# Research team builds framework to quantify brain's control costs

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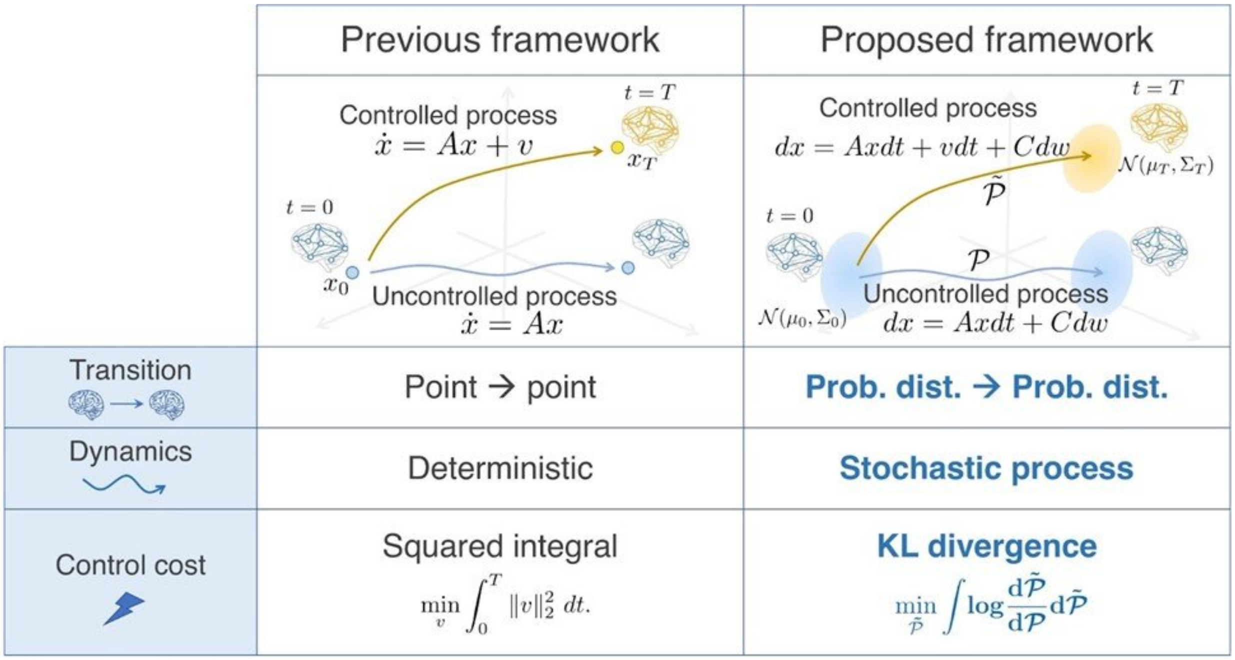


| | Previous framework | Proposed framework |
|---|---|---|
| Transition | Point → point | **Prob. dist. → Prob. dist.** |
| Dynamics | Deterministic | **Stochastic process** |
| Control cost | Squared integral<br>$\min_{v} \int_0^T \lVert v \rVert_2^2 \, dt.$ | **KL divergence**<br>$\min_{\tilde{\mathcal{P}}} \int \log \frac{d\tilde{\mathcal{P}}}{d\mathcal{P}} d\tilde{\mathcal{P}}$ |

The previous framework (left) fails to take into account noises of the brain. The brain state transitions were written as point-to-point, the dynamics as deterministic, and the control cost as the integral of the squared control input. In the current framework (right), the research team introduced a stochastic model, in which brain state transitions were considered as probability distribution to probability distribution, dynamics as stochastic process, and the control cost as KL divergence. Credit: Shunsuke Kamiya, The University of Tokyo

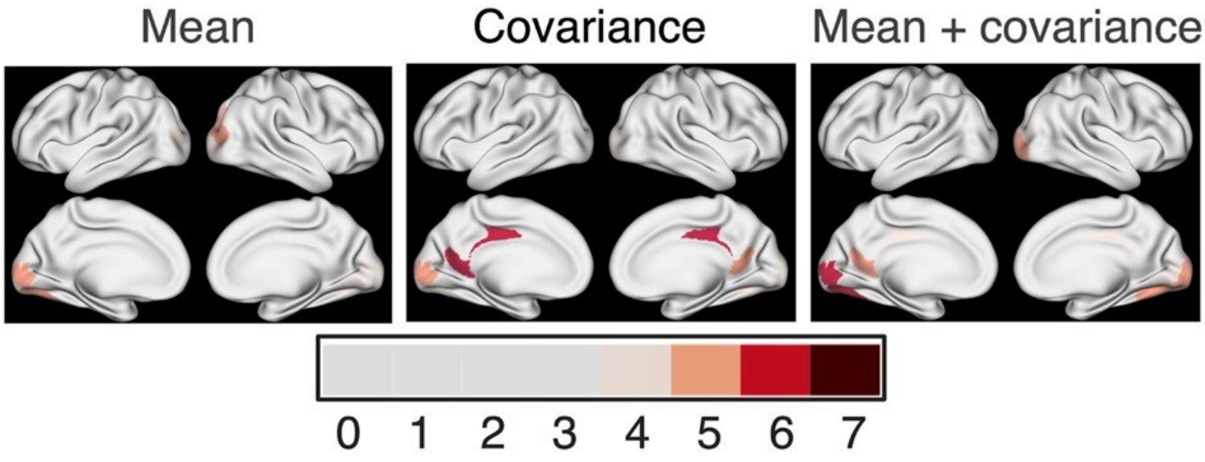
The brain performs various cognitive and behavioral functions in everyday life, flexibly transitioning to various states to carry out these functions. Scientists view the brain as a system that performs these numerous functions by controlling its states.

To better understand the properties of this control in the brain, scientists look for ways to estimate the difficulty of control, or control cost, when the brain transitions from one state to another. So a team of researchers undertook a study to quantify such control costs in the brain, and was successful in building a framework that evaluates these costs.

Controlling transitions to some states incurs greater "costs" than controlling transitions to others. With the development of a framework for quantifying transition costs, scientists will have a way to evaluate the difficulty of the shifts between various brain states. Possibly, they might also have a quantifiable measure for explaining cognitive loads, sleep-wake differences, habituation of cognitive tasks and psychiatric disorders.

The work is published in *The Journal of Neuroscience*.

The team worked to build a novel framework to quantify control cost that takes account of stochasticity, or the randomness, of neural activity. This stochasticity has been ignored in previous studies. The current control paradigm in neuroscience uses a deterministic framework that is unable to consider stochasticity.



One of the merits of the research team's new framework is that it can identify brain regions that play important roles in controlling the mean brain activity and the covariance among brain regions in state transitions. The left and middle panels show areas that contribute to controlling the mean and covariance, respectively. The right panel shows the regions that contribute to control the mean and covariance as a whole. The color of a brain region signifies the number of tasks to which the region contributes to the transition. (As seven tasks are recorded in HCP, the numbers take integer values from 0 to 7.). Credit: Shunsuke Kamiya, The University of Tokyo

But it is well known that the neural dynamics are stochastic and the noise is ubiquitous throughout the whole brain. "In this work, we addressed the issue of stochasticity and first proposed a novel theoretical framework that quantifies the control cost taking account of the stochastic fluctuations of the neural dynamics," said Shunsuke Kamiya, a doctoral student in the Graduate School of Arts and Sciences at the University of Tokyo.

In their study, the researchers established the analytical expression of the stochastic control cost, which enabled them to compute the cost in highdimensional neural data. By the analytical expression, they discovered that the optimal control cost can be decomposed into the costs to control the mean and covariance. "This decomposition enables us to investigate how various brain areas differently contribute to controlling the transitions from one brain state to another," said Kamiya.

The researchers also identified the significant brain regions for the optimal control in cognitive tasks in human whole-brain imaging data. They examined the significant brain regions in the optimal control of transitions from the resting state to seven cognitive task states, using human whole-brain imaging data of 352 healthy adults. They found that, with these different transitions, the lower visual areas commonly played a significant role in controlling the means, while the posterior cingulate cortex commonly played a significant role in controlling the covariances. The posterior cingulate cortex is the upper part of the limbic lobe, that region of the brain that plays an important role in memory and emotional behaviors.

In this study, the team only considered the optimal control cost where brain state transitions are controlled in an optimal manner, with minimization of stochastic control cost. However, in real neural systems, it is not likely that state transitions are controlled in an optimal manner. "An intriguing future direction will be to compare the optimally controlled dynamics and the actual dynamics using neural data during tasks," said Masafumi Oizumi, associate professor in the Graduate School of Arts and Sciences at the University of Tokyo.

Looking ahead to future research, Oizumi explains that the ultimate goal of his lab is to understand the connection between brain dynamics and human behaviors, cognitions and consciousness. "For example, we suspect that the decrease of controllability in the brain dynamics may be related to mental fatigue or the loss of consciousness. We expect that control theoretical perspective will provide a new insight to this goal," said Oizumi.

**More information:** Shunsuke Kamiya et al, Optimal Control Costs of Brain State Transitions in Linear Stochastic Systems, *The Journal of Neuroscience* (2022). [DOI: 10.1523/JNEUROSCI.1053-22.2022](https://doi.org/10.1523/JNEUROSCI.1053-22.2022)

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