Intuitive explanation of FEP related to cognitive neuroscience and developmental disorders

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“Predictive processing” in a broad sense

- Theory of computational rule of the brain explaining the process of ***learning***, ***perception/ cognition***, and ***behavior***.

- Proposed as independent studies using Bayesian inference models (Rao 1999, Friston 2011, etc.) and neural network models (Tani 2003).

Rao RP, Ballard DH (1999) Predictive coding in the visual cortex: a functional interpretation of some extra-classical receptive-field effects. Nat Neurosci. 2: 79-87.
Friston K, Mattout J, Kilner J. Action understanding and active inference. Biol Cybern. 2011 Feb;104(1-2):137-60.
Tani J (2003) Learning to generate articulated behavior through the bottom-up and the top-down interaction processes. Neural Networks 16: 11-23.

History of key concepts

19th century

"Unconscious Inference"

Hermann von Helmholtz
(1821 – 1894)

Our perceptions are not direct reflections of the world, but rather inferences made by our brain based on sensory inputs.

History of key concepts

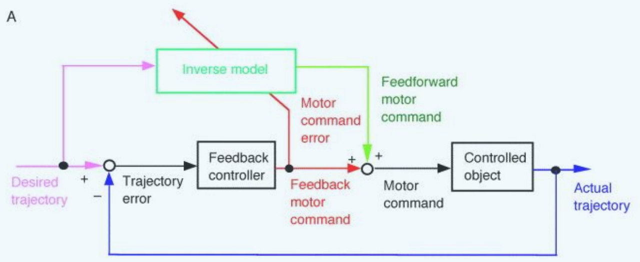
“Unconscious Inference”

Hermann von Helmholtz
(1821 – 1894)

19th century

1990s

“Internal model”



(Wolpert1996, Kawato1999...etc)

The brain constructs internal models to predict sensory outcomes of motor commands.

History of key concepts

19th century

“Unconscious Inference”

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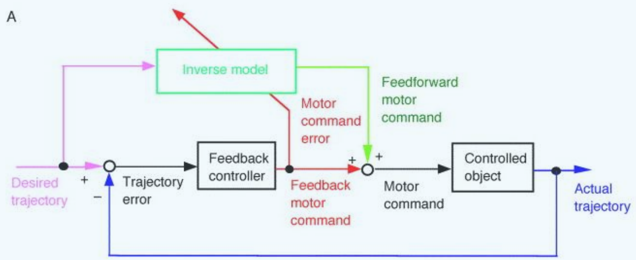
1990s

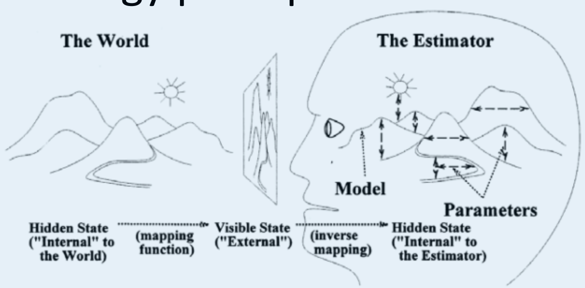
“Internal model”



(Wolpert1996, Kawato1999...etc)

2000s

“Predictive coding”, “Bayesian Brain”, “Free energy principle”



Rao 1999, Tani 2003, Doya2007, Friston2006, etc

The brain is constantly making predictions about incoming sensory data and updating these predictions based on the actual sensory input.

History of key concepts

19th century

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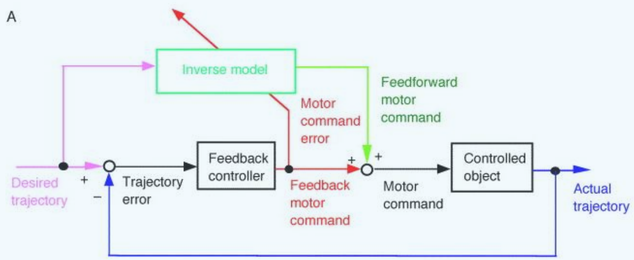
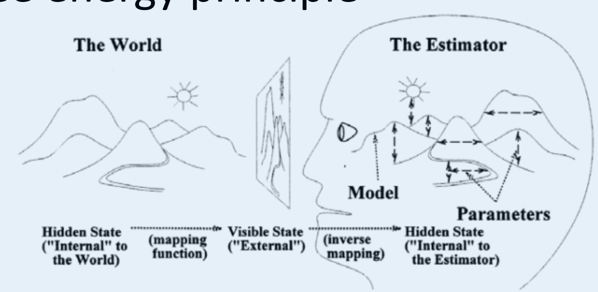
“Internal model”



(Wolpert1996, Kawato1999...etc)

2000s

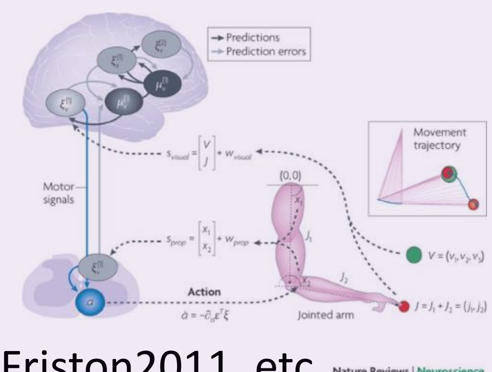
“Predictive coding”, “Bayesian Brain”, “Free energy principle”



Rao 1999, Tani 2003, Doya2007,

2010s

“Active inference”



Friston2011, etc

Organisms don't just passively predict sensory input but actively engage with the environment to minimize prediction errors.

"Predictive processing" in a broad sense

- Brain is a "*predictive machine*" based on internal model of the world.

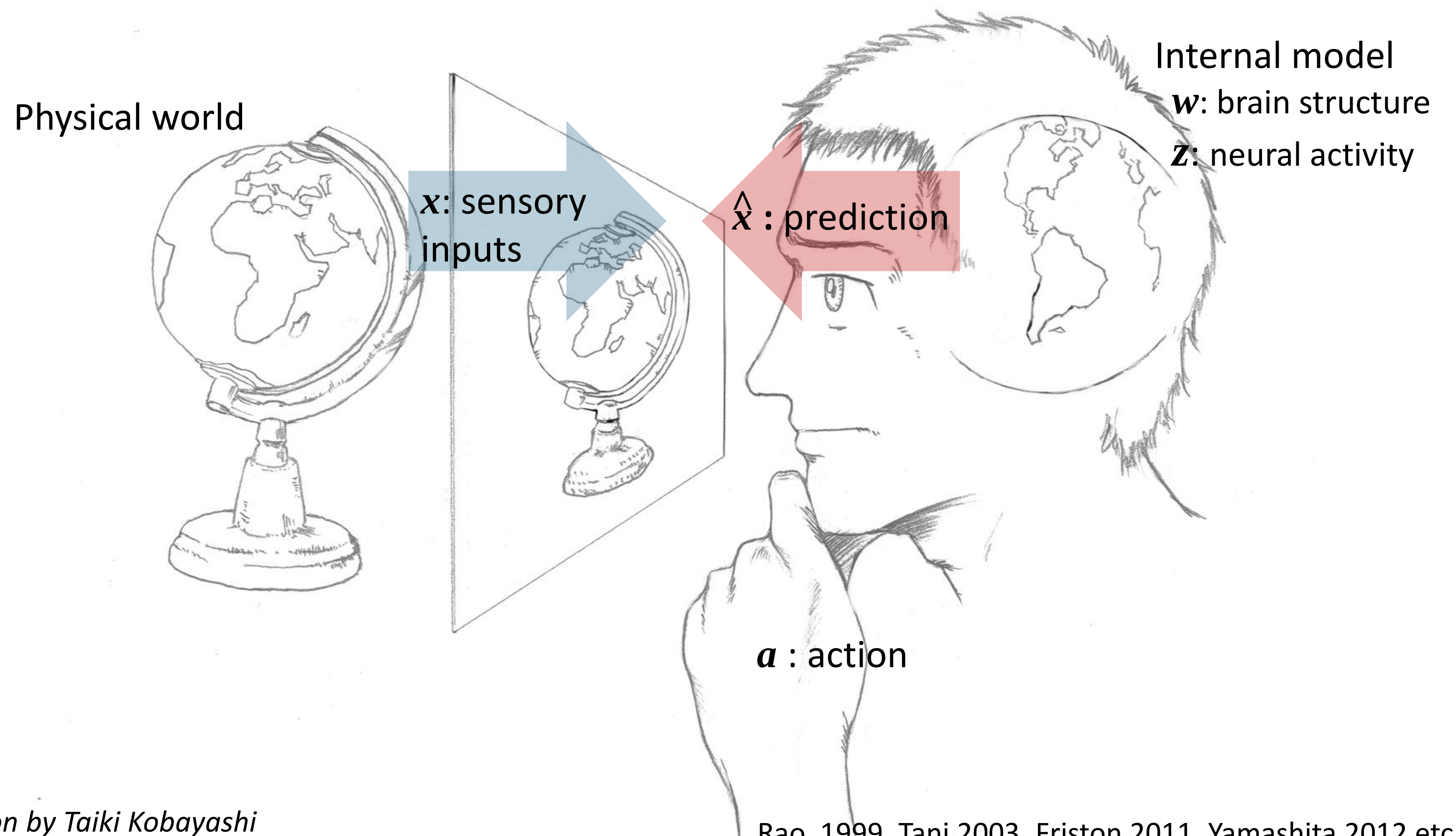


Illustration by Taiki Kobayashi

Rao, 1999, Tani 2003, Friston 2011, Yamashita 2012 etc.

"Predictive processing" in a broad sense

- Interacting with the world via computational rule of "prediction error (PE) minimization"

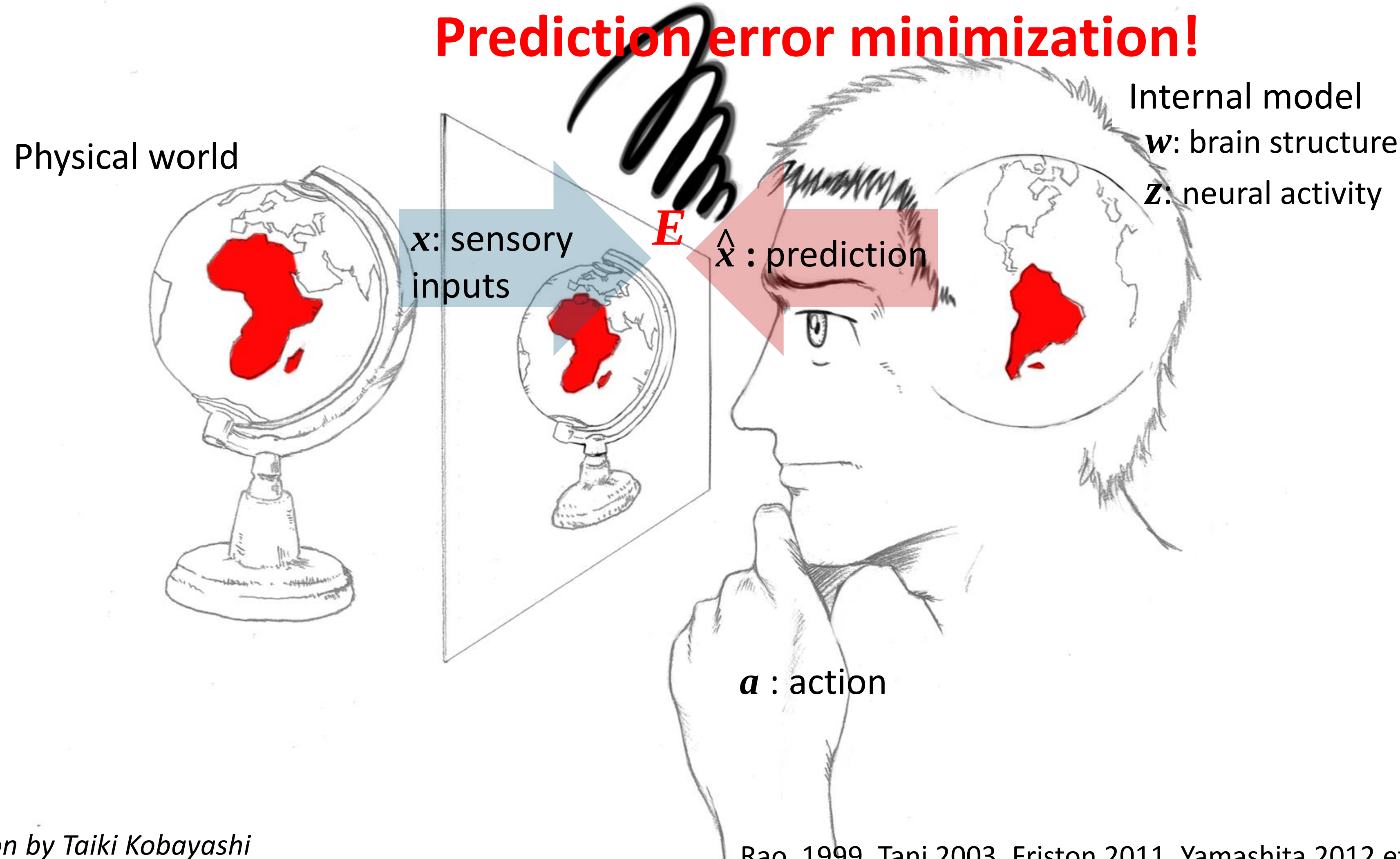


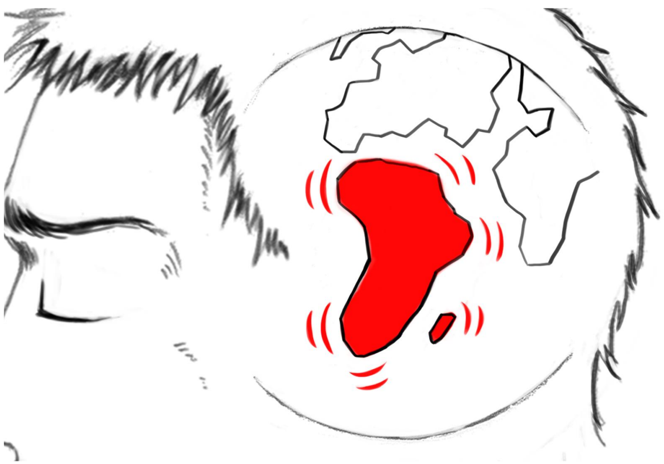
Illustration by Taiki Kobayashi

Rao, 1999, Tani 2003, Friston 2011, Yamashita 2012 etc.

"Predictive processing" in a broad sense

- Three ways to minimize prediction error

Learning



Perception/Cognition

Action

Illustration by Taiki Kobayashi

- When there is prediction error…

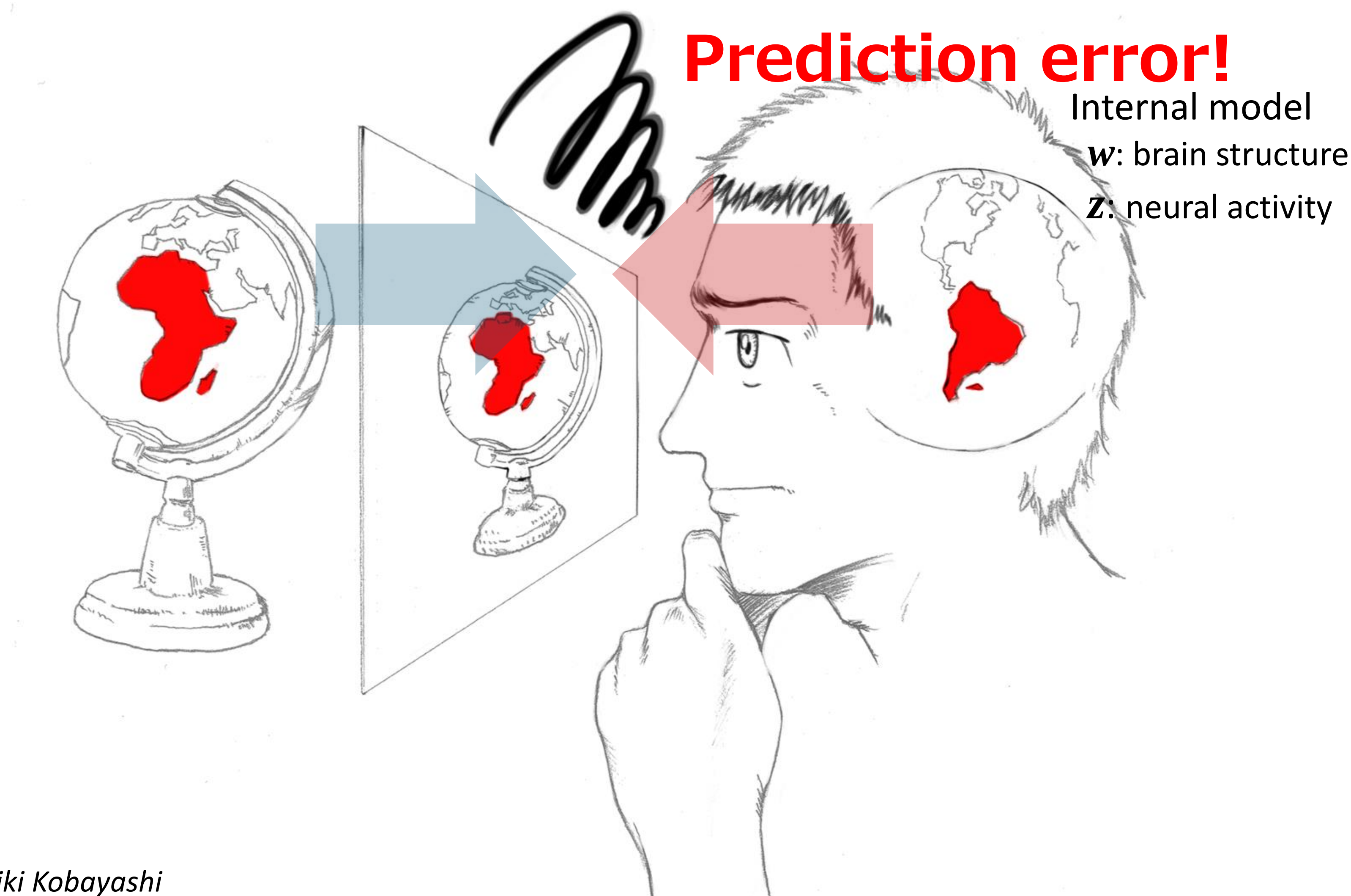


Illustration by Taiki Kobayashi

- Internal model might be wrong…

Illustration by Taiki Kobayashi

- Update internal model (brain structure)…

$$\Delta w = -\alpha_w \frac{\partial E}{\partial w}$$

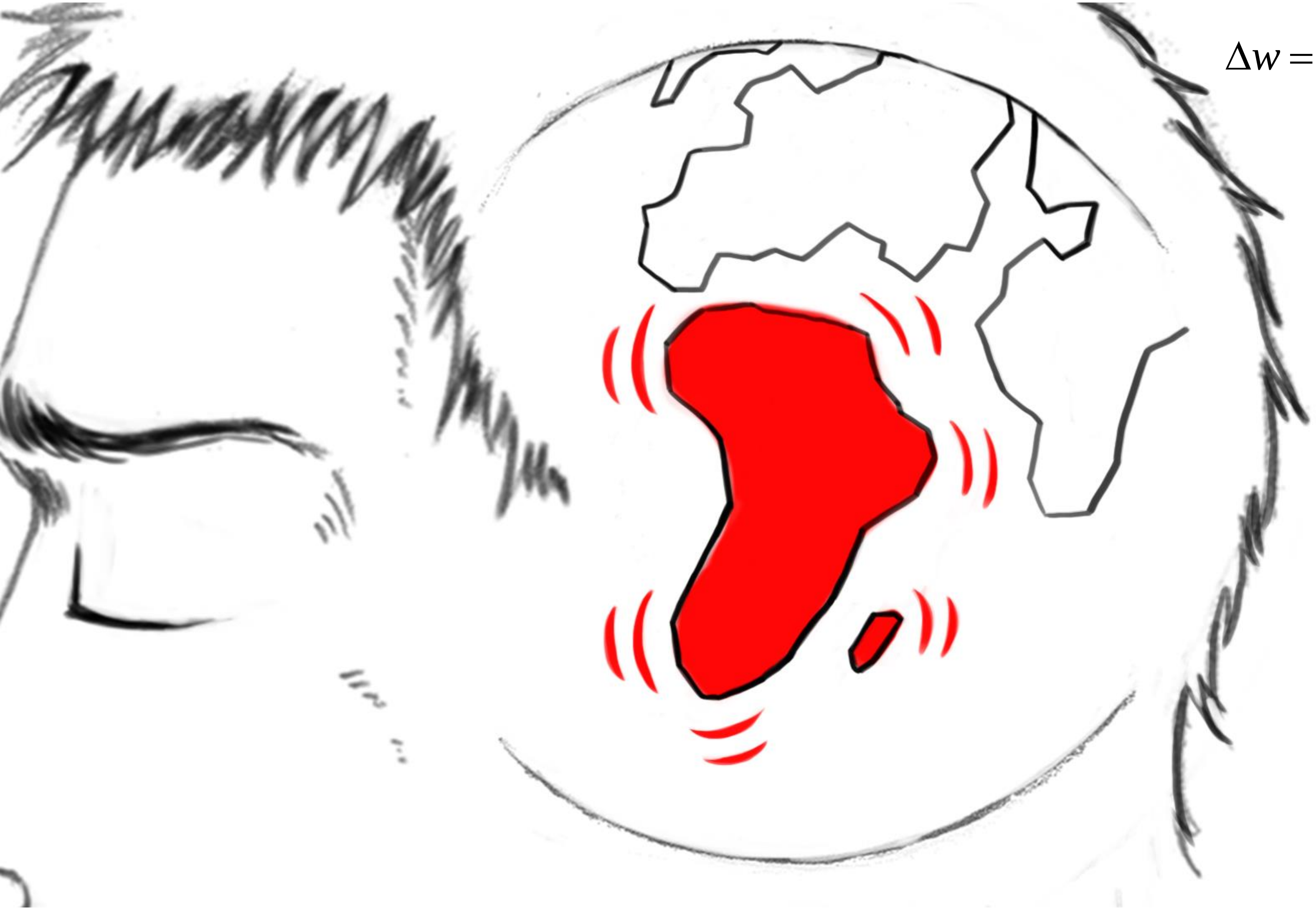


Illustration by Taiki Kobayashi

- PE minimization can be achieved through the modifications of internal model (learning).

$$\Delta w = -\alpha_w \frac{\partial E}{\partial w}$$

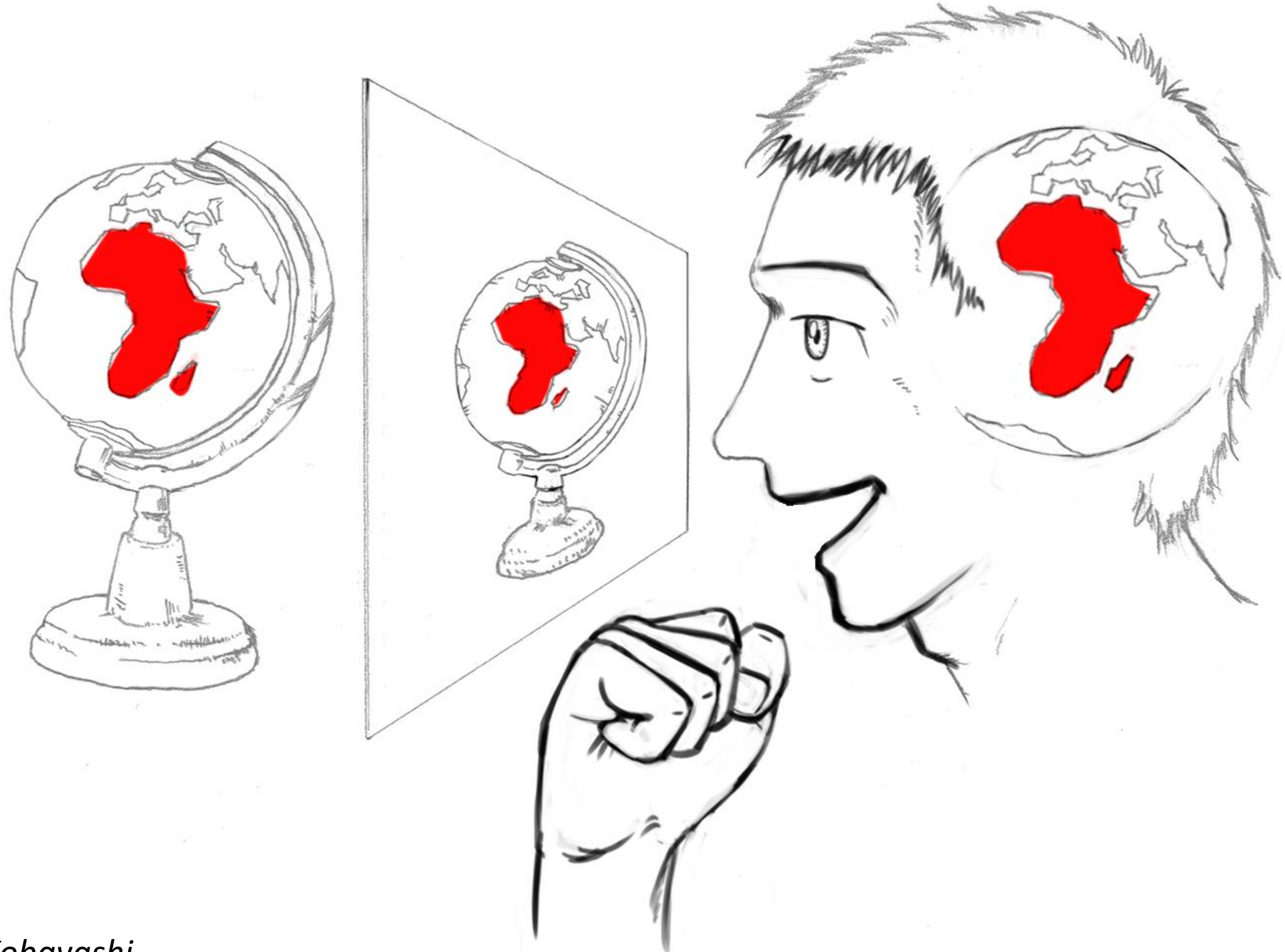


Illustration by Taiki Kobayashi

- When there is prediction error…

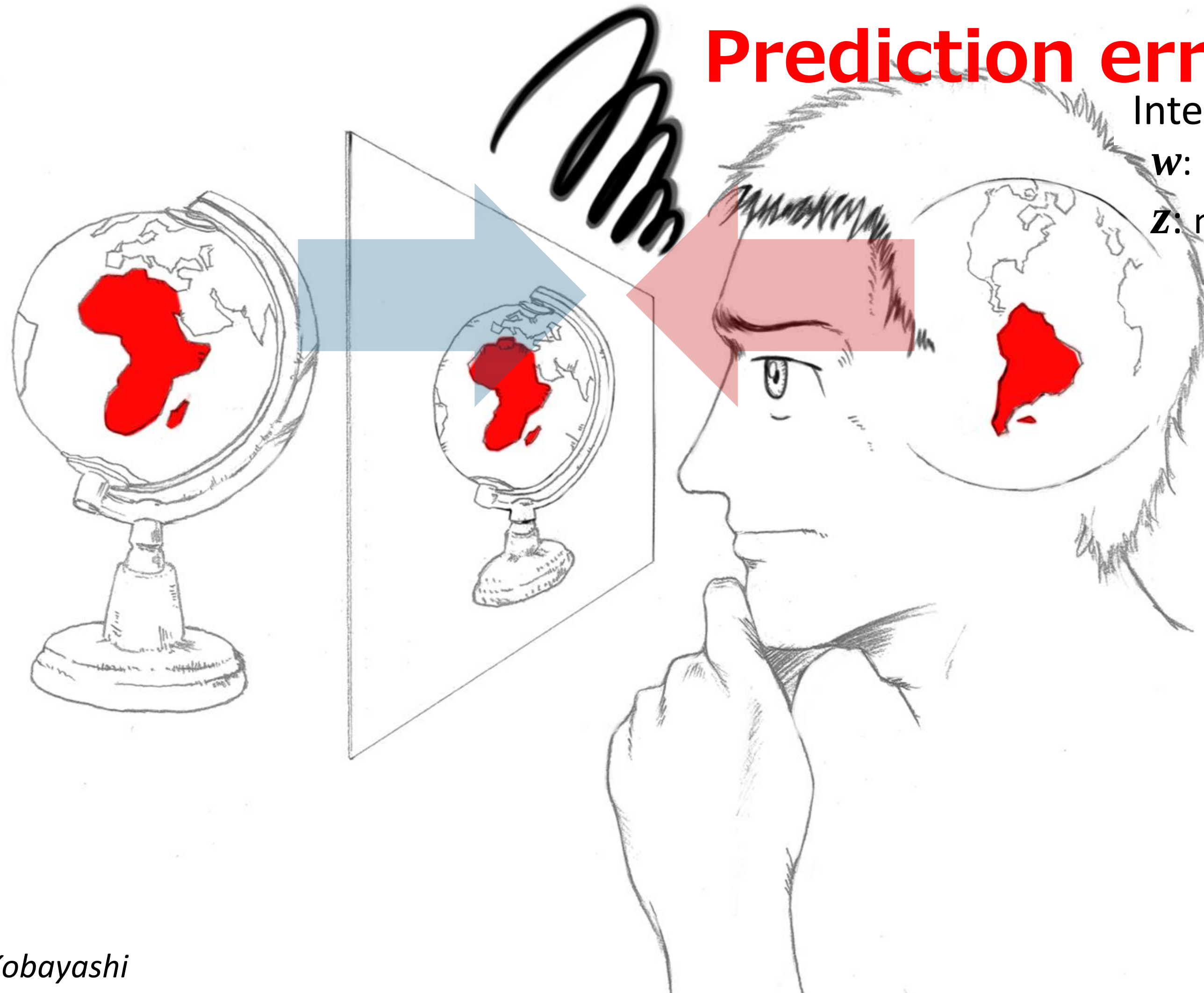


Illustration by Taiki Kobayashi

- Prediction might be wrong…

Illustration by Taiki Kobayashi

- Change the prediction via updating brain states

$$\Delta z = -\alpha_z \frac{\partial E}{\partial z}$$

Illustration by Taiki Kobayashi

- PE minimization can be achieved through the modifications of internal/brain states (perception/cognition)

$$\Delta z = -\alpha_z \frac{\partial E}{\partial z}$$

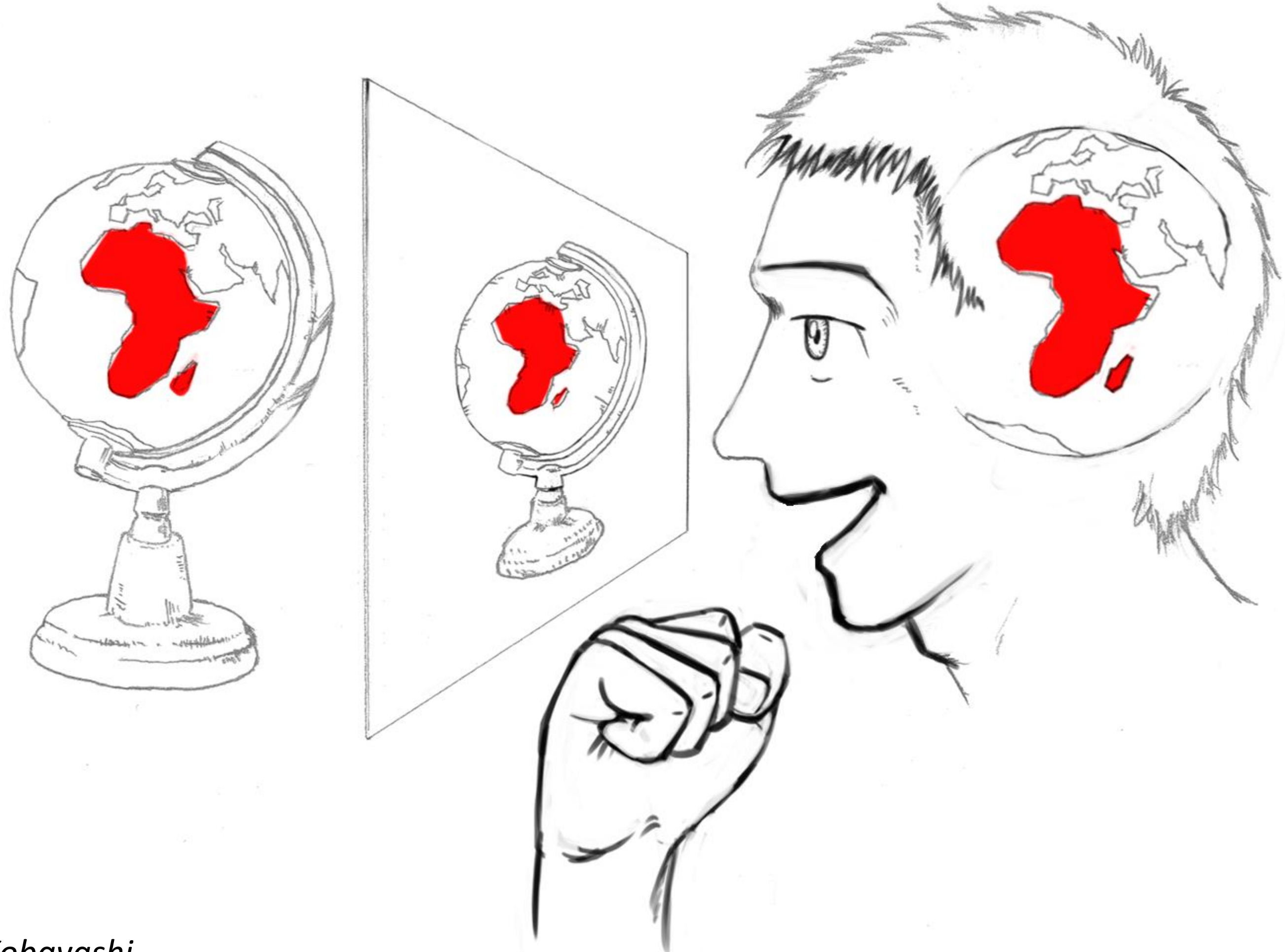


Illustration by Taiki Kobayashi

- When there is prediction error…

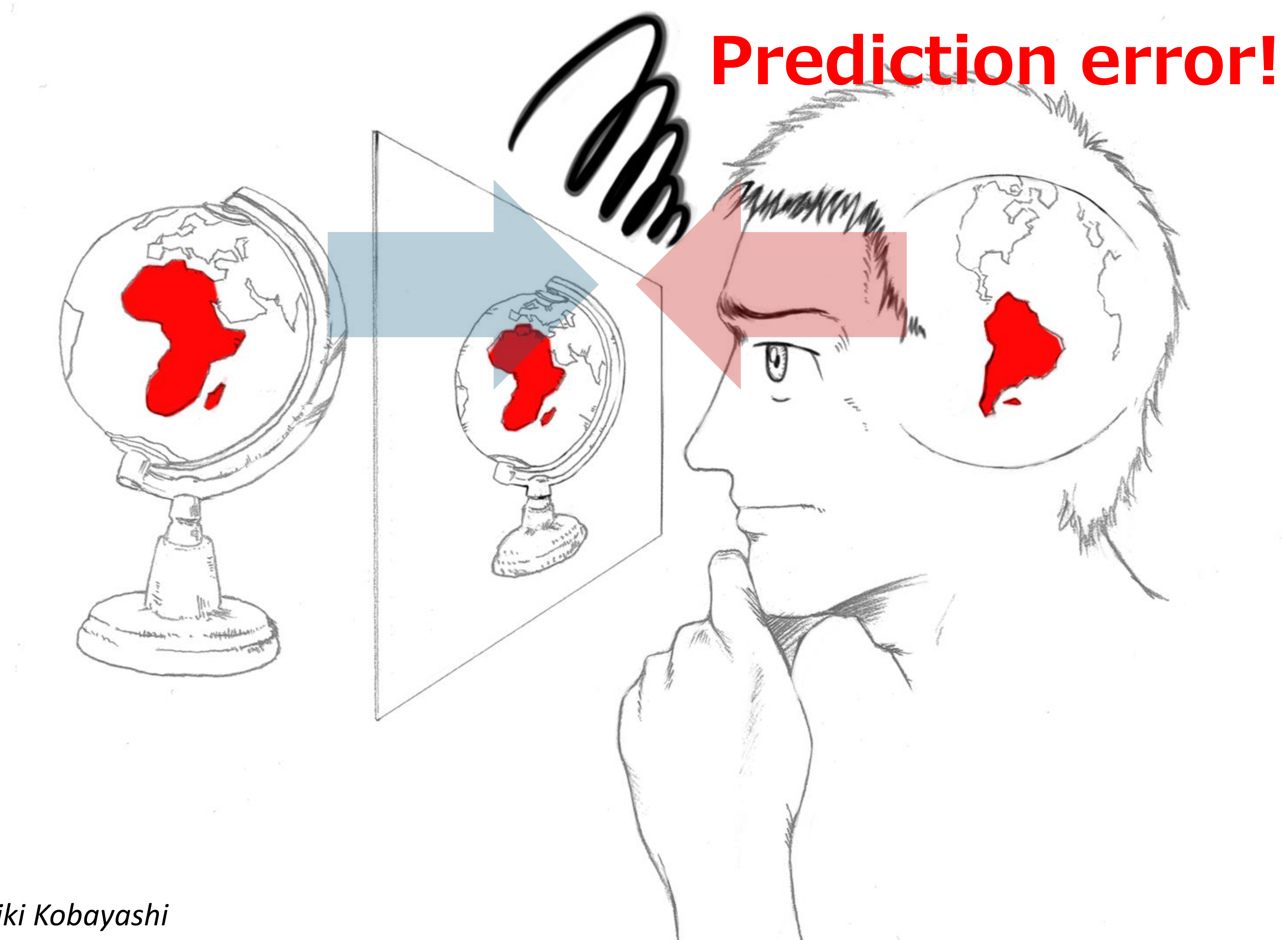


Illustration by Taiki Kobayashi

- External world might be wrong…

Illustration by Taiki Kobayashi

- Change the external world through action…

$$\Delta a = -\alpha_a \frac{\partial E}{\partial a}$$

Illustration by Taiki Kobayashi

- PE minimization can be achieved through the modifications of sensor (change the world via action).

$$\Delta a = -\alpha_a \frac{\partial E}{\partial a}$$

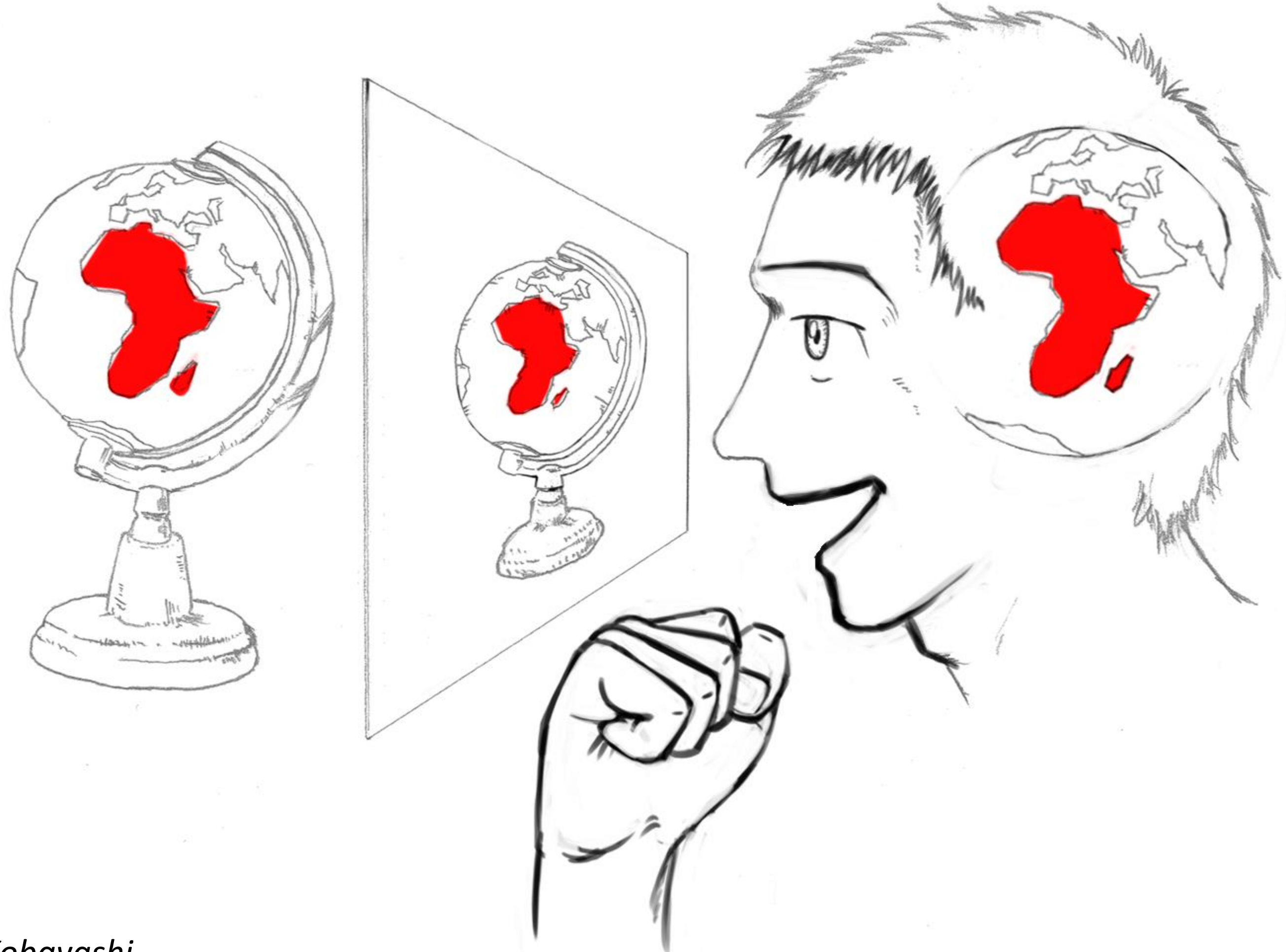
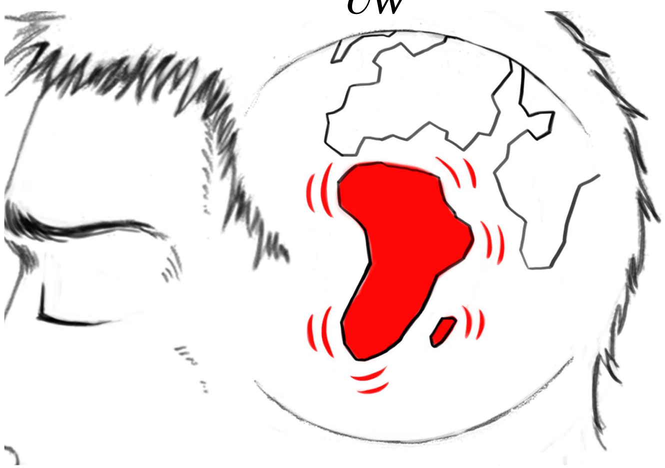


Illustration by Taiki Kobayashi

Predictive processing

- Explaining wide range of brain functions including the learning, perception/cognition and action based on the prediction error minimization.

$$\Delta w = -\alpha_w \frac{\partial E}{\partial w}$$



"Learning": updates internal models

$$\Delta z = -\alpha_z \frac{\partial E}{\partial z}$$

"Perception/cognition": updates neural states

$$\Delta a = -\alpha_a \frac{\partial E}{\partial a}$$

"Action": changes sensory inputs

Illustration by Taiki Kobayashi

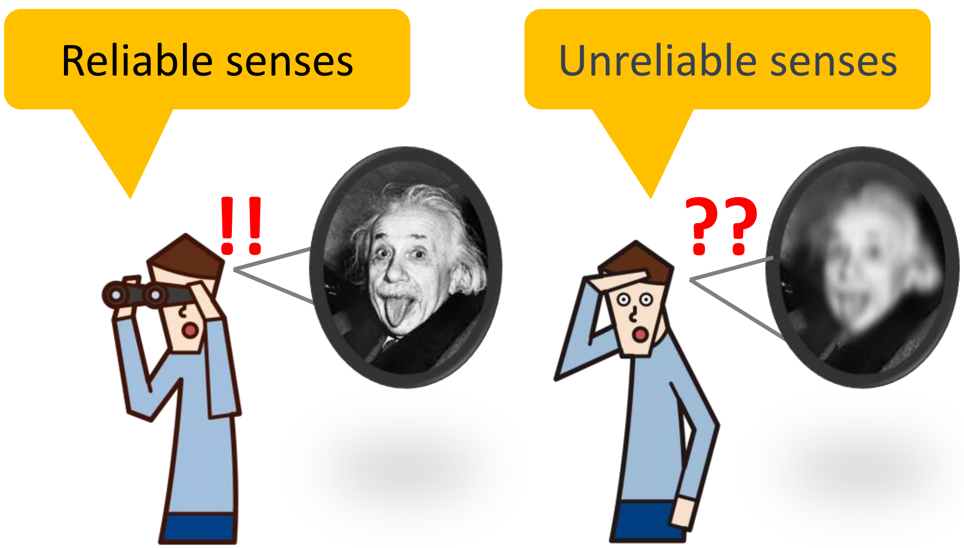
Rao, 1999, Tani 2003, Friston 2011, Yamashita 2012 etc.

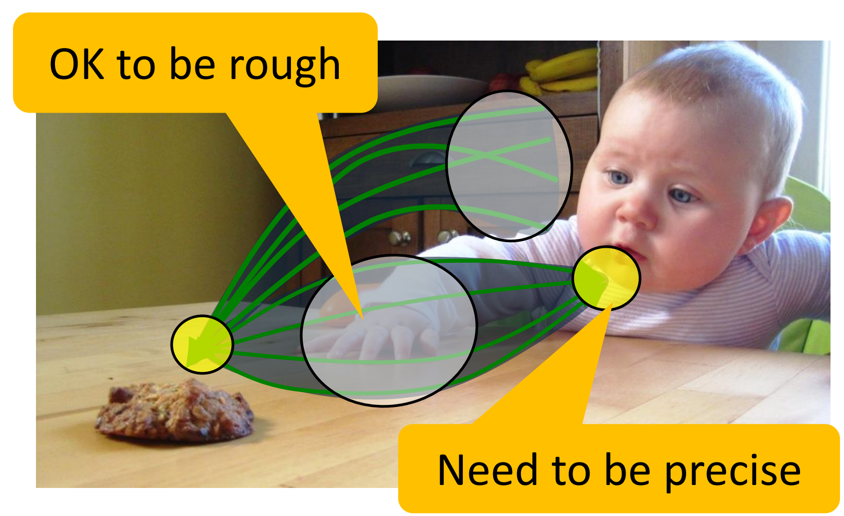
“Precision” is important

"Precision" in predictive processing

- Estimation of precision works as an important parameter in PE minimization process.

- For example…
  - ✓ Estimate low sensory precision (high variability) => PE should be ignored
  - ✓ Estimate high sensory precision (low variability) => PE should be respected



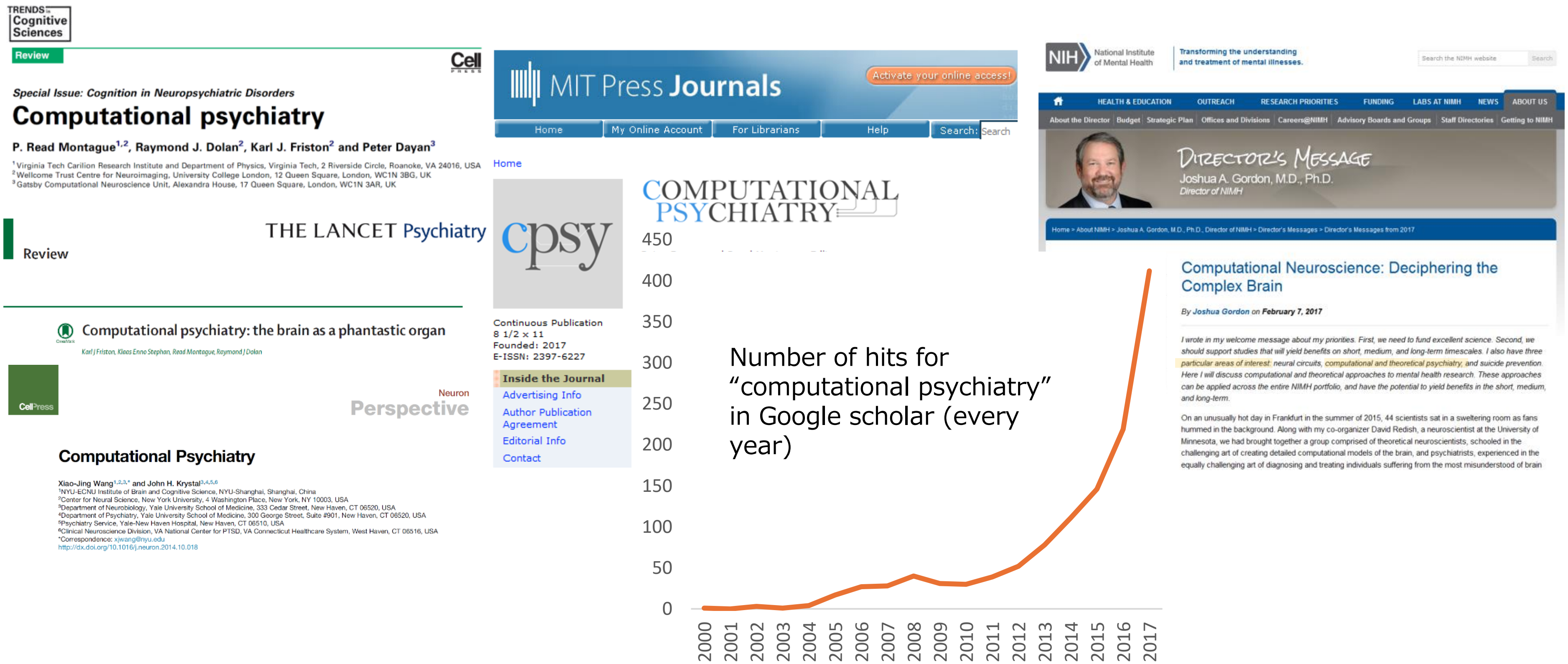


Psychiatric disorders as altered predictive processing:

A major theory in "Computational Psychiatry"

Computational psychiatry is rising to prominence

- Novel area of psychiatric research drawing researchers' attentions.
- New specialist journal "Computational Psychiatry" has been opened (2017).
- Director of NIMH listed computational psychiatry as one of the "three particular areas of interest" in psychiatry



Montague et al. 2012, Friston et al. 2014, Wang XJ et al. 2014

Autism spectrum disorder (ASD) as altered predictive processing:

Autism spectrum disorder (ASD): DSM-5 criteria

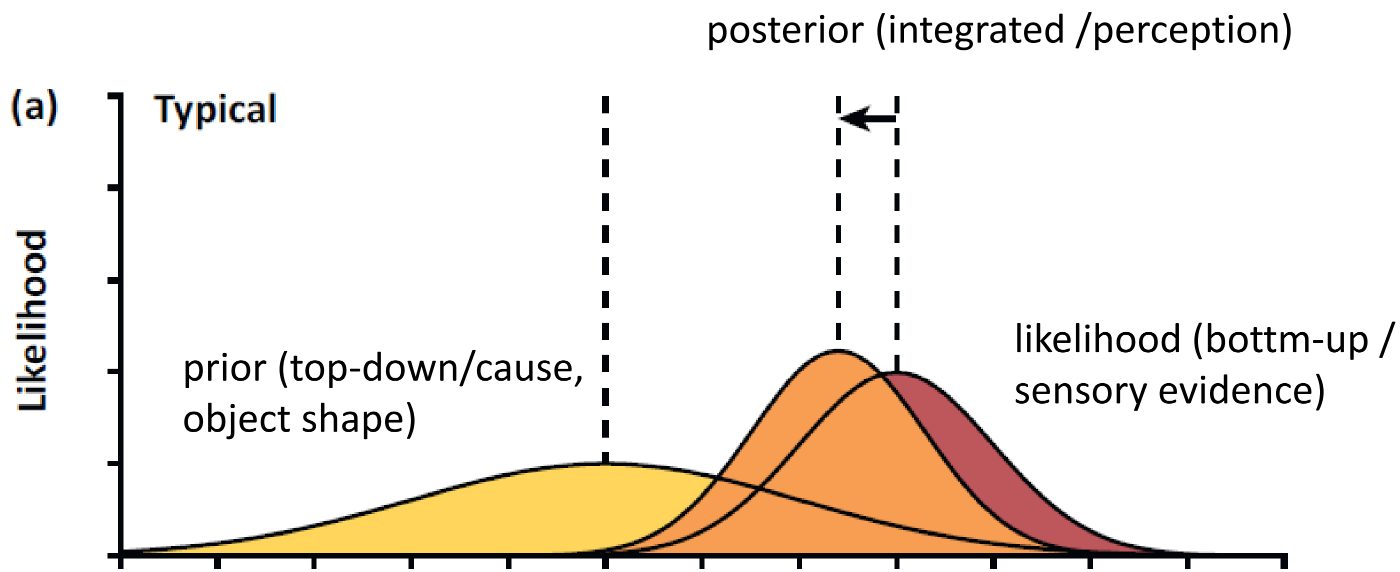
Many recent studies of ASD focus on the non-social symptoms.

A. Persistent difficulties in the social use of verbal and nonverbal communication

B. Restricted, repetitive patterns of behavior, interests, or activities,

- Stereotyped or repetitive motor movements, use of objects, or speech
- Insistence on sameness, inflexible adherence to routines, or ritualized patterns of verbal or nonverbal behavior
- Highly restricted, fixated interests that are abnormal in intensity or focus
- Hyper- or hyporeactivity to sensory input or unusual interests in sensory aspects of the environment

Perception as Bayesian inference



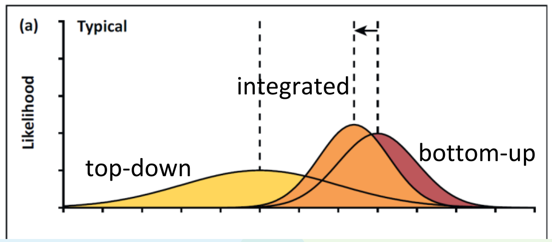
p(S|I) ∝ ***p(I|S)*** ***p(S)***

Probability that object shape is ***S*** given sensory input ***I*** (***p(S|I)***) is determined by the integration of the likelihood of sensory inputs given object shape ***S*** (***p(I|S)***) and prior expectation of object shape (***p(S)***).

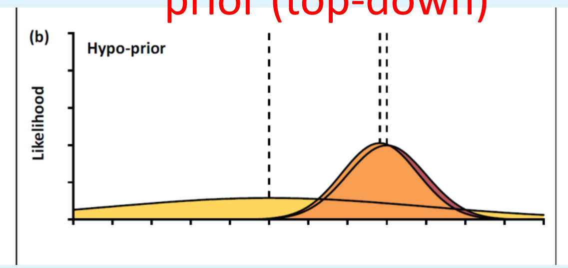
Pellicano E, Burr D. When the world becomes 'too real': a Bayesian explanation of autistic perception. Trends Cogn Sci. 2012 Oct;16(10):504-10.

Aberrant precision accounts for ASD

- Reduced precision of prior leads to high reliability of sensor inputs.
- Similar phenomenon can be expected by increased sensory precision.

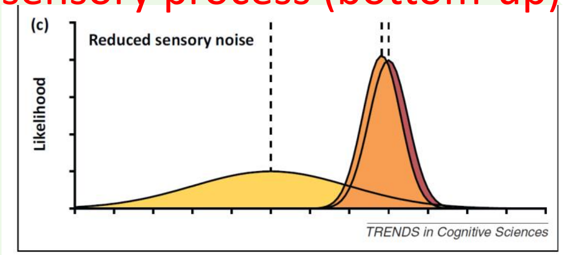


Primary impairment in prior (top-down)



- "Hypo-prior (Increased variance of prior)": *Pellicano & Burr, 2012*

Primary impairment in sensory process (bottom-up)



- "Reduced variance of sensory noise": *Brock, 2012*
- "High and inflexible precision of PE": *Van de Cruys et al., 2014*
- "Reduced endogenous neural noise": *Davis, 2015*

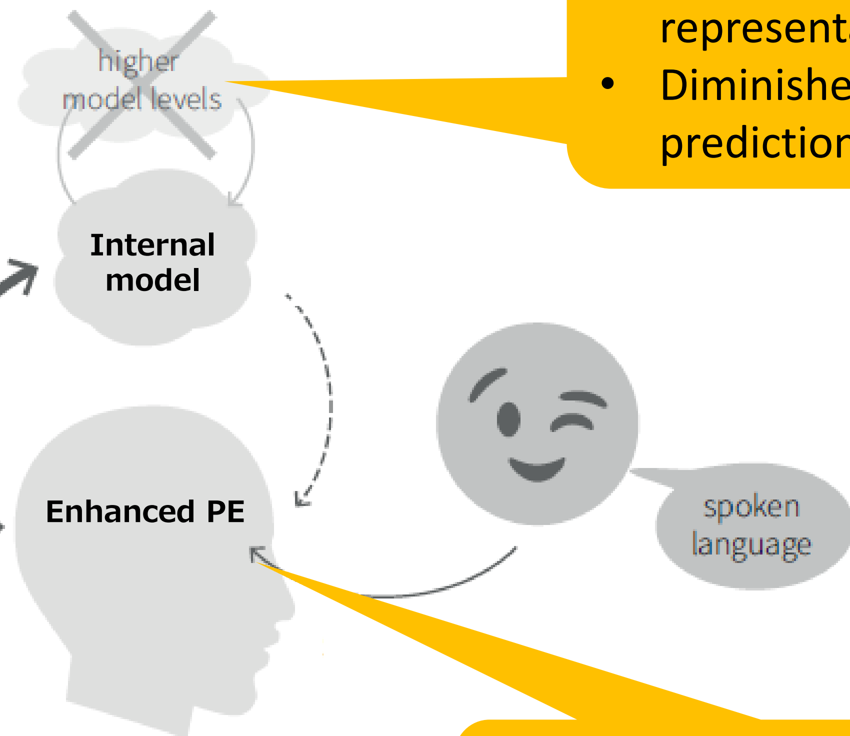
$$\Delta\text{belief} \propto \frac{\text{precision}_{\text{input}}}{\text{precision}_{\text{prior belief}}} \times \text{prediction error}$$

Balance??

- "Imbalance of the precisions of prior belief vs. sensory evidence": *Lawson et al.,* 2014

Aberrant predictive processing for ASD
Hypo-prior (hyper-sensory precision) hypothesis

- Underdeveloped abstract representation
- Diminished higher-level prediction



- Sensitive to minor sensory discrepancies due to enhanced PE
- Overfitting specific events (leading to reduced generalization

- Prefer sensation to prediction （hypo-prior/hyper-sensory precision）

Adapted from “Haker H, Schneebeli M, Stephan KE. Can Bayesian Theories of Autism Spectrum Disorder Help Improve Clinical Practice? Front Psychiatry 7:107, 2016. “

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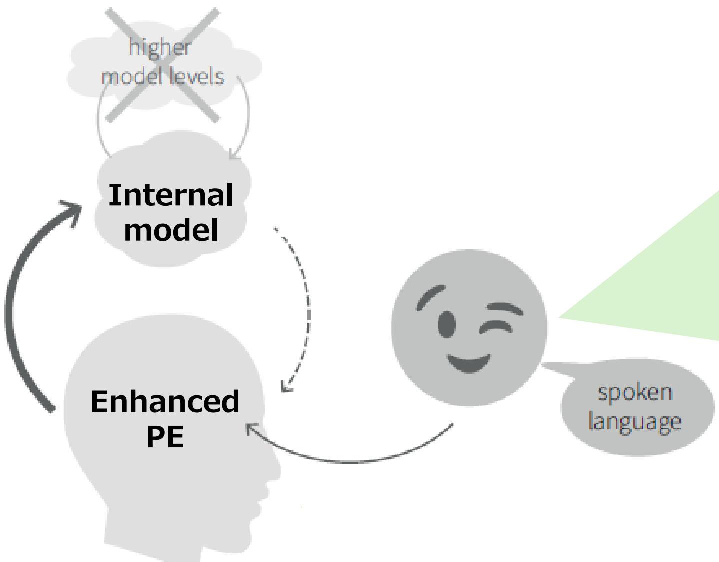

Explaining characteristic symptoms of ASD
For example…

- More accurate perception
- Lack of advantage using prior
- Hyper sensitivity (sensory overload)

- Reduced spontaneous perceptual shift
- Reduced cognitive flexibility
- Reduced capacity for generalization

Adapted from "Haker H, Schneebeli M, Stephan KE. Can Bayesian Theories of Autism Spectrum Disorder Help Improve Clinical Practice? Front Psychiatry 7:107, 2016. "

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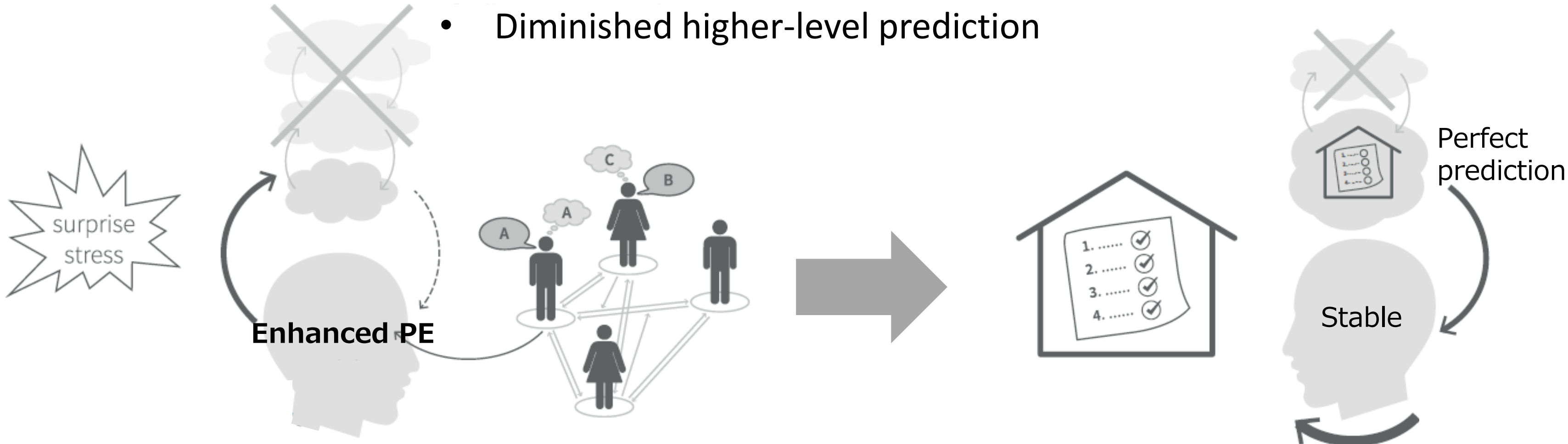

Complex/dynamic social interaction

- Larger prediction errors (surprise, stress)

- Prefers objects that allow for accurate prediction
- Urge for repetitive actions in familiar environments

Adapted from "Haker H, Schneebeli M, Stephan KE. Can Bayesian Theories of Autism Spectrum Disorder Help Improve Clinical Practice? Front Psychiatry 7:107, 2016. "

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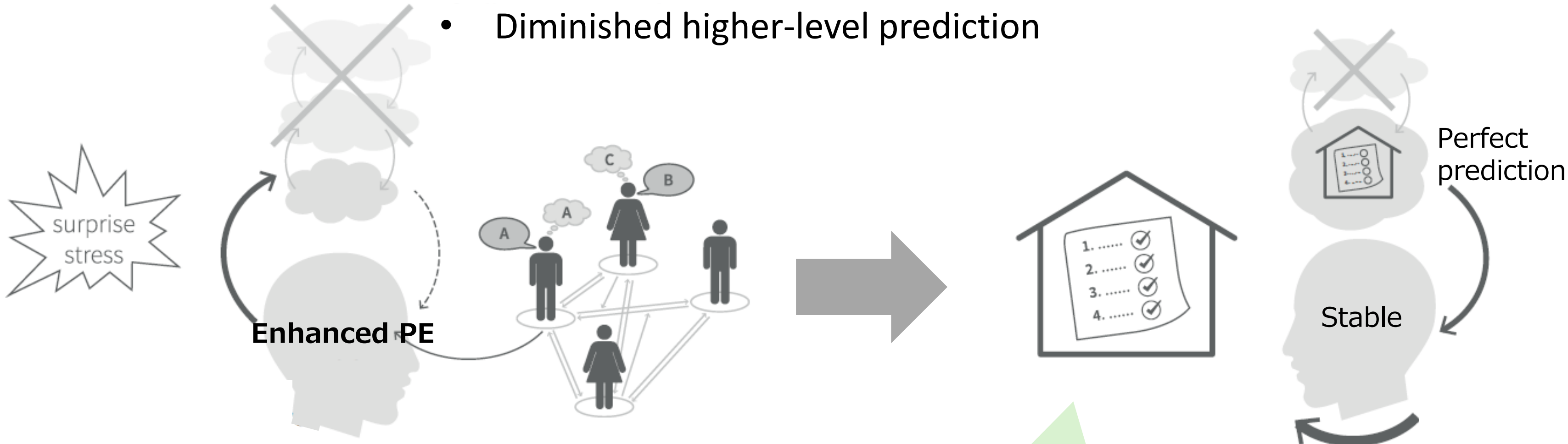


Complex/dynamic social interaction

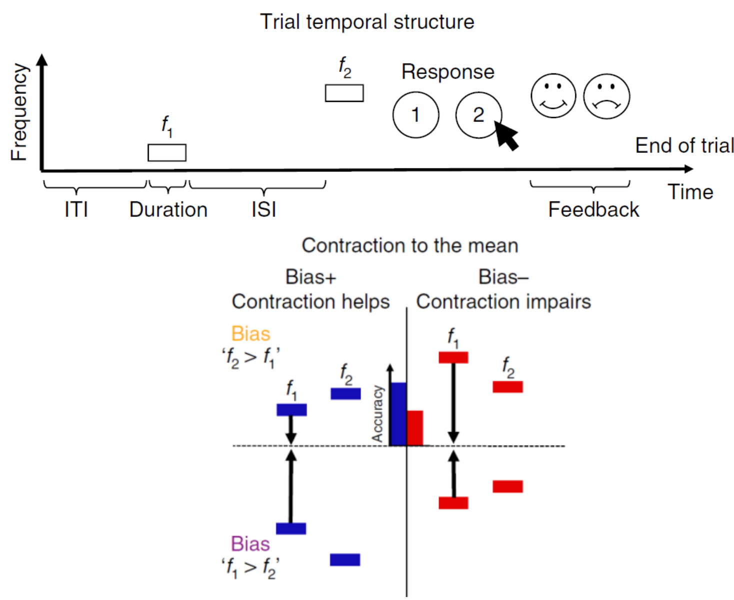
- Desire to sameness
- Repetitive/restricted behavior
- Autistic social interaction

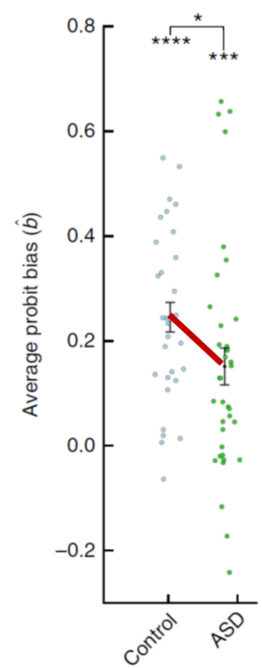
Adapted from "Haker H, Schneebeli M, Stephan KE. Can Bayesian Theories of Autism Spectrum Disorder Help Improve Clinical Practice? Front Psychiatry 7:107, 2016. "

There's also a completely opposite explanation... Hyper-prior hypothesis for ASD

- Inflexibility or slow-updating of internal state observed in ASD can be considered as “hyper-prior” (strong top-down/resistance to PE).

Controversial!?





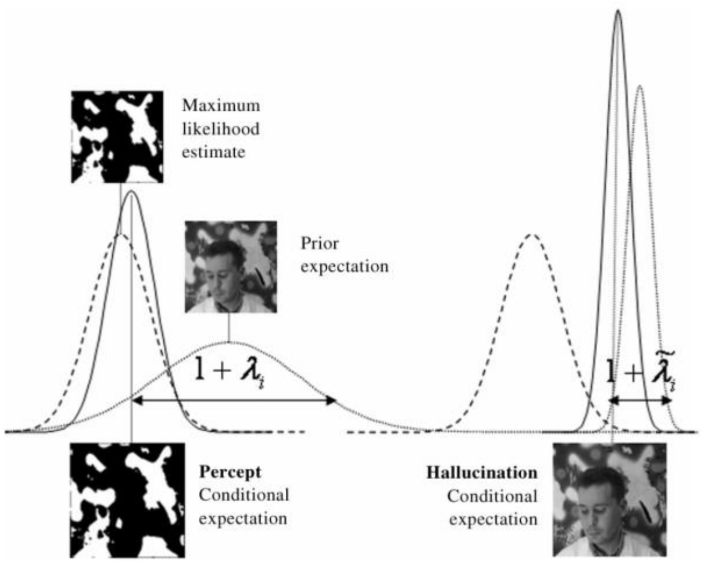
- Lieder I, Adam V, Frenkel O, Jaffe-Dax S, Sahani M, & Ahissar M (2019) Perceptual bias reveals slow-updating in autism and fast-forgetting in dyslexia. Nature Neuroscience 22: 256-264.
- Vishne G, Jacoby N, Malinovitch T, Epstein T, Frenkel O, & Ahissar M (2021) Slow update of internal representations impedes synchronization in autism. Nature Communications 12: 5439.

Aberrant precision account for schizophrenia (SZ)

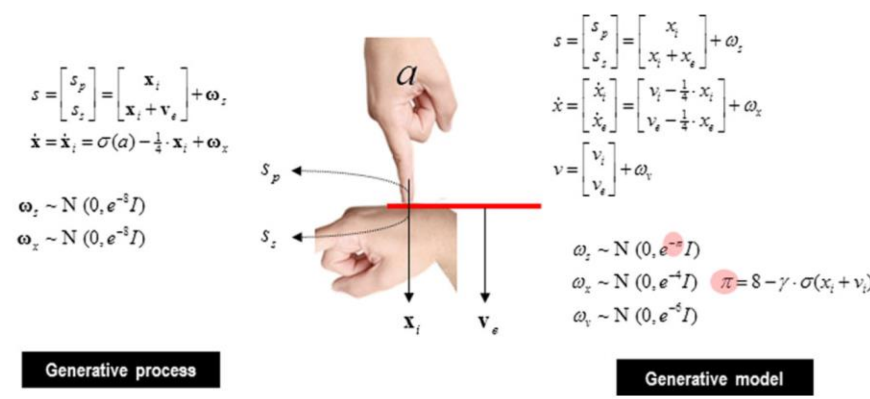
Hallucinations result from the overestimation of the precision of prior beliefs

Hyper-sensory precision leads to impaired sensory attenuation and mis attribution of agency

Hyper-prior precision hypothesis for hallucination



Hyper-sensory precision (hypo-prior) hypothesis for altered sense of agency



Karl J. Friston. Hallucinations and perceptual inference Behavioral and Brain Sciences 28 (6):764-766 (2005)
Brown H, Adams RA, Parees I, Edwards M, Friston K.Active inference, sensory attenuation and illusions. Cogn Process. 2013 Nov;14(4):411-27.
Adams RA, Stephan KE, Brown HR, Frith CD and Friston KJ (2013) The computational anatomy of psychosis. *Front. Psychiatry* **4**:47.

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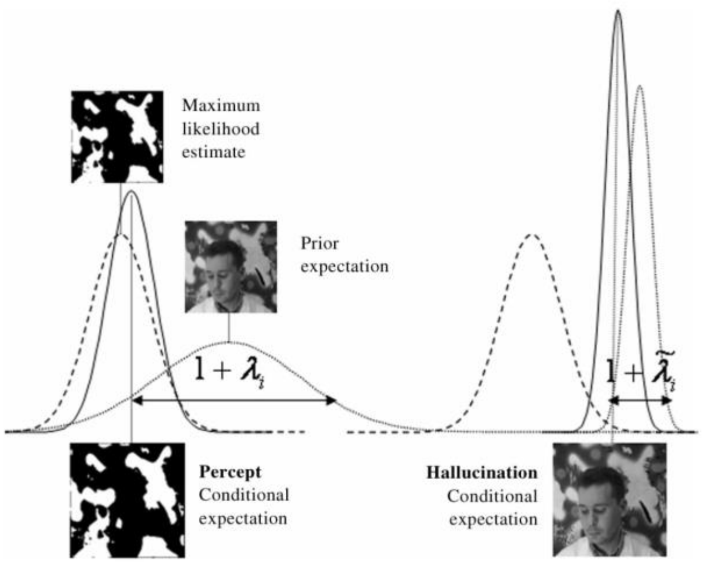

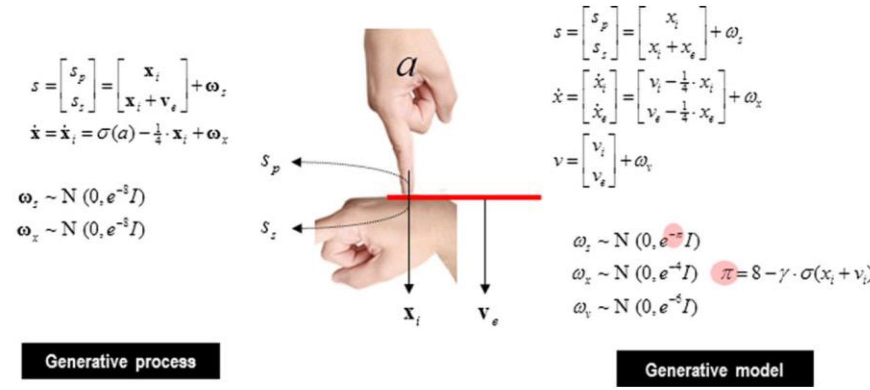

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Altered AiF process of neurorobots

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Predictive processing: A major theory in "Computational Psychiatry"

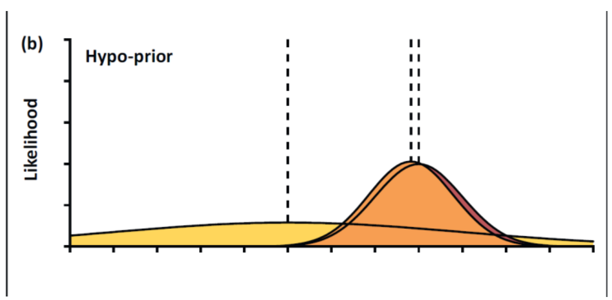
There is hope that the pathology of ASD and SZ can be explained as altered predictive processing.

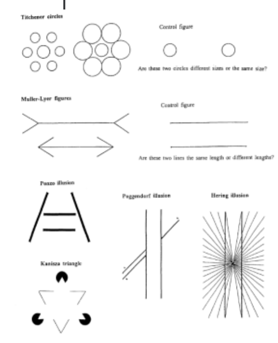
However….

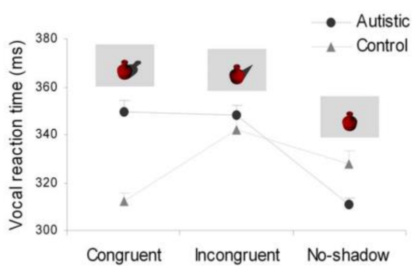
- Similarity of the pathologies postulated in SZ and ASD (altered prior)
- Opposing mechanistic hypotheses for SZ and ASD (hypo-prior vs hyper-prior hypothesis)

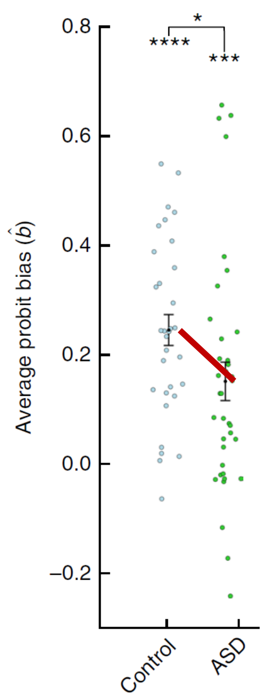
Controversy in aberrant predictive processing in ASD

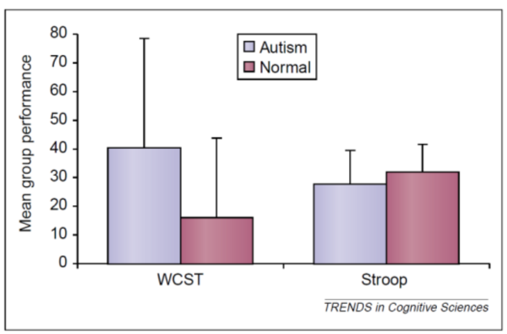
- Reduced precision of prediction (hypo-prior hypothesis)
  - ✓ More accurate perception, hyper-sensitivity, reduced generalization
- Slow-updating of prediction (hyper-prior hypothesis)
  - ✓ Reduced cognitive flexibility











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Controversy in aberrant predictive processing in SZ

- Excessive precision at the sensory level = reduced precision of prediction (hypo-prior hypothesis)
  - ✓ Abnormal response to PE (misattribution of beliefs, aberrant salience)

- Excessive precision of prediction (hyper-prior hypothesis)
  - ✓ Reduced response to PE (perceptions/beliefs not based on external stimuli (hallucinations and delusions))

Table 1. Predictive Coding and Positive Symptoms: Theory and Controversy

Symptom	Feature	Theory	Literature	Controversy
Hallucinations	Percepts without external stimulus	Strong perceptual priors	Powers *et al.* (120)	Entails weak and strong prior beliefs—for perception and action—in the same brain at the same time
	Speech from external agents	Weak corollary discharge	Thakkar *et al.* (86)	
Delusions	Delusional mood/aberrant salience	Weak perceptual priors	Corlett *et al.* (121)	Necessitates a transition from weak to strong priors as delusions form, foment, and become ingrained
	Fixed in the face of contradictory evidence	Strong memory reconsolidation/ strong conceptual priors	Corlett *et al.* (103); Schmack *et al.* (72)	

Sterzer, P., Adams, R. A., Fletcher, P., Frith, C., Lawrie, S. M., Muckli, L., Petrovic, P., Uhlhaas, P., Voss, M., & Corlett, P. R. (2018). The Predictive Coding Account of Psychosis. Biological Psychiatry, 84(9), 634–643.

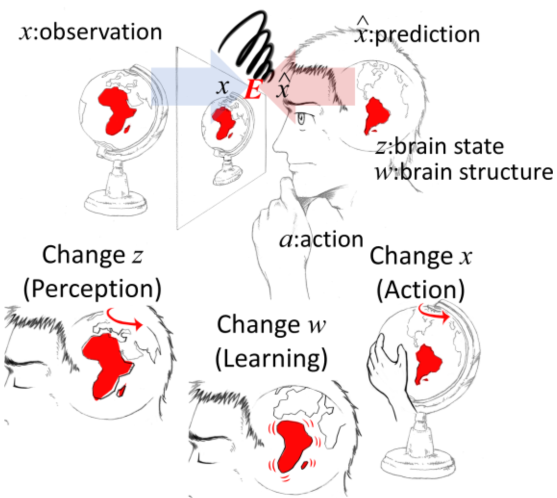
Our perspective

Need for a unified framework that can deal with

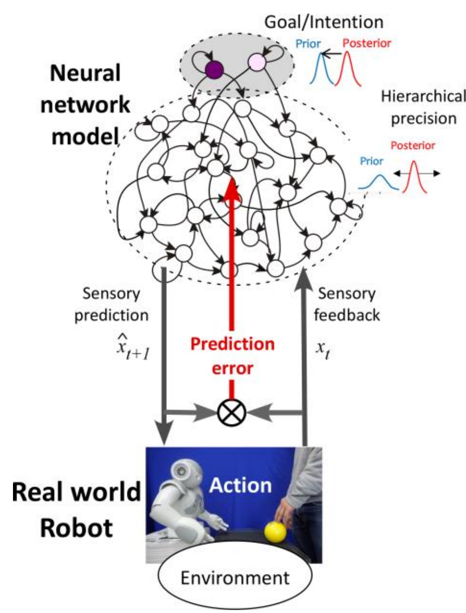
- Developmental *persistent trait* and impact of *episodic change*
- Detailed consideration of hierarchy of precision

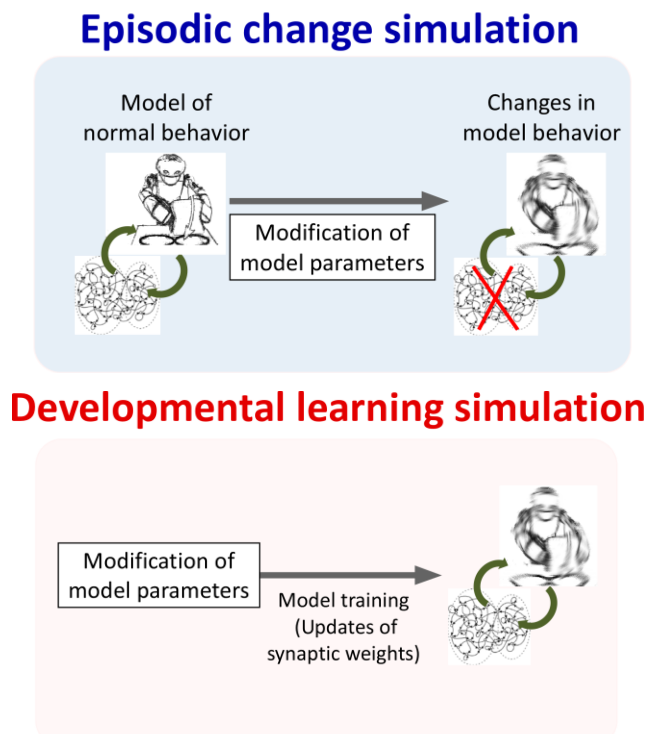
=> Developmental neurorobotics approach!!

Predictive processing theory



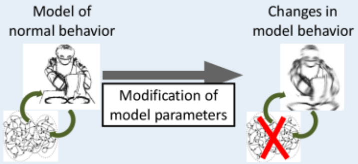
Neurorobotics system with hierarchical neural network



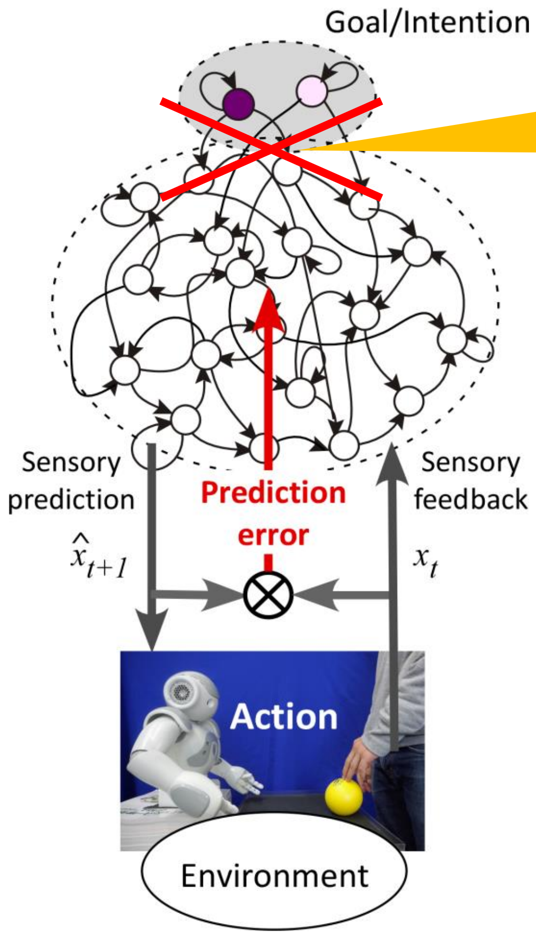


Part1:

Functional disconnection as acute episode (SZ)/inherent characteristics (ASD)



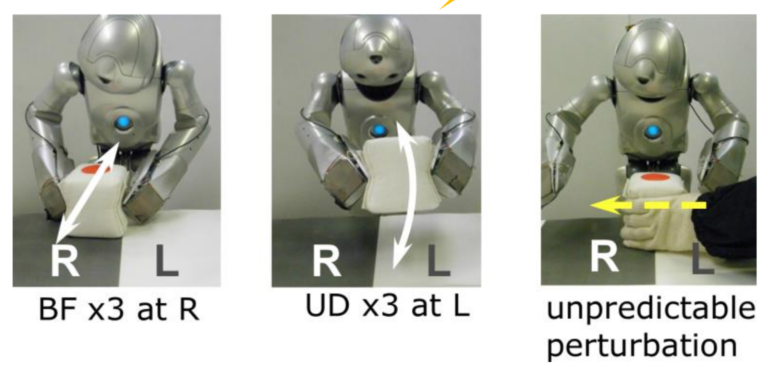
Episodic change simulation (Normal learning => Functional disconnection simulation) [Yamashita2012]



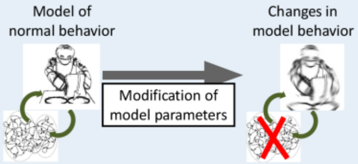
Functional disconnection was applied after normal learning…

$$\mathrm{w}^{\mathrm{dis}} = \mathrm{w} + \mathrm{U}(|\mathrm{K}\mathrm{w}|)$$

Task that requires switching actions depending on the situation



Yamashita Y, Tani J (2012) Spontaneous Prediction Error Generation in Schizophrenia. PLoS ONE 7(5): e37843.

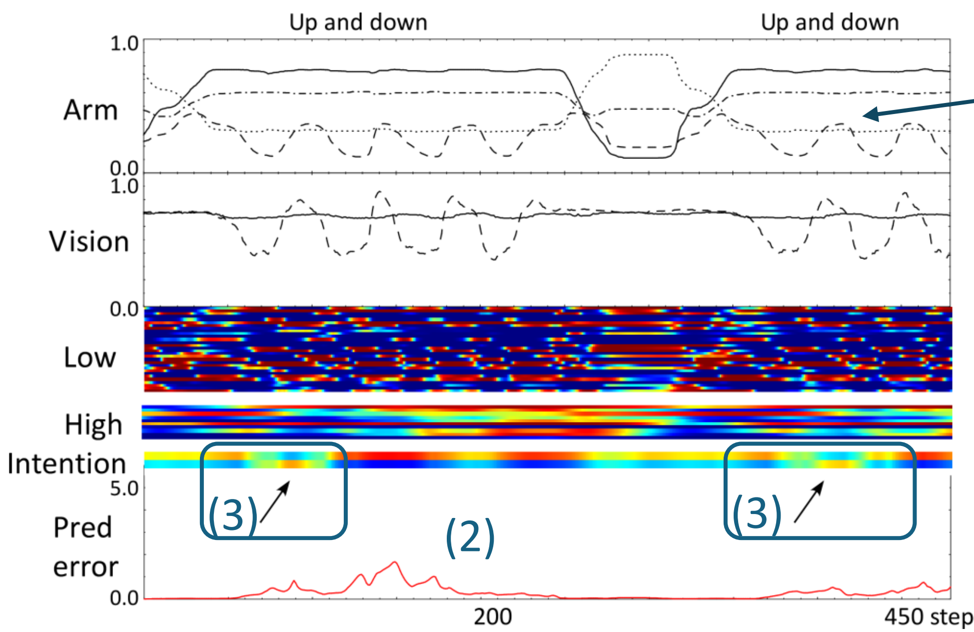


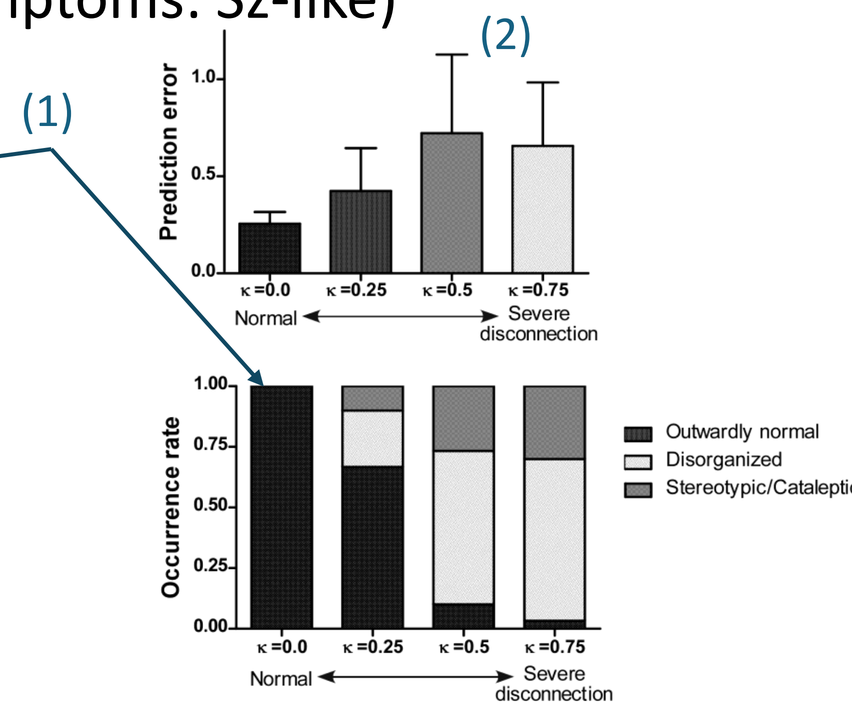
Episodic change simulation (Normal learning => Functional disconnection simulation) [Yamashita2012]

Functional disconnection after normal learning can induce

- Seemingly normal behavior (1)
- Spontaneous prediction error generation (2)
- Aberrant higher-level modulation (3)

=>Miss-attribution of behavioral intention?
(delusion of control/passivity symptoms: Sz-like)





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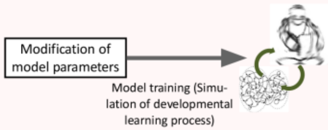
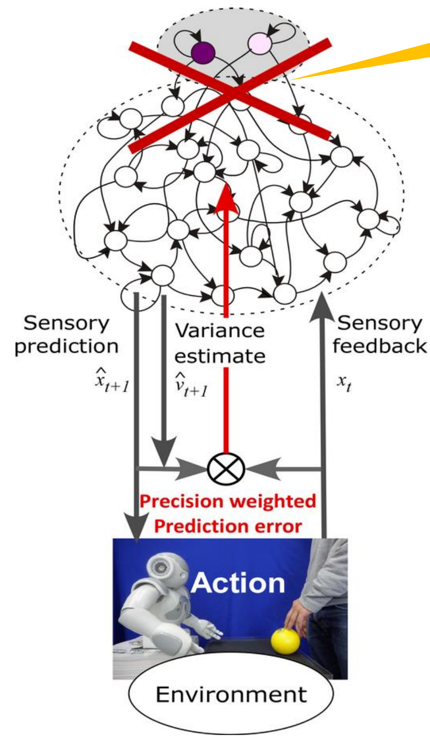
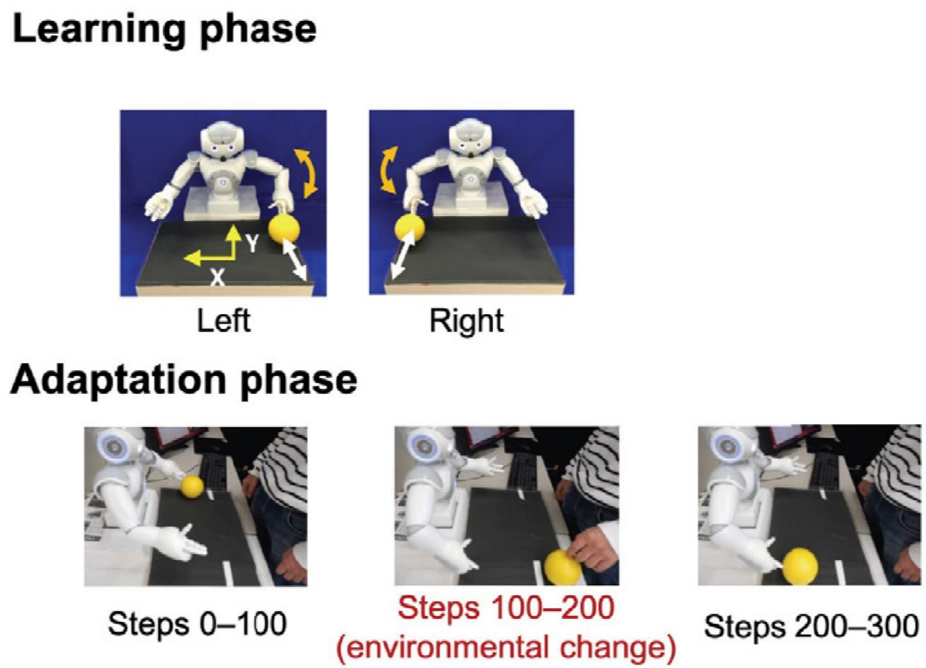
Developmental learning simulation (Functional disconnection simulation => Network Learning) [Idei2021]



$$\mathrm{w}^{\mathrm{dis}} = \mathrm{w} + \mathrm{U}(|\mathrm{K}\mathrm{w}|)$$

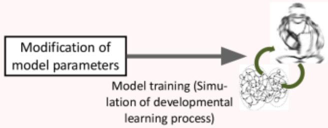
Functional disconnection was applied during developmental learning...





$$L_{\text{out}} = \prod_{s \in I_S} \prod_{t=1}^{T^{(s)}} \prod_{i \in I_O} \frac{1}{\sqrt{2\pi v_{t,i}^{(s)}}} \exp\left(-\frac{(y_{t,i}^{(s)} - \hat{y}_{t,i}^{(s)})^2}{2 v_{t,i}^{(s)}} \right)$$

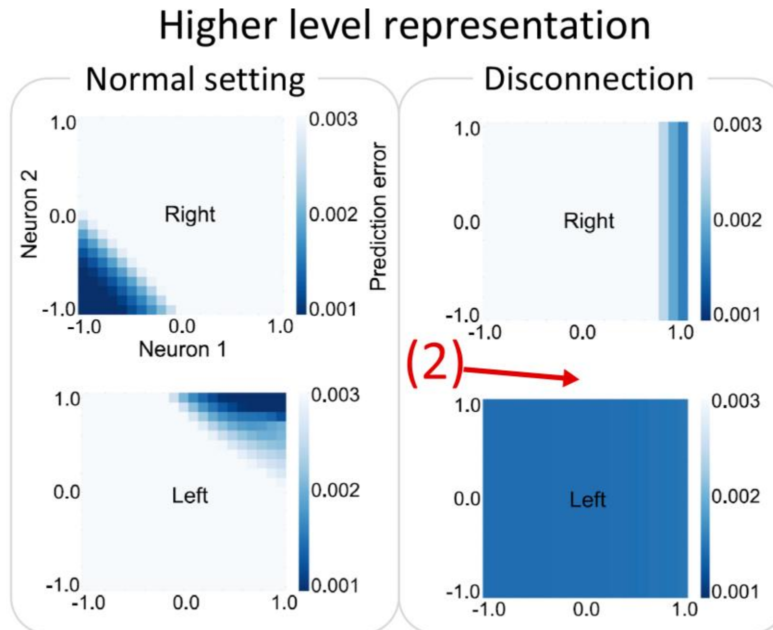
Idei H, Murata S, Yamashita Y, Ogata T (2021) Paradoxical sensory reactivity induced by functional disconnection in a robot model of neurodevelopmental disorder. Neural Networks 138, 150-163.

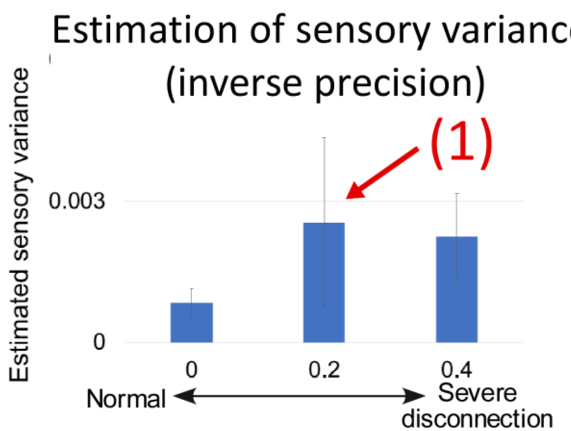


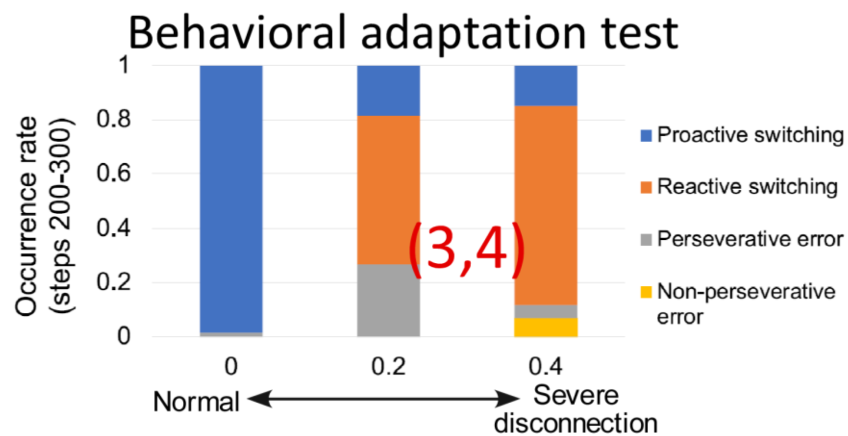
Developmental learning simulation (Functional disconnection simulation => Network Learning) [Idei2021]

Development under functional disconnection leads to ASD-like features including...

- Reduced estimation of sensory precision (1)
- Reduced precision (vague behavioral representation) at higher levels (2)
- Coexistence of hyper- and hypo-reactivities to sensations (3)
- Reduced flexibility of behavior (4)







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Part2

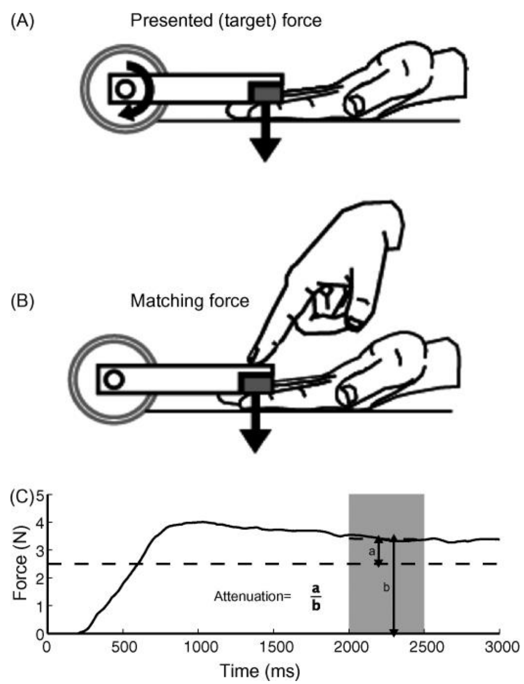
Hierarchy of precision and traits for SZ and ASD

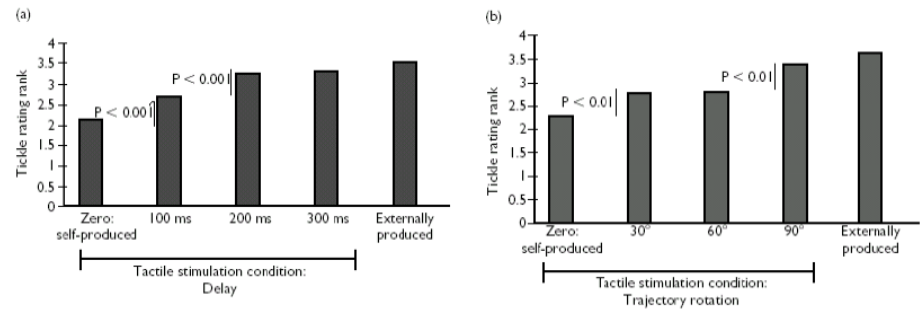
Sensory attenuation (SA)

- Phenomenon in which the level of perception/neural activity is diminished when generated by oneself, compared to that generated externally.

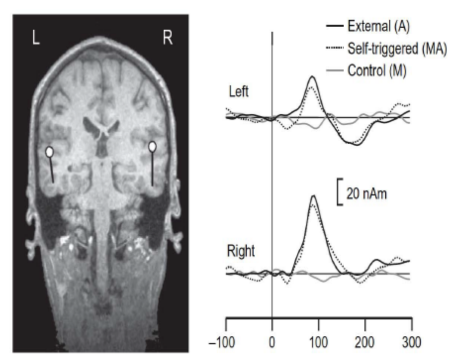
Ex) Force matching, tickling, self-generated voice

- Reduced SA in SZ
- Intact SA in ASD

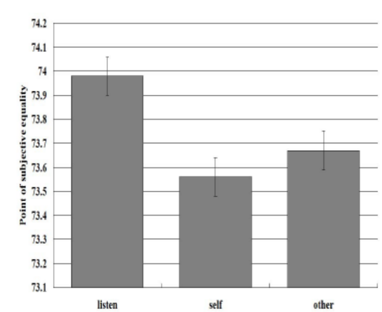




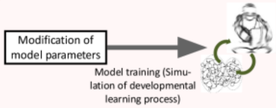
Blakemore et al., 1999, J Cogn Neurosci.



Martikainen et al., 2004, Cereb Cortex



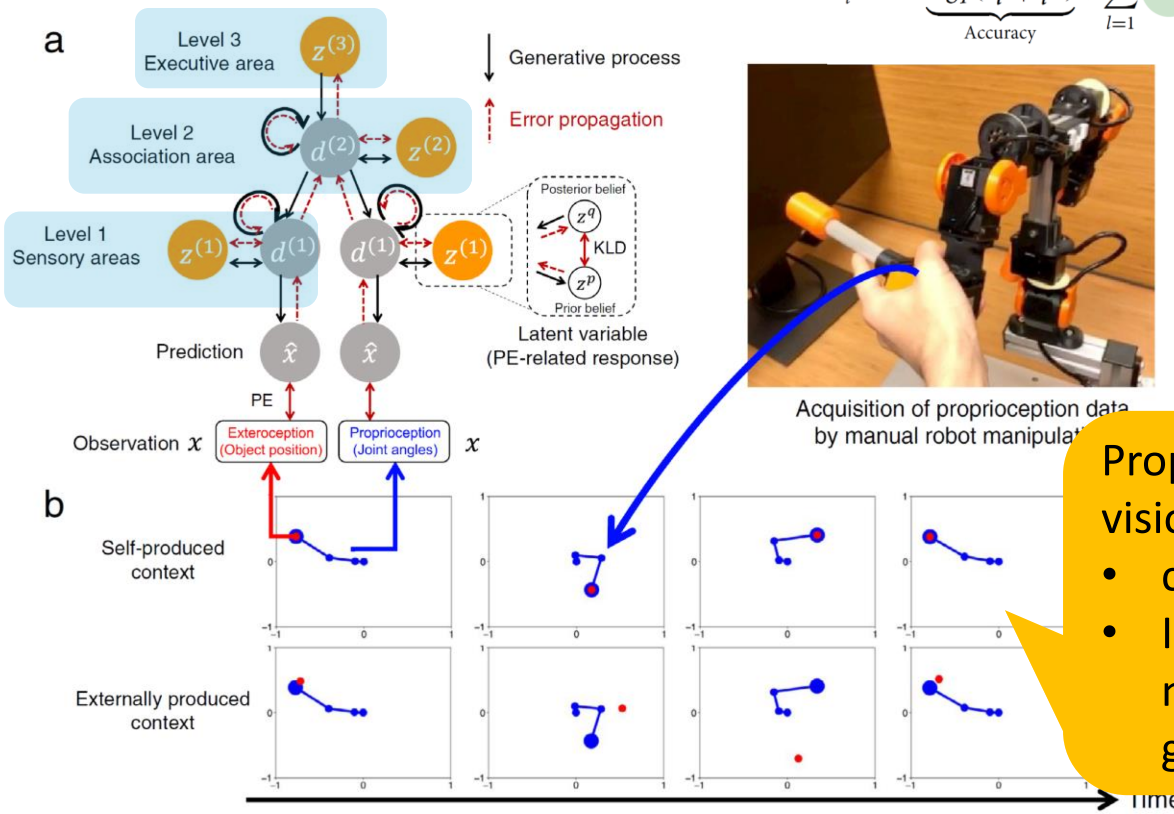
Sato, 2008, Conscious Cogn.



Developmental learning simulation (Modulate intrinsic relative impact of prior between hierarchy =>Traits in cognition and sensory attenuation) [Idei2022, Idei2023]

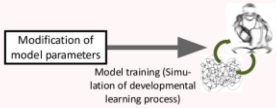
- Free energy (FE) minimization model with hierarchical latent state precisions
- Self/non-self action generation conditions

$$F_t^{(s)} = -\underbrace{\log p(\boldsymbol{x}_t^{(s)}|\boldsymbol{d}_t^{(s)})}_{\text{Accuracy}} + \sum_{l=1}^{3} W^{(l)} \underbrace{\left(D_{KL}[q(\boldsymbol{z}_t^{(l),(s)}|\boldsymbol{e}_{t:T}^{(s)})||p(\boldsymbol{z}_t^{(l),(s)}|\boldsymbol{d}_{t-1}^{(l),(s)})]\right)}_{\text{Complexity}}$$



Proprioception & vision are
- consistent => self
- Inconsistent => non-self (externally generated)

Idei H, Ohata W, Yamashita Y, Ogata T, Tani J (2022) Emergence of sensory attenuation based upon the free-energy principle. Sci Rep 12, 14542.
Idei H, and Yamashita Y (2023) Elucidating Multifinal and Equifinal Pathways to Developmental Disorders by Constructing Real-world Neurorobotic Models. Neural Networks (in press)



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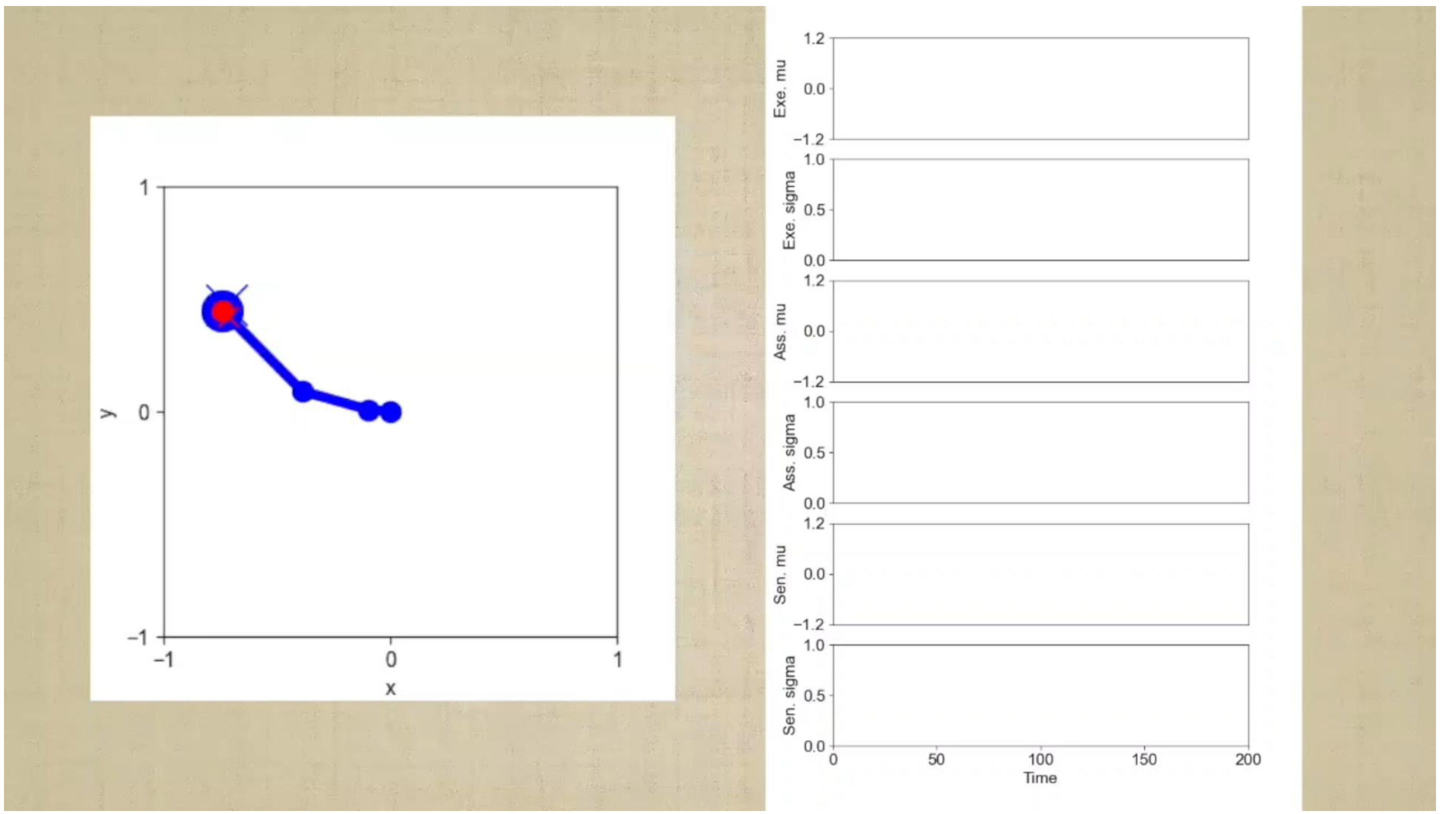

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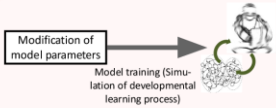
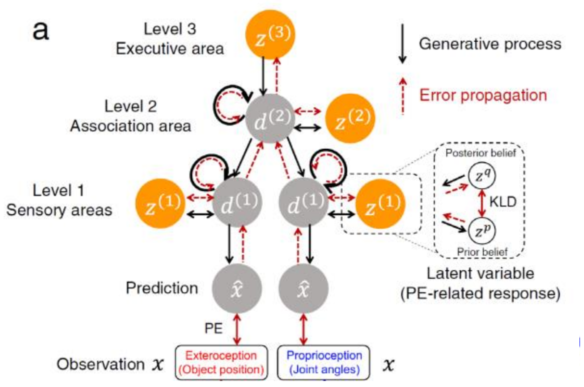
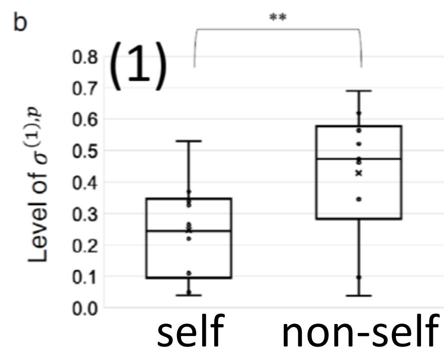


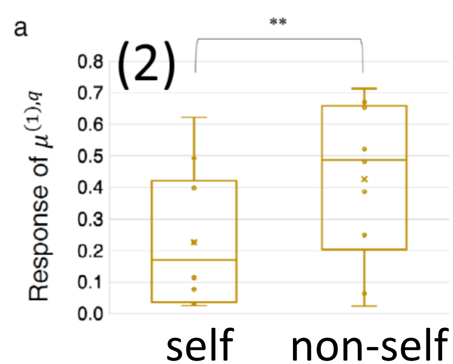
Developmental learning simulation (Modulate intrinsic relative impact of prior between hierarchy =>Traits in cognition and sensory attenuation) [Idei2022, Idei2023]

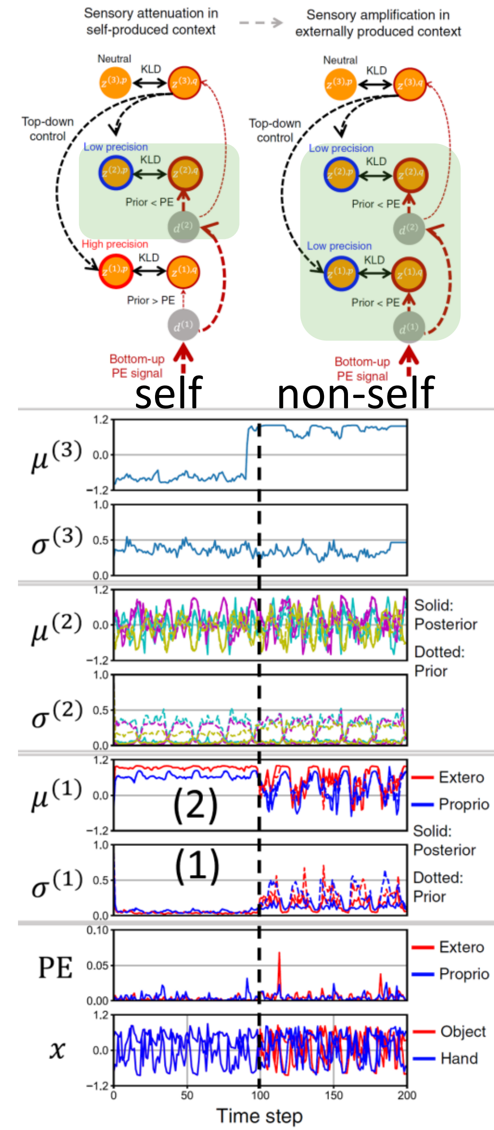
Through the experience of self/non-self conditions

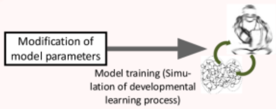
- Self-organized temporally dynamic changes in precisions of latent states (1)
- Emergence of "sensory attenuation (SA)" phenomenon (2)











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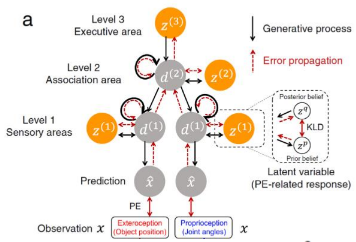

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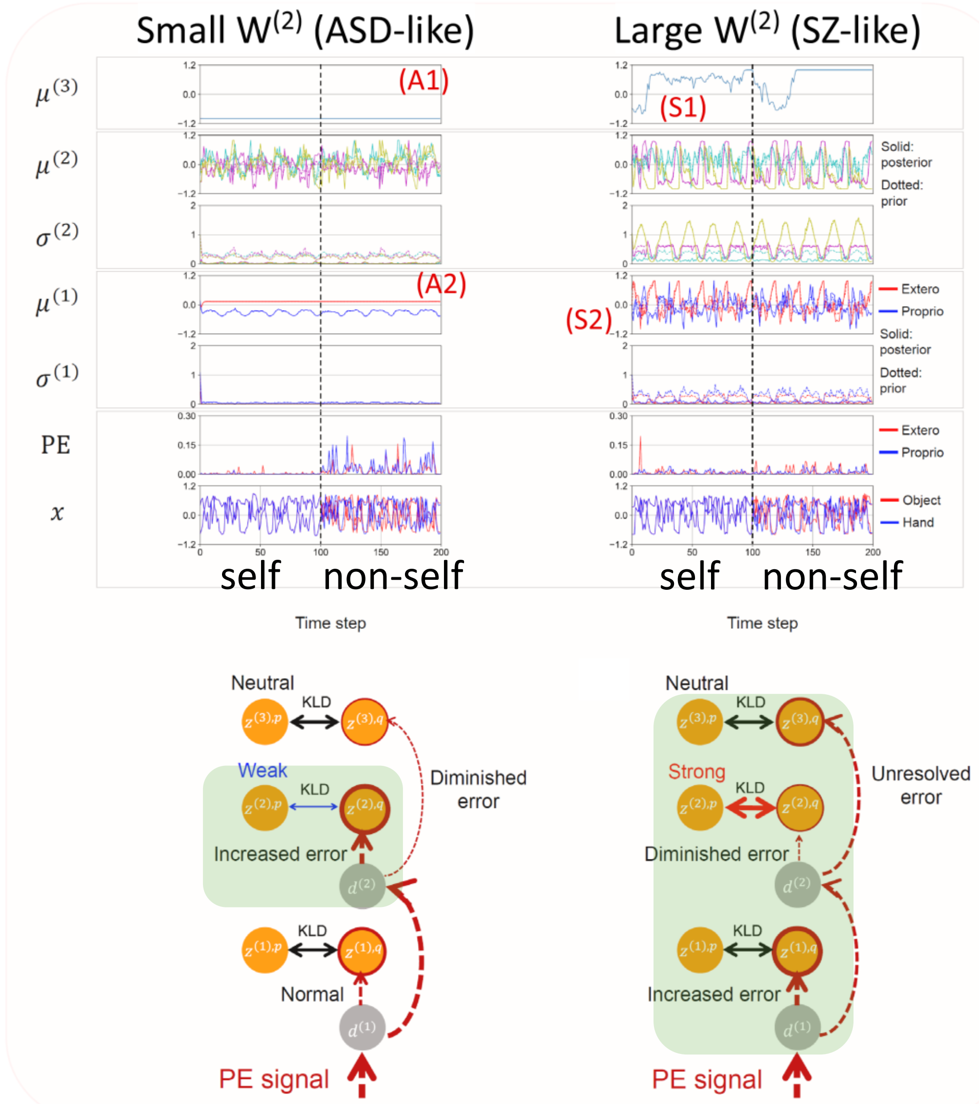
Difference in the "intrinsic" relative influences of prior between hierarchies (W-value) results in SZ-like and ASD-like phenotype including...

- Weak associative level prior

=> Over-fitting, reduced flexibility(A1), intact SA(A2) (ASD-like)

- Strong associative level prior

=> Spontaneous recognition switch(S1), reduced SA(S2) (SZ-like)



Take-home messages

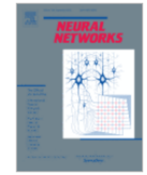
- Functional disconnection in hierarchical predictive processing system can result in distinct symptom formations of SZ and ASD.
- By considering detailed hierarchical and developmental learning aspects, distinct sets of primary and secondary alterations of hierarchical precision estimation might capture differences between SZ and ASD.
- Developmental neurorobotics approaches may serve as a complementary research framework for computational psychiatry with the predictive processing theory.

ELSEVIER

Neural Networks

Available online 6 October 2023

In Press, Journal Pre-proof What's this?



Elucidating multifinal and equifinal pathways to developmental disorders by constructing real-world neurorobotic models

Hayato Idei, Yuichi Yamashita

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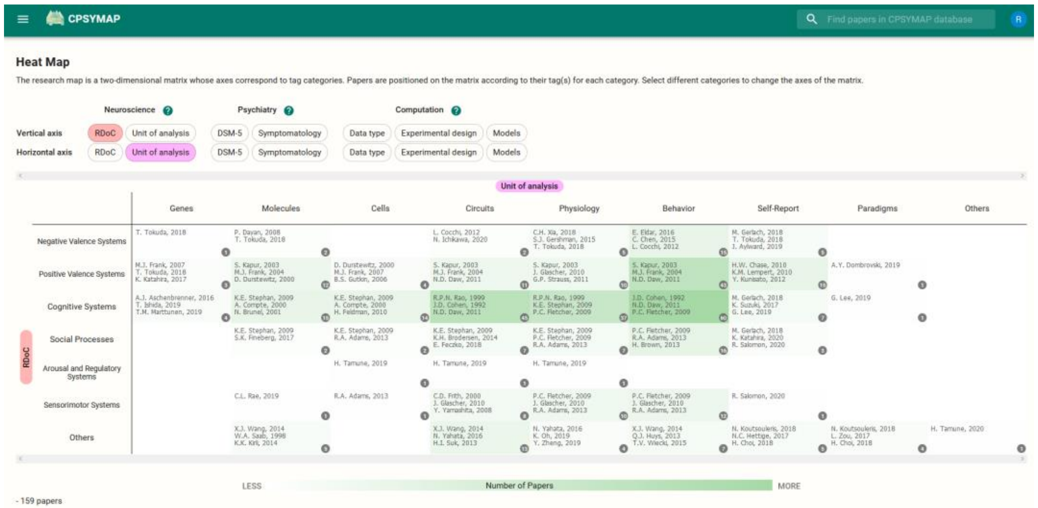
Computational Psychiatry Research Map (CPSYMAP)



https://ncnp-cpsy-rmap.web.app/

Collaborators

- Jun Tani (OIST)
- Tetsuya Ogata (Waseda Univ.)
- Shingo Murata (Keio Univ.)
- Hayato Idei (NCNP)

We are looking for researchers, research associates, and students who are interested in computational psychiatry!

Contact: yamay@ncnp.go.jp

Grants: JSPS KAKENHI (JP20H00625,JP24H00076, JP24K00499)
JST CREST (JPMJCR21P4), JST Moonshot R&D (JPMJMS2031)
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