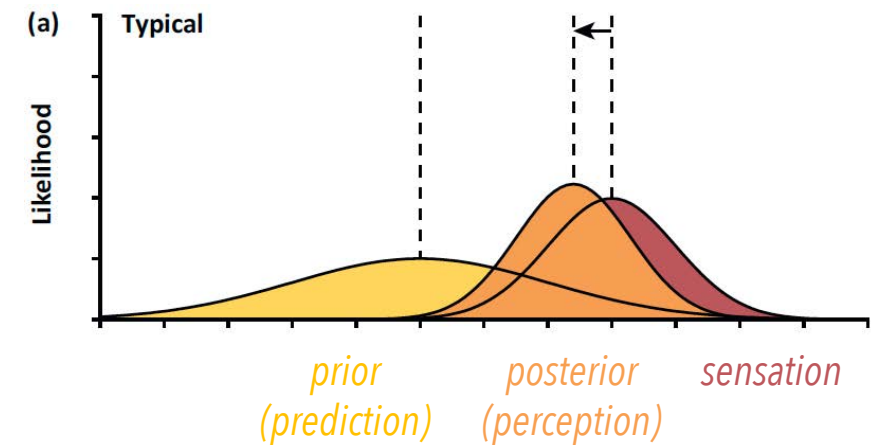
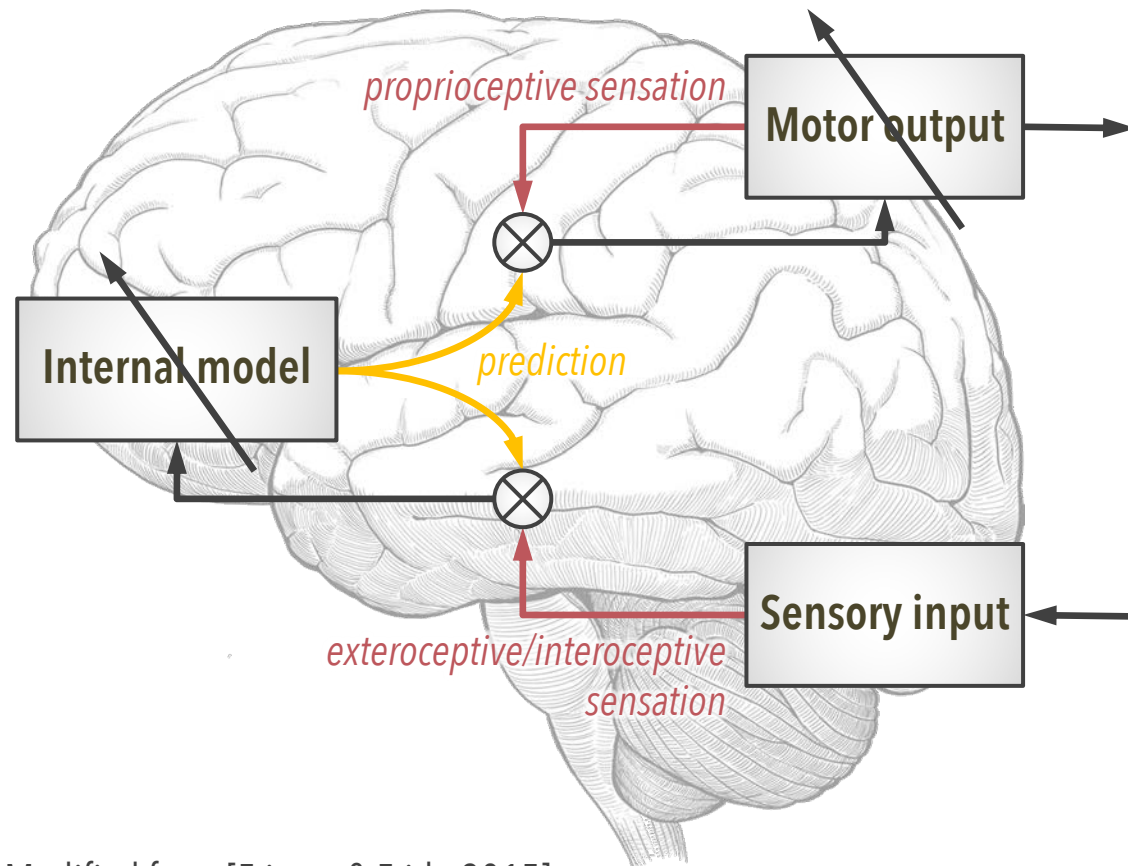
- What **neural mechanisms** underlie human cognitive development?
- Can they account for both **the continuity and diversity** in cognitive development?



Predictive Coding: A Unified Theory of Human Brain

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

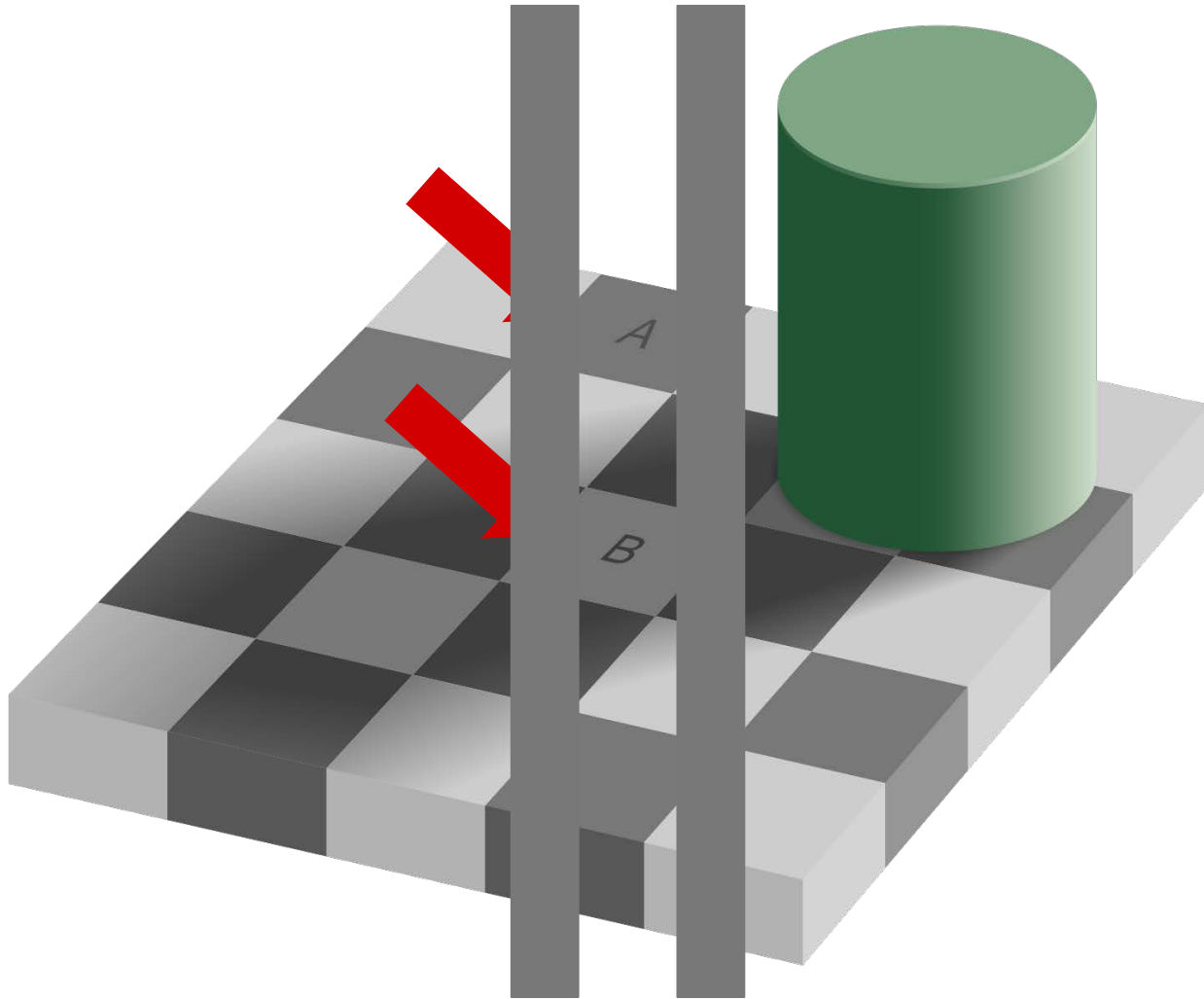
- The human brain perceives the world (i.e., perceptual inference) and acts on the world (i.e., active inference) so as to **minimize prediction errors**.



[Brock, 2012]

Modified from [Friston & Frith, 2015]

Optical Illusion Generated by Predictive Brain



Which square looks brighter, A or B?

Perception (recognition)

$$A < B$$

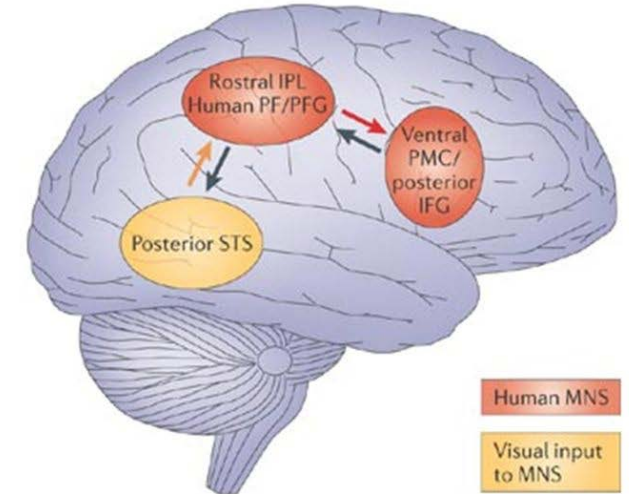
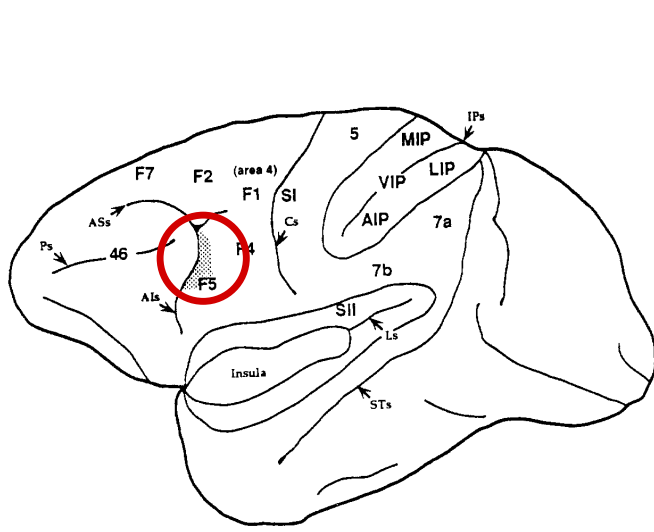
Sensation (physical stimuli)

$$A = B$$

Development from Non-Social to Social Cognition



Mirror Neurons and Mirror Neuron Systems [Rizzolatti et al., 1996; 2001]



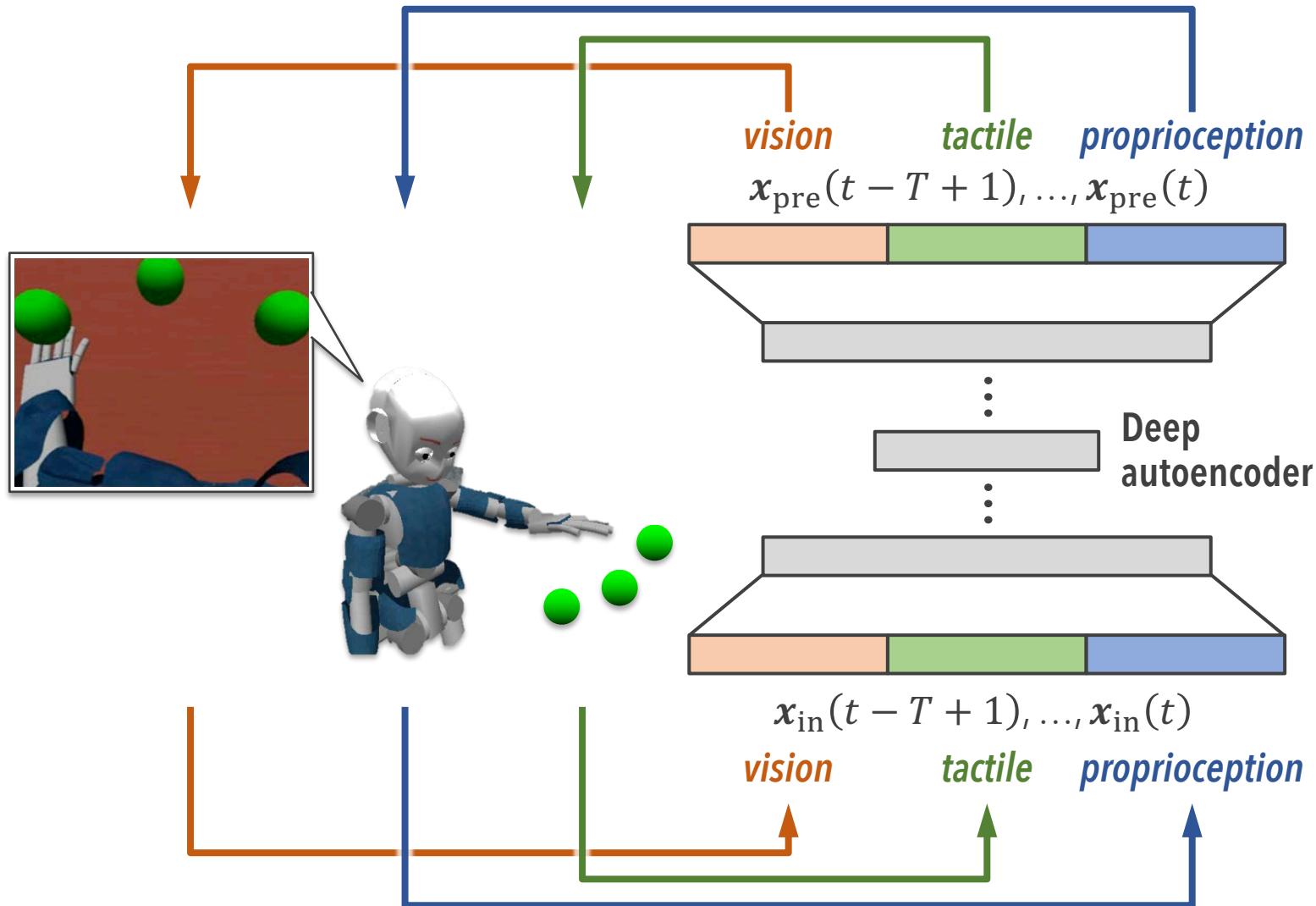
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[Iacoboni & Dapretto, 2006]

- 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 non-social experiences

Predictive Learning for Action Production and Perception

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

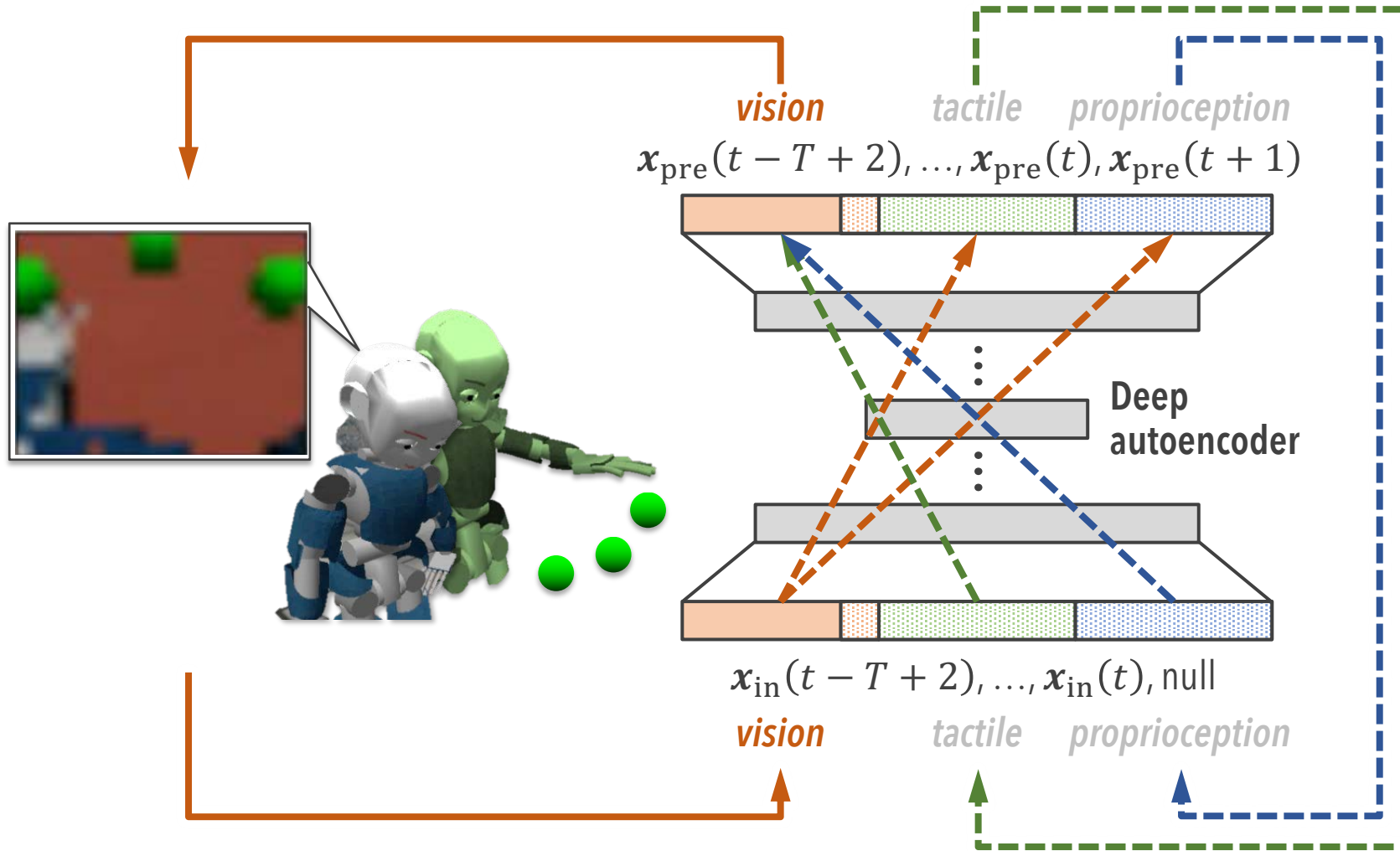


Action production:

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

Predictive Learning for Action Production and Perception

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Action production:

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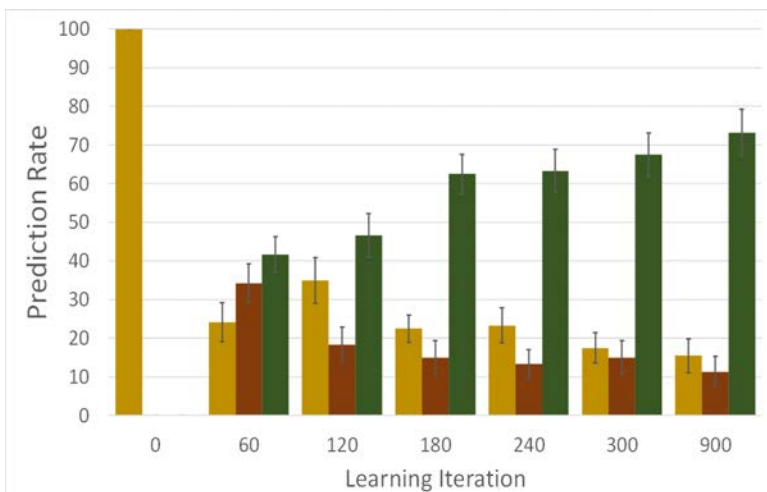
Action perception:

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

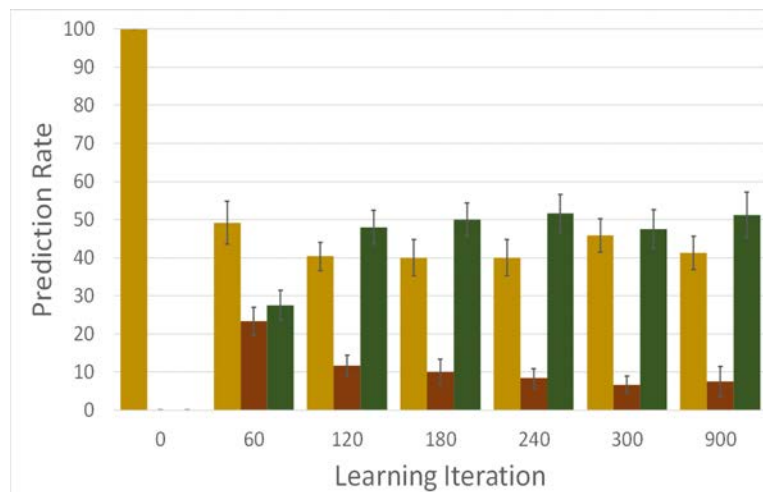
Exp: Prediction Accuracy Improved by Action Generation

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

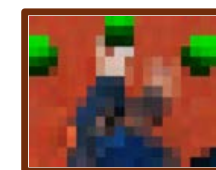
Learning through action *generation*



Learning through action *observation*



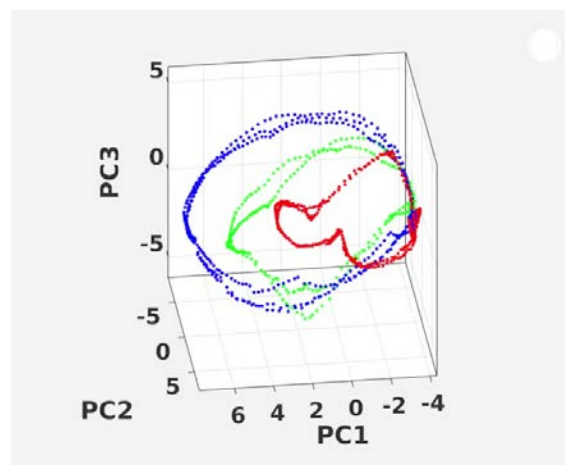
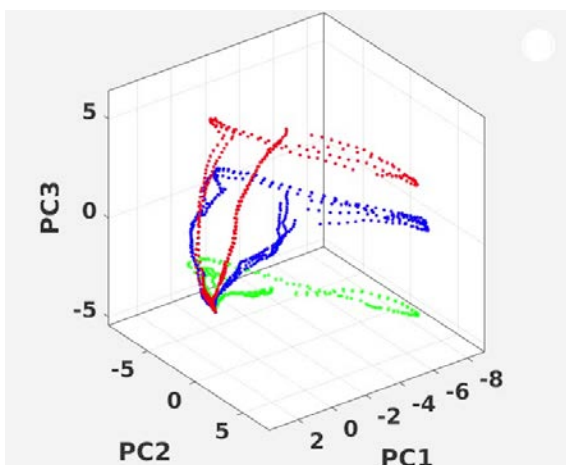
Correct goal



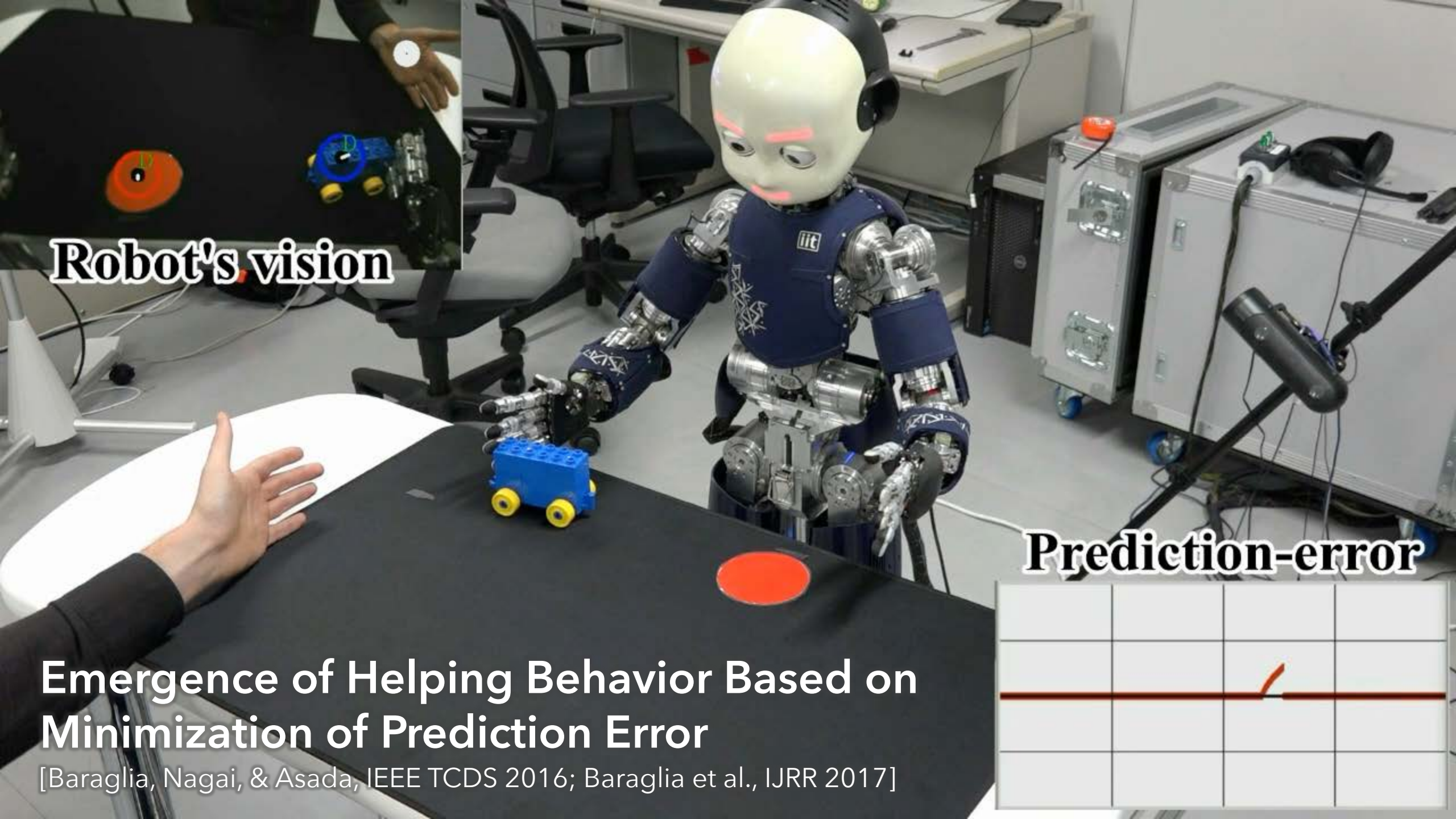
Incorrect goal



No goal



- Reaching for left
- Reaching for center
- Reaching for right



Robot's vision

Prediction-error

Emergence of Helping Behavior Based on Minimization of Prediction Error

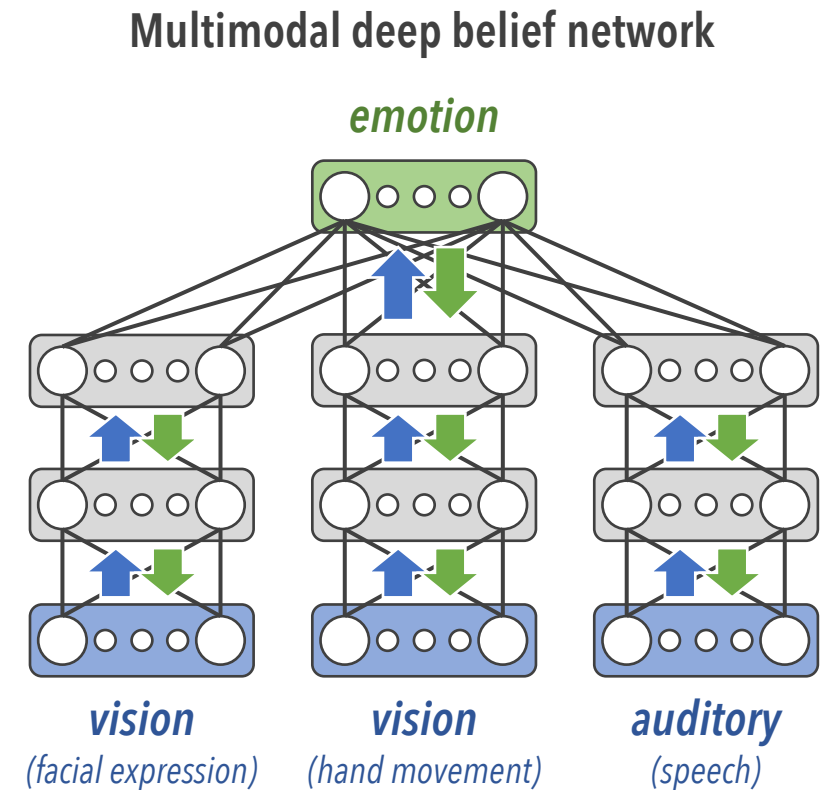
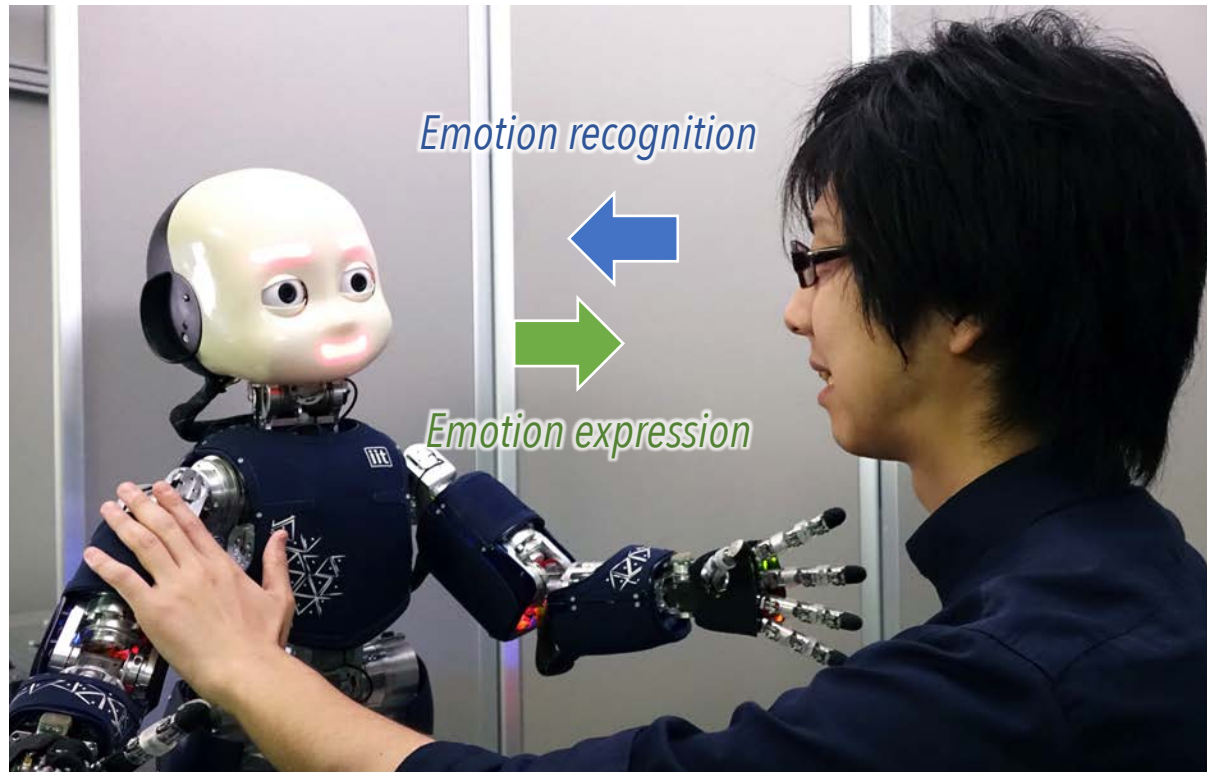
[Baraglia, Nagai, & Asada, IEEE TCDS 2016; Baraglia et al., IJRR 2017]



Development of Emotion Estimation and Imitation

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

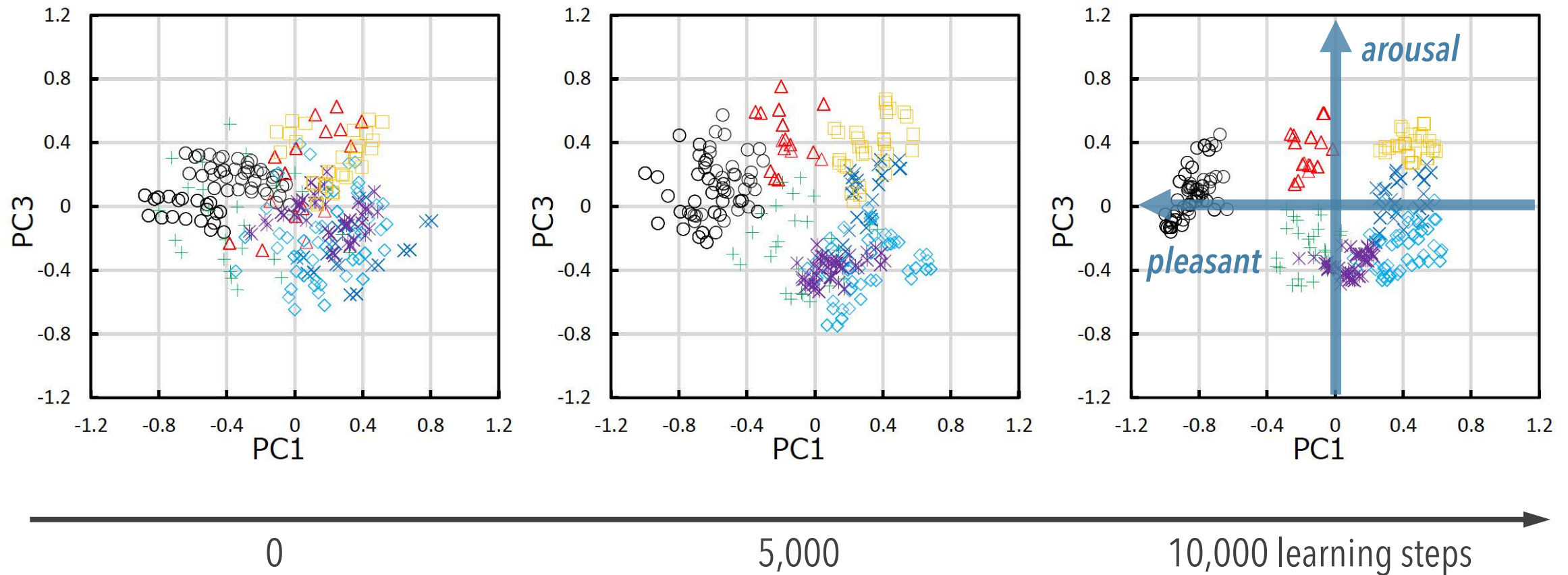
- The internal representation learned through **prediction error minimization of multimodal sensory signals** enables robots to estimate and imitate others' emotion.



Exp 1: Developmental Differentiation of Emotion

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

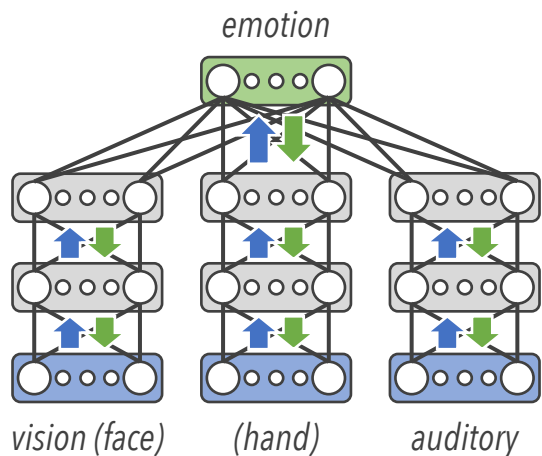
○ Joy △ Surprise + Neutral × Anger ◇ Disgust × Sadness □ Fear



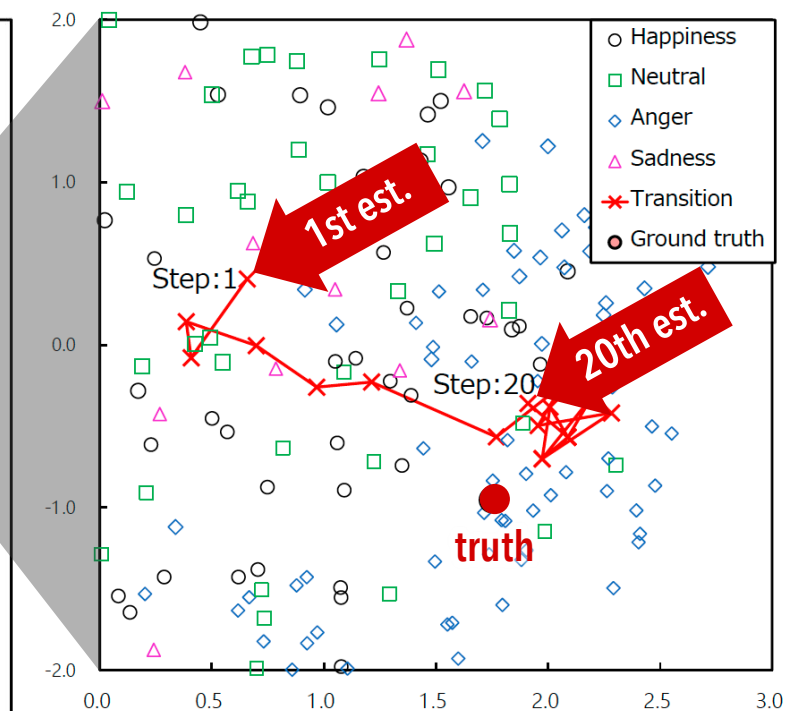
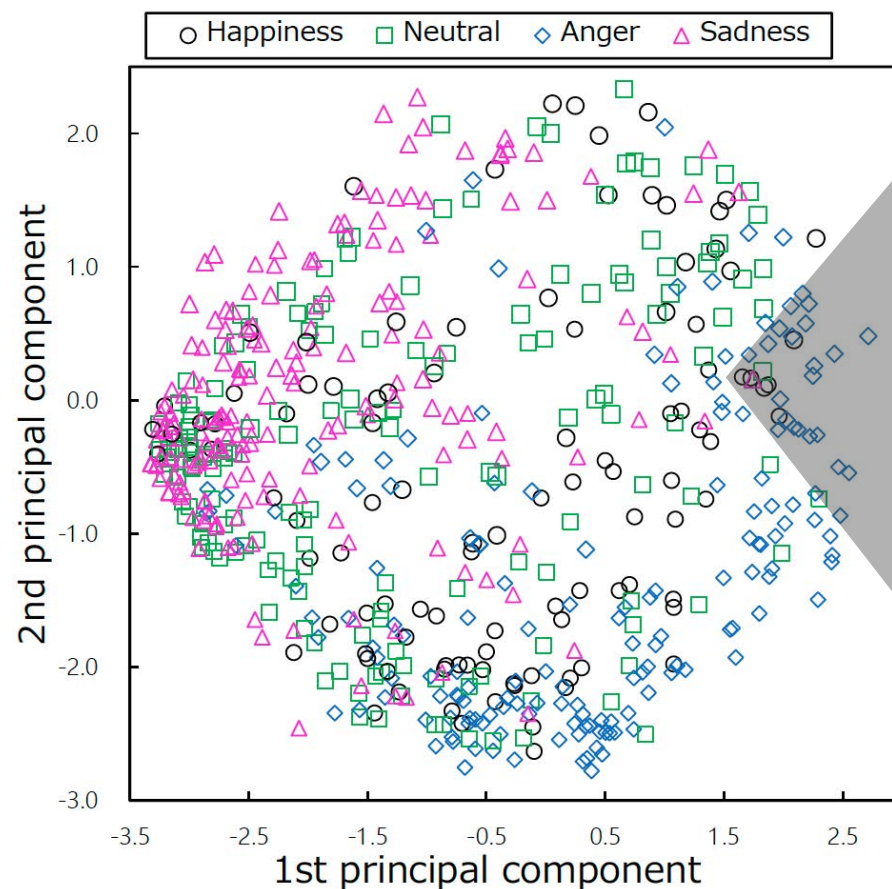
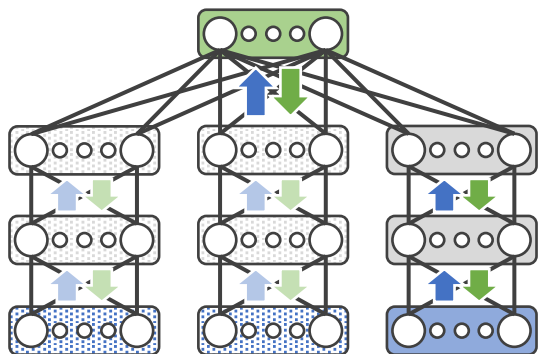
Exp 2: Emotion Estimation Facilitated by Mental Simulation

[Horii, Nagai, & Asada, Paladyn 2016]

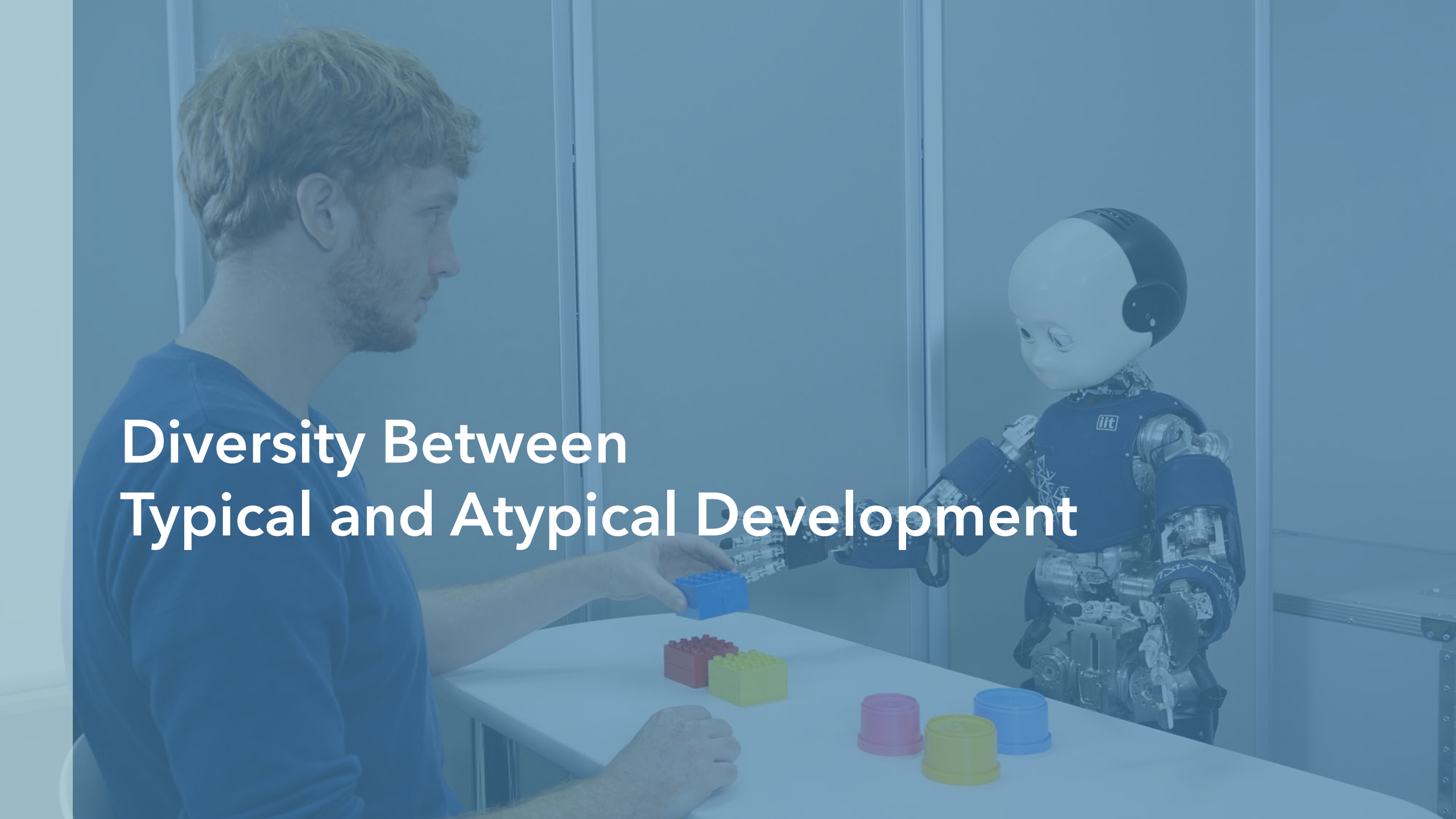
Training: given all signals



Testing: given only auditory
→ imaginary visual prediction

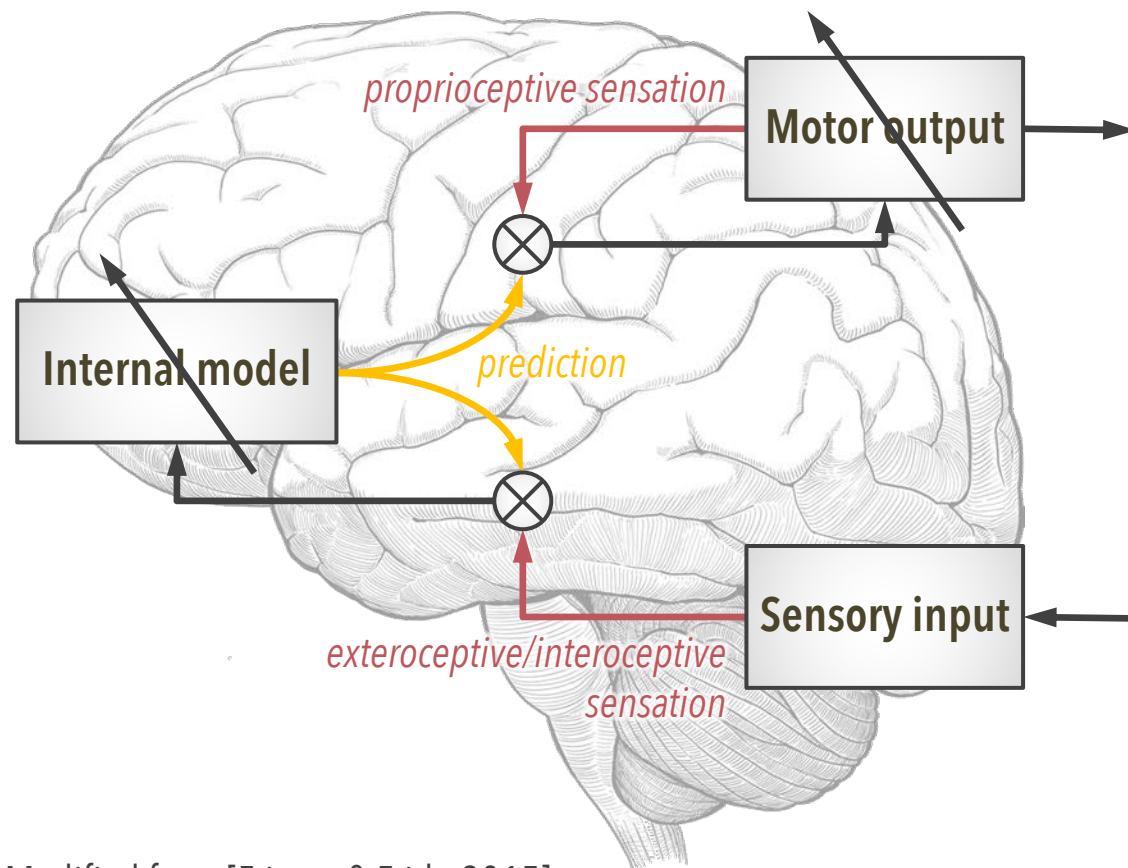


Diversity Between Typical and Atypical Development

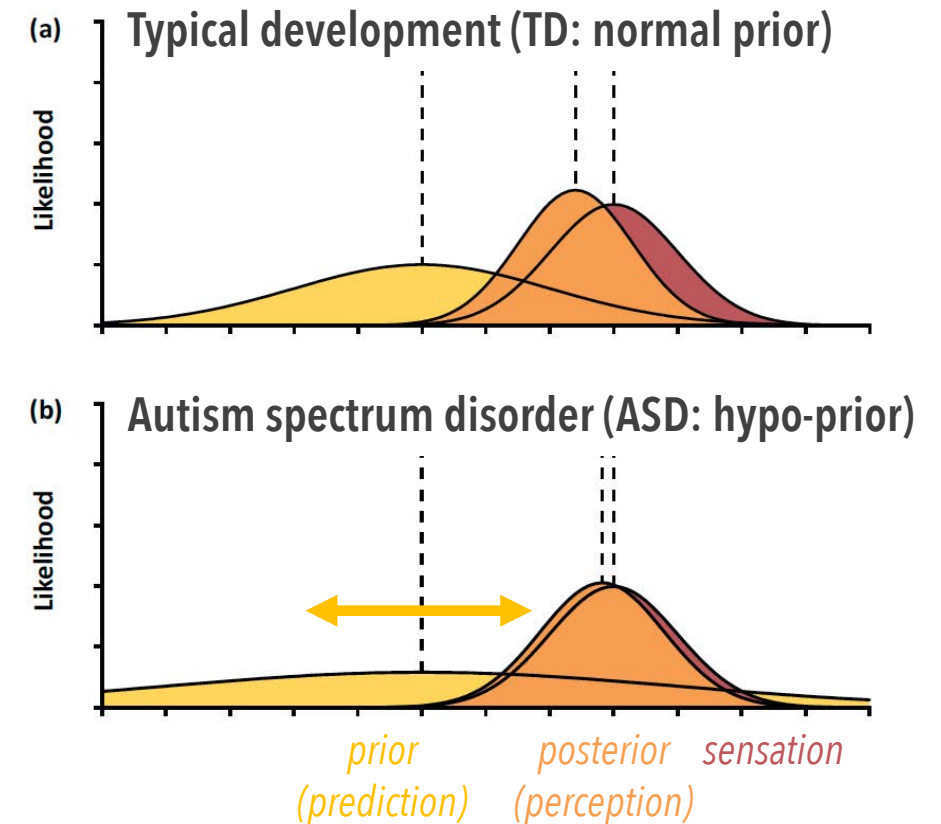
A man with curly hair and a beard, wearing a blue long-sleeved shirt, is seated at a white table. He is looking towards a humanoid robot on the right. The robot has a white head with large eyes, a black neck, and a blue torso with visible mechanical components. It is reaching out with its right arm towards a blue toy block on the table. On the table, there are several other toys: a red and yellow toy block, and three small plastic cups in pink, yellow, and blue. The background is a light blue wall with vertical lines. The entire image has a blue tint.

Predictive Coding Account for Autism Spectrum Disorder

- **Aberrant precisions of top-down predictions** (i.e., hypo-priors) may cause atypical cognitive abilities in autism spectrum disorder (ASD). [Brock, 2012]



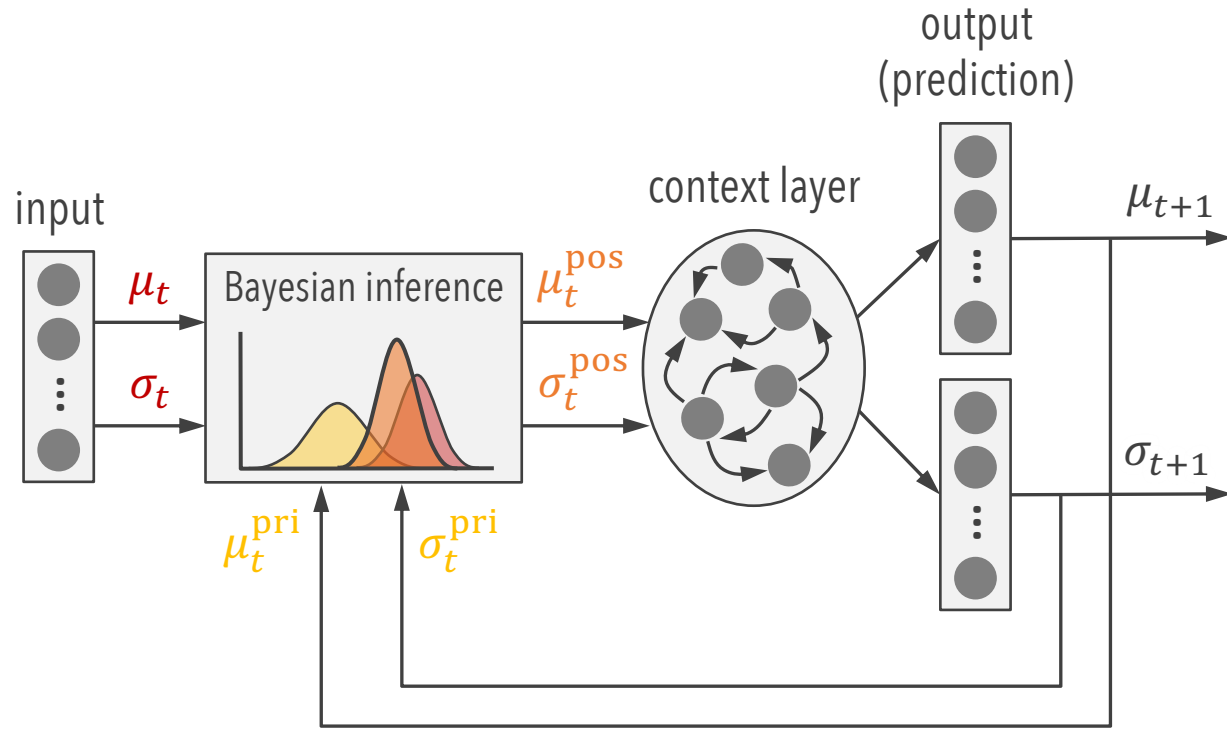
Modified from [Friston & Frith, 2015]



[Brock, 2012]

Recurrent Neural Network of Bayesian-Based Predictive Coding

[Oliva, Philippsen, & Nagai, ICDL-EpiRob 2019]



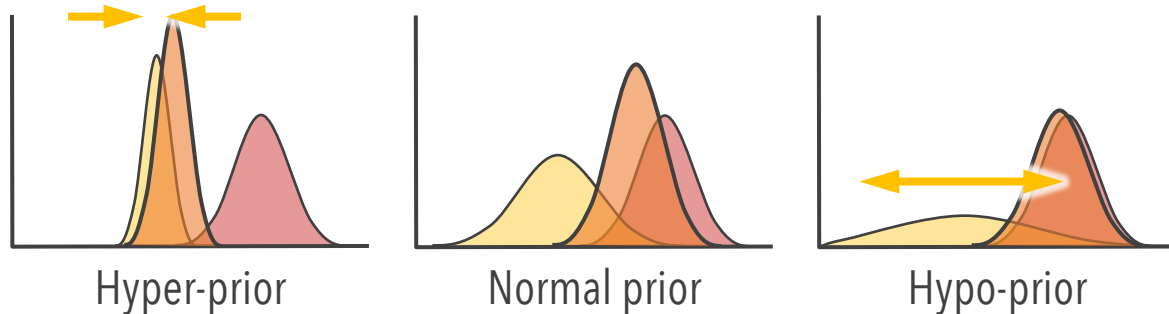
- Bayesian-based S-CTRNN

- To learn to predict the mean μ_{t+1} and variance σ_{t+1} of the sensory signal at the next time step based on the current signal μ_t^{pos} and σ_t^{pos} [Murata et al., 2013]

- To generate the perception (posterior) μ_t^{pos} by integrating the sensory signal μ_t with the prediction (prior) μ_t^{pri} based on their variances

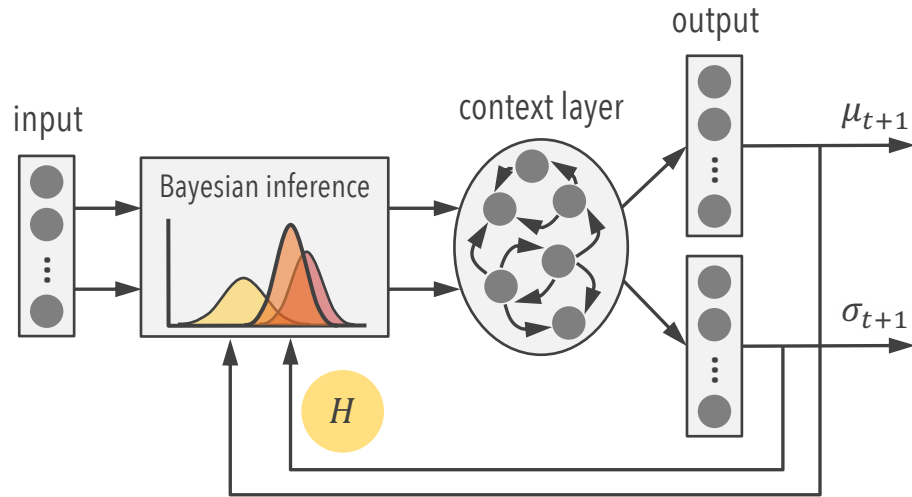
- Our hypothesis

- Not only hypo-priors but also hyper-priors may account for diverse characteristics of ASD



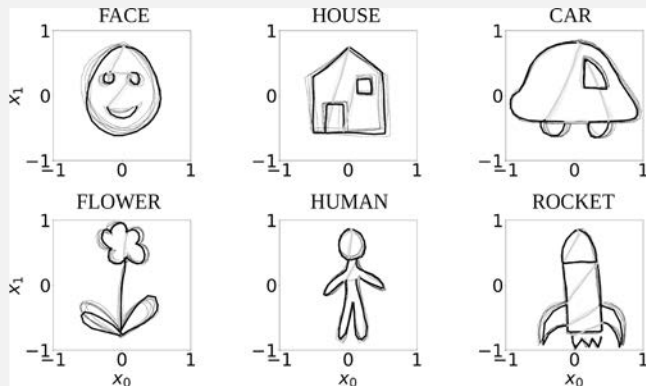
Predictive Learning of Representational Drawing

[Philippsen & Nagai, IEEE TCDS, in press]

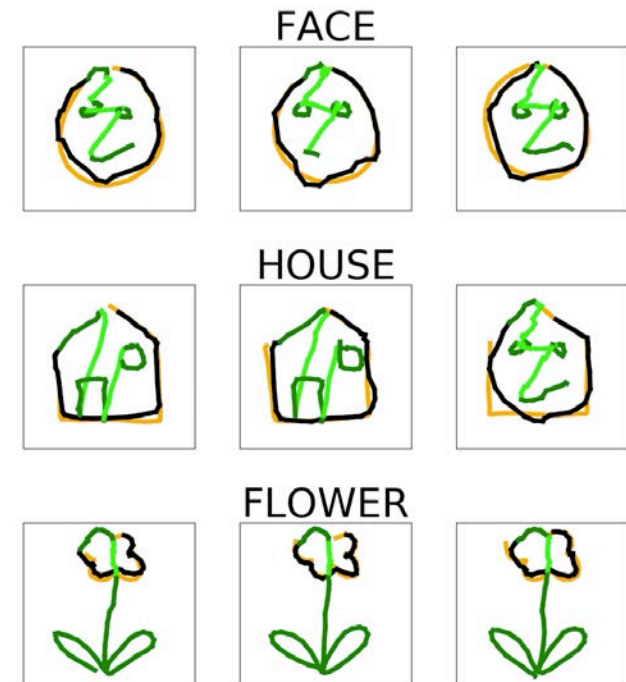
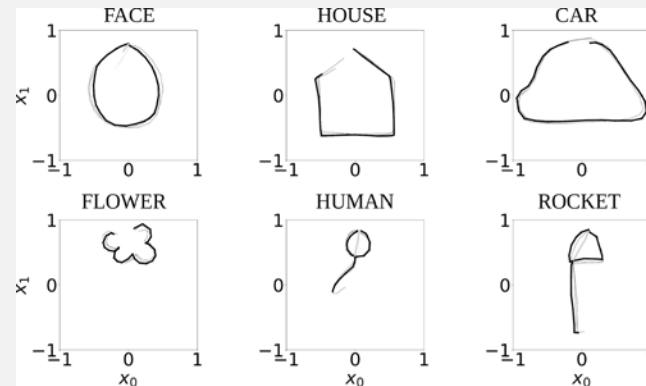


- How **aberrant precisions of predictions H** affect the completion ability in representational drawing
 - Training: learn to draw six types of objects
 - Testing: infer the intended objects from the first 33% of trajectories and complete missing parts

Training data

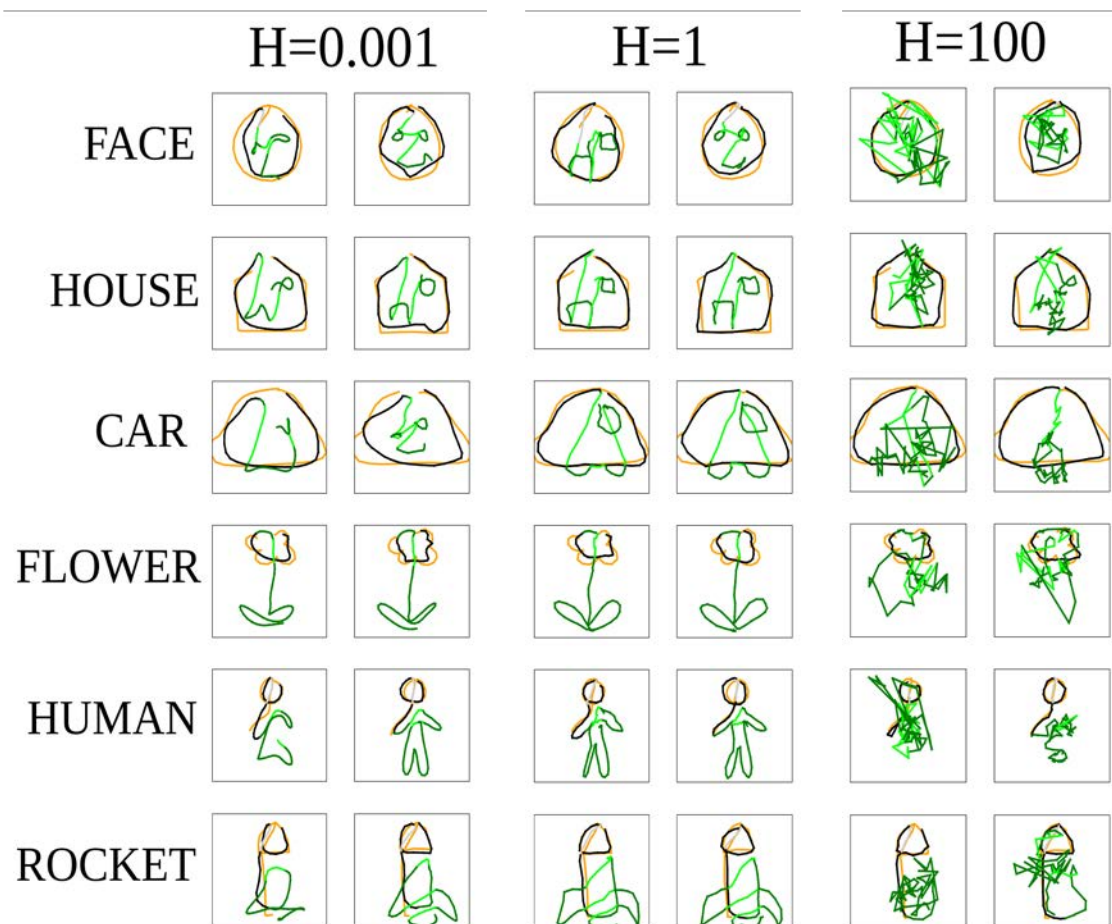


Testing data

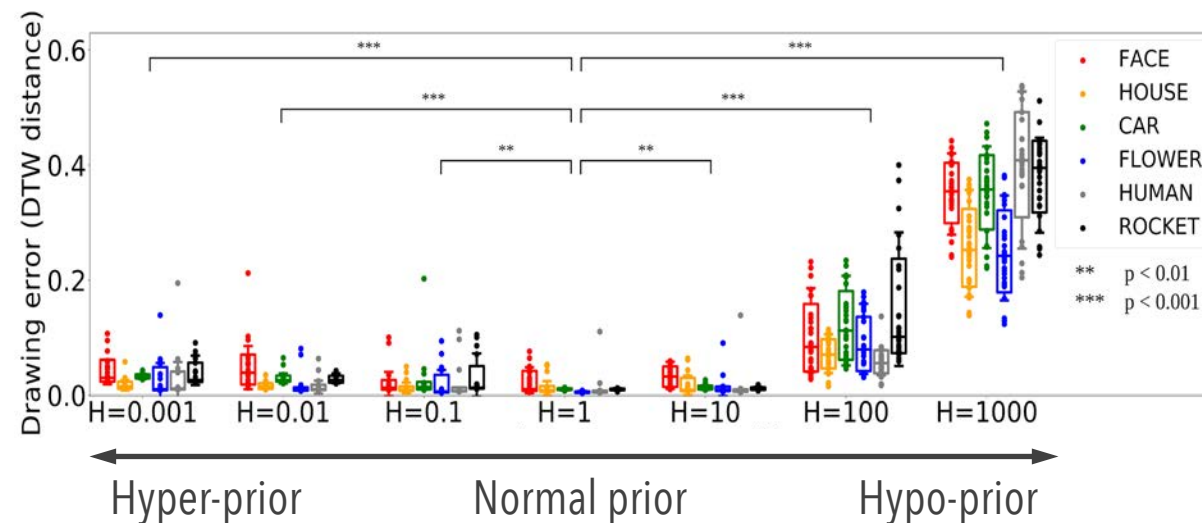


Exp 1: Influence of Aberrant Prediction on Drawing Performance

[Philippsen & Nagai, IEEE TCDS, in press]



- Influences of prediction precisions H
 - Hyper-priors ($H \ll 1$): **misinterpretation** of intended patterns, abstract drawing
 - Normal priors ($H \approx 1$): successful completion of missing parts
 - Hypo-priors ($H \gg 1$): **failure** of intention estimation, scribbling

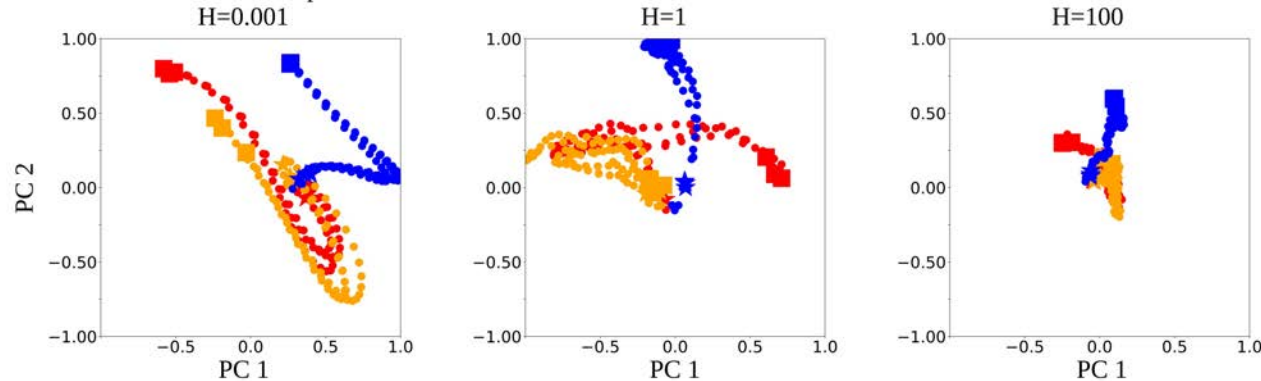


Exp 2: Influence of Aberrant Prediction on Internal Model

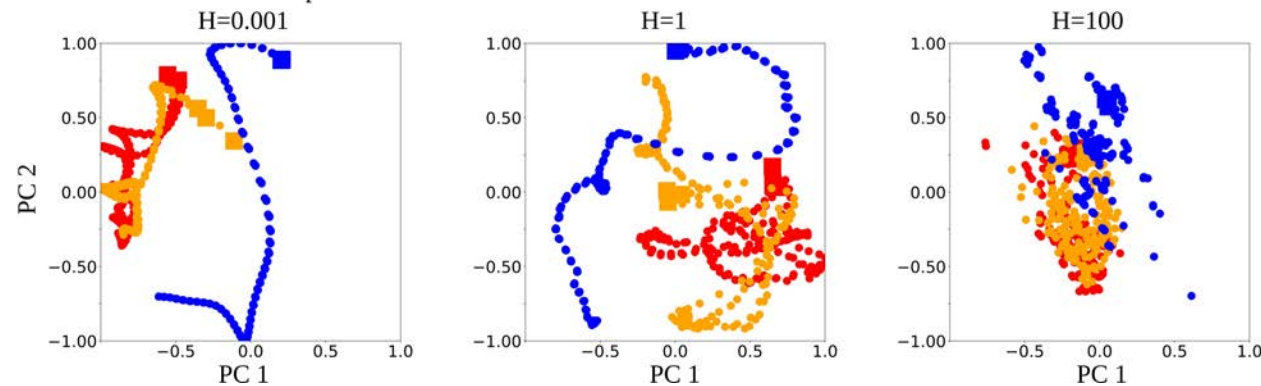
[Philippsen & Nagai, IEEE TCDS, in press]

PCA space of 100 context neurons

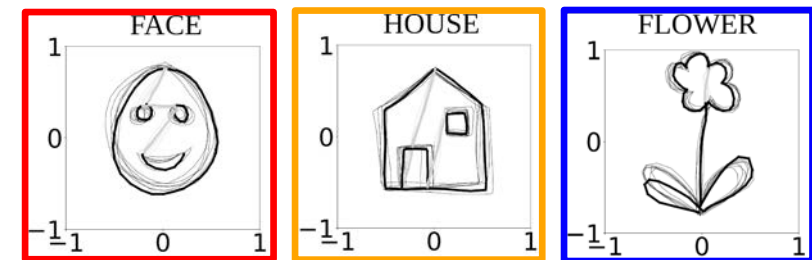
Neuron activations of time steps 1 to 30:



Neuron activations of time steps 30 to 90:



- Influences of prediction precisions H
 - Hyper-priors ($H \ll 1$): **undifferentiated but strong** attractors
 - Normal priors ($H \approx 1$): properly differentiated attractors
 - Hypo-priors ($H \gg 1$): **no or weak** attractors



HMD Reproducing Atypical Visual Perception in ASD

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



(<https://www.jst.go.jp/kisoken/jyonetsu/interview/h29/nagai.html>)

Hallucination Machine [Suzuki et al., 2017]



Original Image



Higher Layer (inception_4d/pool)



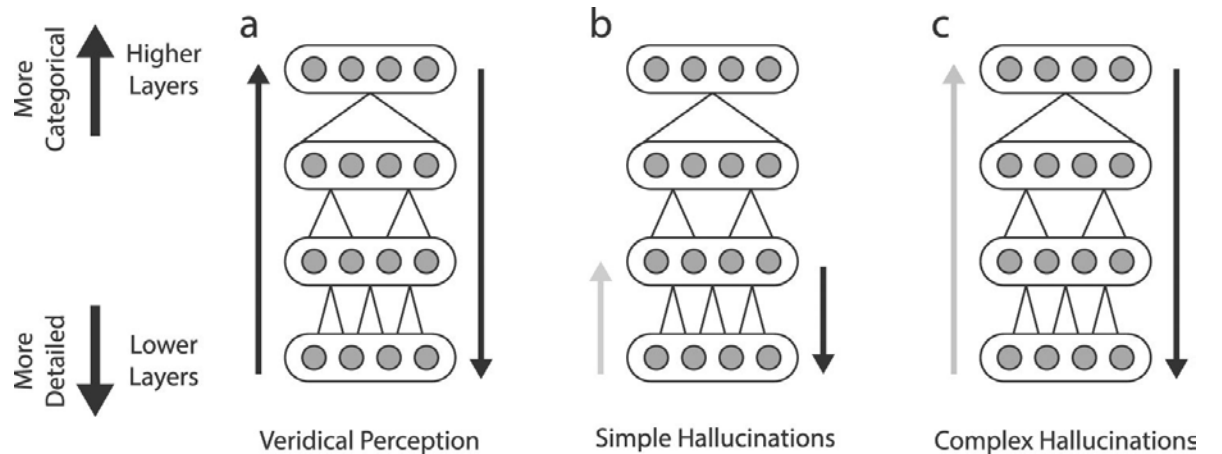
Lower Layer (conv2/3x3)



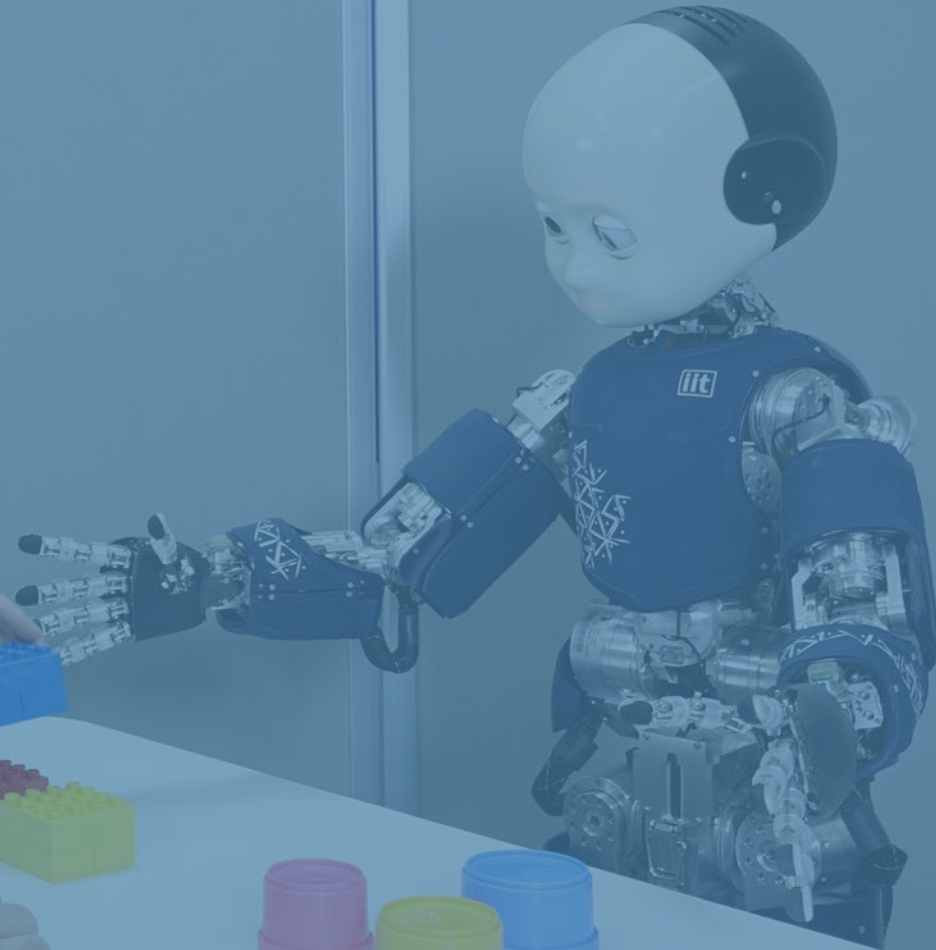
Middle Layer (inception_3b/output)

Deep-Dreamed Images

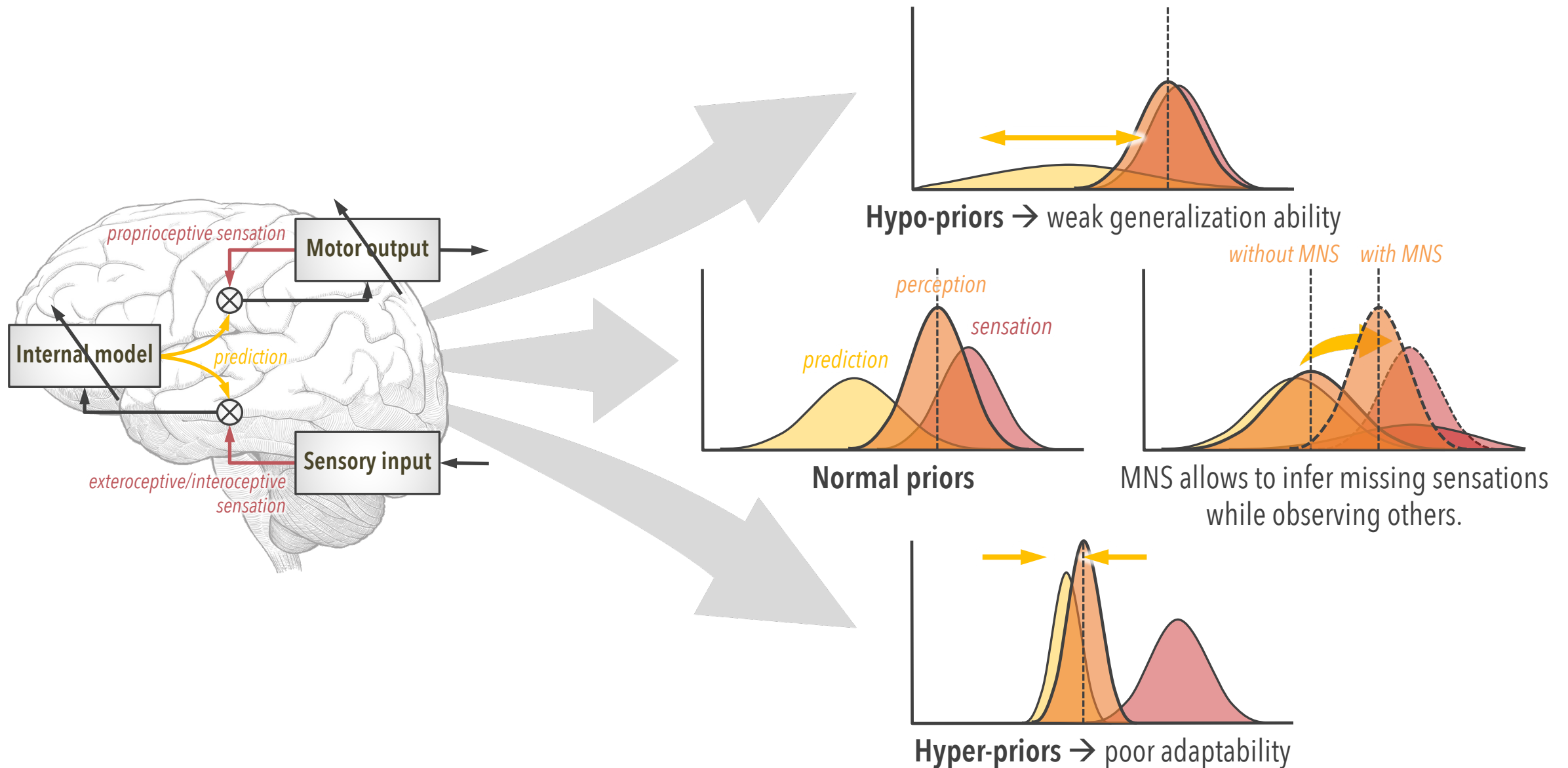
- To produce visual phenomena that are **qualitatively similar to classical psychedelics** by applying Deep Dream to panoramic videos
- Deep Dream [Mordvintsev et al., 2015]
 - To clamp the node activity at a specific layer in a DCNN and then invert the information flow, so that an input image is changed until the network settles into a stable state



Conclusion



Predictive Coding Account for Cognitive Development



Conclusion

- **Predictive coding** as a principle that accounts for the continuity and the diversity in cognitive development
 - Minimization of prediction errors
 - Bayesian influence for perception
- **Hypo- and hyper-priors** as two potential causes for cognitive difficulties in ASD
 - Hypo-priors: high sensitivity to sensory signals, weak generalization ability
 - Hyper-priors: strong reliance on own belief, poor adaptability

Thank you!



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- Takato Horii
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- Shibo Qin (-2015.03)
- Jorge L. Copete (-2019.03)

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- Emre Ugur

Ozyegin University

- Erhan Oztop