Tutorial in IEEE ICDL-2024
Typical and Atypical Development of Neurorobots Based on Free Energy Principle

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***Abstract*— The current tutorial seeks to deepen understanding of how predictive and reflective minds can develop based on the free energy principle (FEP) by taking neurorobotics modeling approach. Especially, the tutorial examines both cases of normal development and abnormal one which is caused by psychiatric disorders such as schizophrenia (SZ) and autism spectrum disorders (ASD). The tutorial begins with an intuitive explanation of FEP, followed by introduction of two essential frameworks derived from FEP, predictive coding (PC) which accounts for perception, and active inference (AiF) for action generation. Thereafter, we explain how these frameworks can be implemented in various types of Bayesian neural networks models with focusing on "typical development of competencies for hierarchical prediction and inference with precision (Bayesian belief) at each level. Next, we introduce a recent approach, so-called computational psychiatry which aims to gain theoretical understanding of developmental disorder mechanisms. We look at computational models for developmental disorders using FEP wherein we elaborate on how malfunctions in hierarchical prediction/inference due to altered belief update could lead to development of SZ and ASD. We introduce a series of neurorobotics studies using the models to showcase some emergent phenomena which have been observed both in typical and atypical development in the embodied experiments.**

***Index Terms*— Free energy principle, Predictive coding, Active inference, Developmental disorder, Neurorobotics**

I. Introduction

This tutorial provides basic ideas on how to apply the free energy principle (FEP) [1] to develop cognitive mechanisms in robots. It is thought that the cognitive mind comprises emergent phenomena, which appear via intricate and often conflictive interactions between top-down intention for acting on the external world and bottom-up inference of the resultant sensory reality [2]. It is presumed that skills for generating complex actions, knowledge, and concepts to represent the world can develop naturally by allowing entangling interactions between these two processes of predicting the future and reflecting the past. This thought can be evaluated by conducting synthetic neurorobotics experiments using predictive coding (PC) [3] and active inference (AiF) [1] based on FEP. This is because the dense interaction between the top-down and the bottom-up processes can be effectively carried out by coupling AiF for action generation and PC for perception in which cognitive processes of prediction, action generation, perceptual inference, and learning can be performed rationally under a unified principle of free energy minimization.

We consider that if the proposed neurorobotics models represent typical cognitive development of humans, certain types of limited alternation to the models should be able to reconfigure atypical development. Indeed, attempts to clarify the pathology of neurodevelopmental disorders such as schizophrenia (SZ) and autism spectrum disorder (ASD) in terms of computational models of the brain have formed the emerging field of "computational psychiatry in recent years [9]. In this tutorial, we will discuss what kind of changes in the model cause these mental disorders from the viewpoint of computational psychiatry.

The tutorial starts with an intuitive explanation of FEP using minimal mathematical description. This includes explanations of how FEP corresponds to empirical findings in cognitive neuroscience. We also explain why this principle is expected to gain understanding of developmental disorder mechanisms [9] while providing a brief introduction of symptoms of ASD and SZ. Then, a basic mathematical description of FEP is provided wherein we explain how PC for perception and AiF for action generation can be formulated by extending Bayesian statistics. Especially, we explain how prior probability distribution and an approximation of posterior probability distribution can be obtained being incorporated with precision or Bayesian belief.

Then, we introduce a hierarchically organized Bayesian recurrent neural network (RNN) model [4] which implements the frameworks of PC and AiF. Simple simulation examples using this model illustrate how the prior, posterior, and their precision structure can be self-organized in the model hierarchy through the course of free energy minimization during learning and inference. We also show that self-organization of such properties depends on a few dimensions of meta-parameters set in the model as well as the statistical characteristics of the observed data (i.e., target sensory sequences for learning or inference) given.

Next, we introduce a series of neurorobotics experiments using Bayesian RNN models which aim to reconstruct both typical and atypical development of cognitive and sensorimotor competency. These robotic experiments were conducted under various task contexts including goal-directed object manipulation by an individual robot, huma-robot as well as dyadic robot imitative interactions, and dyadic robot interaction for object manipulation. These neurorobotic experiments aim to reconstruct both typical and atypical development of cognitive and sensorimotor competency.

First, we review typical development cases generated by setting diverse types of meta-parameters in the models in adequate ranges. These meta-parameters include the number of neurons, amount of connectivity, timescale in neural activation dynamics, and those regulating the precision structure. Some studies [4,5] show that compositional goal-directed actions can be learned through self-organization of functional hierarchy wherein a set of sensorimotor primitives is developed in the lower level while an abstract representation for sequencing of them is developed in the higher level. Successful developments of the functional hierarchy depend on setting of timescale at each level. Another study [4,6] shows that a balance between the strength in top-down actional intention and bottom-up sensory affordance can be arbitrated by setting of meta-parameters regulating the precision structure developed in the Bayesian RNN. We demonstrate that robust and flexible object manipulation can be performed by setting this meta-parameter in an adequate range. Other studies [7,8] show that a leader-follower relationship and its turn-taking in imitative interaction emerge with adequate setting of this meta-parameter.

Second, we show that neurorobotics experiments with alternation in diverse dimensions of meta-parameters can successfully simulate formations of wide range symptoms in SZ and ASD with the integration of causal relationships among neural, computational, and behavioral characteristics. For example, we demonstrate that the manipulation of meta-parameters in developmental learning process can induce cognitive and behavioral phenotypes reminiscent of developmental disorders such as ASD. Specifically, this manipulation leads to changes in the acquisition of hierarchical neural representations and results in diminished cognitive flexibility [10]. In addition, by considering detailed hierarchical and developmental learning aspects, we show that distinct sets of primary and secondary alterations of hierarchical precision estimation could capture differences between SZ and ASD [11, 12].

The final session is devoted to open discussion on this topic with participants.

II. Contents

The tutorial is provided as a half day lecture course. Contents are as itemized here.

1 Introduction of FEP
- 1.1 Intuitive explanation of FEP related to cognitive neuroscience and developmental disorder. (Yamashita)
- 1.2 Mathematical formulation of FEP, PC, and AiF (Tani)

2 Introduction of Bayesian RNN models based on FEP (Tani)
- 2.1 Basic architecture and mechanisms
- 2.2 Mathematical and numerical characteristics

3 Typical development of neurorobots (Tani)
- 3.1 Development of compositionality and hierarchy
- 3.2 Arbitrating top-down and bottom-up processes by regulating precision structure in goal-directed object manipulation tasks
- 3.3 The same as above in social interaction tasks

4 Atypical development of neurorobots (Yamashita)
- 4.1 Altered hierarchical representation and behavioral inflexibility in ASD
- 4.2 Hierarchy of precisions and traits for SZ and ASD

5 Open discussion with participants

III. Target audience

Participants may be graduate students or researchers from various backgrounds including robotics, neural network modeling, neuroscience, machine learning, developmental psychology, and philosophy of minds.

IV. Lecturer

The tutorial lecture will be given by Prof. Jun Tani and Dr. Yuichi Yamashita. JunTani is the director of Cognitive Neurorobotics, Okinawa Institute of Science and Technology in Japan. Jun Tani has studied cognitive neurorobotics using PC and AiF frameworks more than 25 years. He summarized his research results in a book [2]. Yuichi Yamashita is the Section Chief at the Department of Information Medicine, National Center of Neurology and Psychiatry. As a clinical psychiatrist, he has dedicated over 15 years to studying computational psychiatry, employing PC and AiF frameworks.

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