Rationalizing sensorimotor deficits in autism spectrum disorder during spatial navigation

Yizhou Chen(yizhouc3@andrew.cmu.edu)
Neuroscience Institute, Carnegie mellon university, 4400 Fifth Avenue
Pittsburgh, PA 15213

Jean-Paul Noel (jeanpaulnc@gmail.com)
Center for Neural Science, New York University
New York, NY 10003 USA

Ruiyi Zhang (rz31@nyu.edu)
Tandon School of Engineering, New York University
Brooklyn, NY 11201 USA

Dora E Angelaki (da93@nyu.edu)
Center for Neural Science & Tandon School of Engineering, New York University
New York, NY 10003 USA

Xaq Pitkow (xaq@cmu.edu)
Neuroscience Institute, Carnegie mellon university, 4400 Fifth Avenue
Pittsburgh, PA 15213

Abstract

To perform well in natural environment or a task, subjects need to maintain and update beliefs about relevant latent variables. Understanding how subjects update beliefs during tasks is important, and we need a tool to measure such beliefs. Previous methods for inferring beliefs often rely on the assumption of optimal behavior, ignoring the fact that most of behavior are rational rather than optimal. Inverse Rational Control (IRC) is a novel framework to infer subjects' beliefs from behavior. We applied it for the first time to real experimental data to analyze sensorimotor anomalies in Autism Spectrum Disorder (ASD) during spatial navigation. Subjects navigated using a joystick toward transiently visible targets guided by optic flow cues. Subjects' beliefs about target locations with uncertainty and subjective task costs, were inferred using IRC. Analysis of behavioral trajectories revealed reduced angular velocity estimates and lower subjective action costs in individuals with ASD. This approach enables rich characterization of latent dynamics in behavior, advancing neuroscience's understanding of neural computation in perception, prediction, and planning.

Keywords: Spatial navigation; Autism spectrum disorder; Inverse Rational Control; Reinforcement learning.

Background

To perform optimally in tasks, subjects must continually update their beliefs regarding relevant latent variables. Understanding the intricate mechanism of cognition and belief update requires inferring these beliefs from subject behavior. Inverse Rational Control (IRC) is a new theoretical framework to infer subjects' beliefs about the world from their behavior(Kwon, Daptardar, Schrater, & Pitkow, 2020; Wu, Kwon, Daptardar, Schrater, & Pitkow, 2020). Here we apply IRC for the first time to real experimental data and use it to interpret sensorimotor anomalies present in individuals with Autism Spectrum Disorder (ASD) during a spatial navigation task.

In this task, subjects navigate to a transiently visible target using optic flow cues. They need to maintain and update a posterior distribution over the latent target location, which we define as beliefs. These beliefs represent the subject's estimated target location with uncertainty and subjective reward and cost of the task. Previous methods of inferring beliefs are often built upon the assumption that subjects are near-optimal, so their predictions will be falsified if the subject is sub-optimal. IRC does not assume agents are optimal, but rational — attempting to maximize subjective reward according to their (perhaps erroneous) internal model of the task. Here, we assumse subject has a cognitive model of latent dynamics parameterized by his/her hidden assumptions and subjective preference, and obtained the rational policy by reinforcement learning. Via model fitting of the subjects behavioral trajectories, we inferred their internal models that can reproduce the observed behavior. Analysis of the best-fitting model revealed that individuals with ASD demonstrated reduced estimates of angular velocity and lower subjective action costs. Our results demonstrate the utility of our approach for richly characterizing latent dynamics underlying behavior, and will thereby help advance the neuroscience community's understanding of neural computations involved in perception, prediction, and planning.

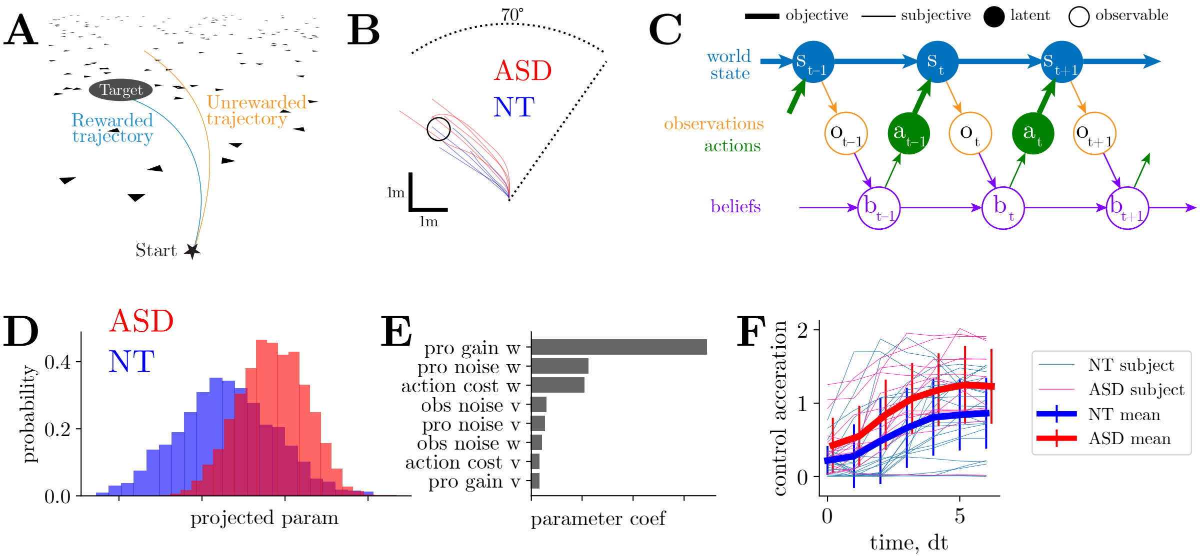

Figure 1: **IRC explains the Autism Spectrum Disorder(ASD) cognition during navigation.** **A**. Subject's view of the task. **B**. Overhead view of the task. ASD paths have more exaggerated curvatures. Circle: target. Line: subject paths. **C**. The Partially Observable Markov Decision Process model. **D**. Support Vector Machine separates ASD from NT using the inferred parameters. **E**. Contribution of each parameter in describing the ASD abnormalities. **F**. ASD subjects prefer to accelerate faster when trials begin. Error bar: standard deviation.

Results

Subjects with ASD (n = 14) and the neurotypical cohort (NT, n = 25) were tasked for spatial navigation in virtual reality (Figure 1A). Subjects used a 2D joystick to control their virtual velocity to move in the environment and stop at the firefly location (Figure 1B). The environment was devoid of landmarks and instead was composed solely of ground plane textural elements with a limited lifetime to provide an optic flow velocity signal. The subjects had to continuously integrate their velocity cues to estimate their own position.

We modeled the task as a Partially Observable Markov Decision Process (Figure 1C). The world state s_t changes according to the stochastic nonlinear discrete-time dynamics $s_{t+1} = f(s_t, a_t, \text{noise})$, where a_t denotes the action chosen by the agent and f specifies the stochastic nonlinear dynamics. The model agent's actions are drawn from a policy $\pi(a_t|b_t)$ based on a belief b_t about the world. This belief summarizes the posterior over the world state s_t given observations $o_{0:t}$ and actions $a_{0:t-1}$.

Instead of assuming the subjects behave optimally, we hypothesized that they act rationally, based on their own possibly mistaken internal model of the task and maximizing their subjective reward. To account for the rational but sub-optimal behavior, we used reinforcement learning to derive a rational solution family of all possible task assumptions and subjective preferences. Then, we identify which model within the solution family best explains the experimentally measured behaviors.

In this specific case, the parameters we chose to include in our model are: 1) the control gains and associated noises, 2) the observation noises of the optic flow, 3) the initial observation uncertainty, and 4) the costs of moving the joystick Each of these elements had a parameter for both radial and angular dimensions.

We applied IRC to the subjects' data to infer their internal models. The fitted models successfully reproduced ASD and NT subjects' behavior. For any single parameter, the differences between the ASD group and NT group are subtle, and are small compared to the uncertainties on those individual parameters. However, when taking the correlated *joint* uncertainty among the parameters into account, we could better separate the two groups. For visualization, we projected the ASD and NT parameters onto the most separable axis solved by linear Support Vector Machine (SVM) as shown in Figure 1B. The weights of each parameter in the projection represent the relative contribution in dissociating between ASD and NT participants (Figure 1D). The parameter most heavily contributing to dissociating ASD from NT subjects is the subjective angular control gain, which defined how action is transformed into self-rotation. A few other notable parameters are the angular process noise (the noise associated with the angular gain) and the angular action cost. The combination of these parameters explains the paths taken by subjects with ASD, which had more exaggerated curvatures compared to NT subjects when navigating to the same target location (Figure 1E), and faster acceleration when trials begin (Figure 1F).

In summary, IRC was able to highlight structure in the set of parameters defining the internal model of individuals with ASD that was dissimilar from that of NT subjects. Our results suggested that participants with ASD perceived rotational velocity differently from NT subjects and had a different motor control preference. With an inferred model, we can reconstruct subjects' beliefs over time, which can then serve as novel targets for studying neural representations. Our results demonstrate the utility of the IRC approach for richly characterizing latent dynamics underlying behavior, and will thereby help advance the neuroscience community's understanding of neural computation involved in perception, prediction, and planning.

References

Kwon, M., Daptardar, S., Schrater, P. R., & Pitkow, Z. (2020). Inverse rational control with partially observable continuous nonlinear dynamics. *Advances in Neural Information Processing Systems*, *33*.

Wu, Z., Kwon, M., Daptardar, S., Schrater, P., & Pitkow, X. (2020). Rational thoughts in neural codes. *Proceedings of the National Academy of Sciences*, *117*(47), 29311–29320. doi: 10.1073/pnas.1912336117