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A spiking neural model of strategy shifting in a simple reaction time task

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Trevor Bekolay[1], Benjamine Liu[2], Chris Eliasmith[1], Mark Laubach[3,4]

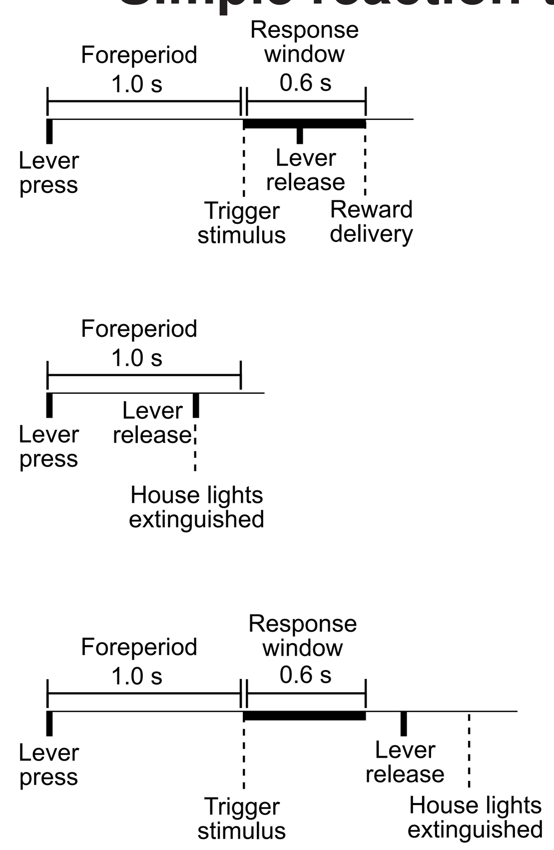
[1]Centre for Theoretical Neuroscience, University of Waterloo, [2]Cambridge Computational Biology Institue, University of Cambridge, [3]The John B. Pierce Lab., [4]Dept. of Neurobiology, Yale Univ. School of Medicine

Abstract

In a simple reaction-time (RT) task with predictable foreperiods, subjects employ two strategies. They either **wait until the cue and then respond**, or they **time the foreperiod and respond when the cue should occur**. Evidence for these performance strategies has been detected in rodents, humans, and other primates. A key brain region for implementing these control strategies is the medial prefrontal cortex (mPFC). Neurons in this brain region show changes in firing rates around the start of trials, or fire persistently during the foreperiod of simple RT tasks, and exert control over the motor system by influencing firing rates in the motor cortex during the foreperiod (Narayanan & Laubach, 2006).

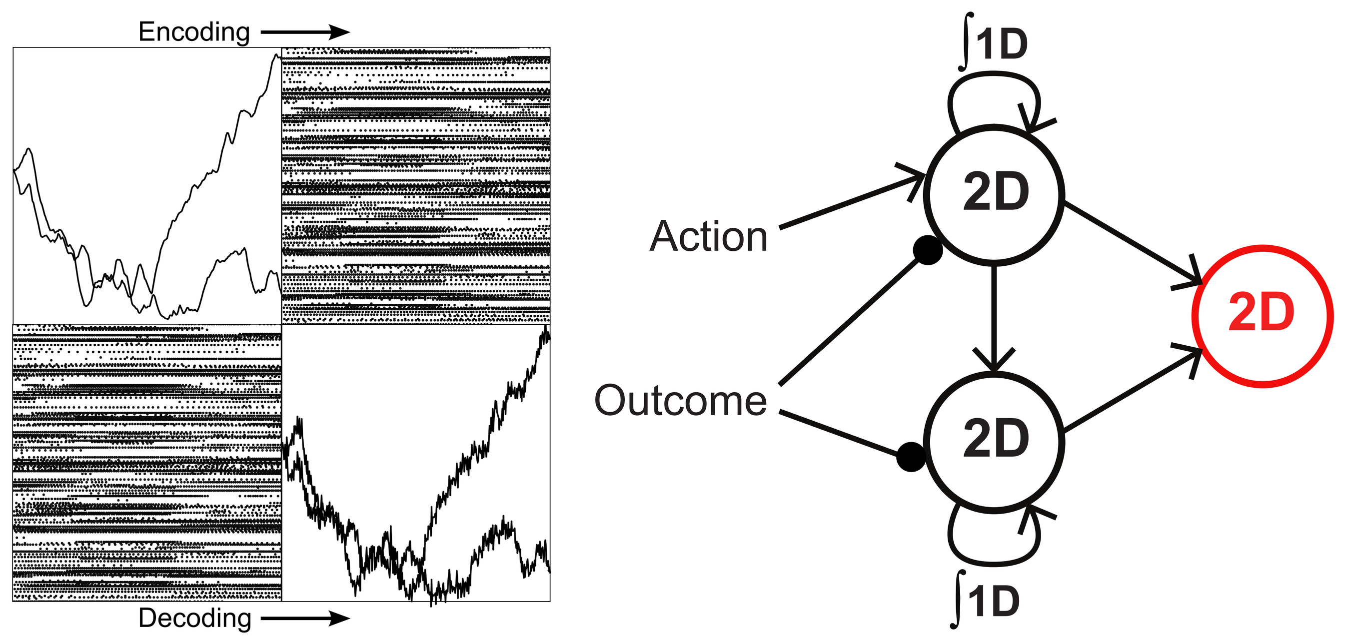
Here, we describe a neural circuit model based on the known neuroanatomy that reproduces the observed activity patterns in rat mPFC and exhibits adjustments in the behavioral strategy based on the subject's recent outcomes. A neural circuit based on Singh and Eliasmith, 2006 tracks the behavioral state and the time elapsed in that state. This circuit serves as a top-down controller acting on a neural control system. When the top-down control is not being exerted, the system waits for the cue and responds at cue onset. When the foreperiod can be timed, top-down control forces a response when the cue is predicted to occur. These adjustments can occur at any time and do not require synaptic weight changes.

Simple reaction-time task



1. Subject presses lever to begin trial.
2. Subject holds down lever for 1 second (*foreperiod*).
3. An audible trigger stimulus occurs, indicating that the lever should be released.
4. Releasing withing 600 ms results in reward delivery.
5. Failing to release, or releasing early, results in a timeout.

Multi-dimensional neural integrators



Principal component analysis on medial PFC activity suggests that neural integration is a key neural mechanism in rodents performing the simple RT task. A double integrator model by Singh & Eliasmith (2006), using the methods of the Neural Engineering Framework (NEF; Eliasmith & Anderson, 2003), was modified such that the "press" action drives the first neural integrator. Critically, we further modify the model such that integration is controlled by the outcome of the current trial.

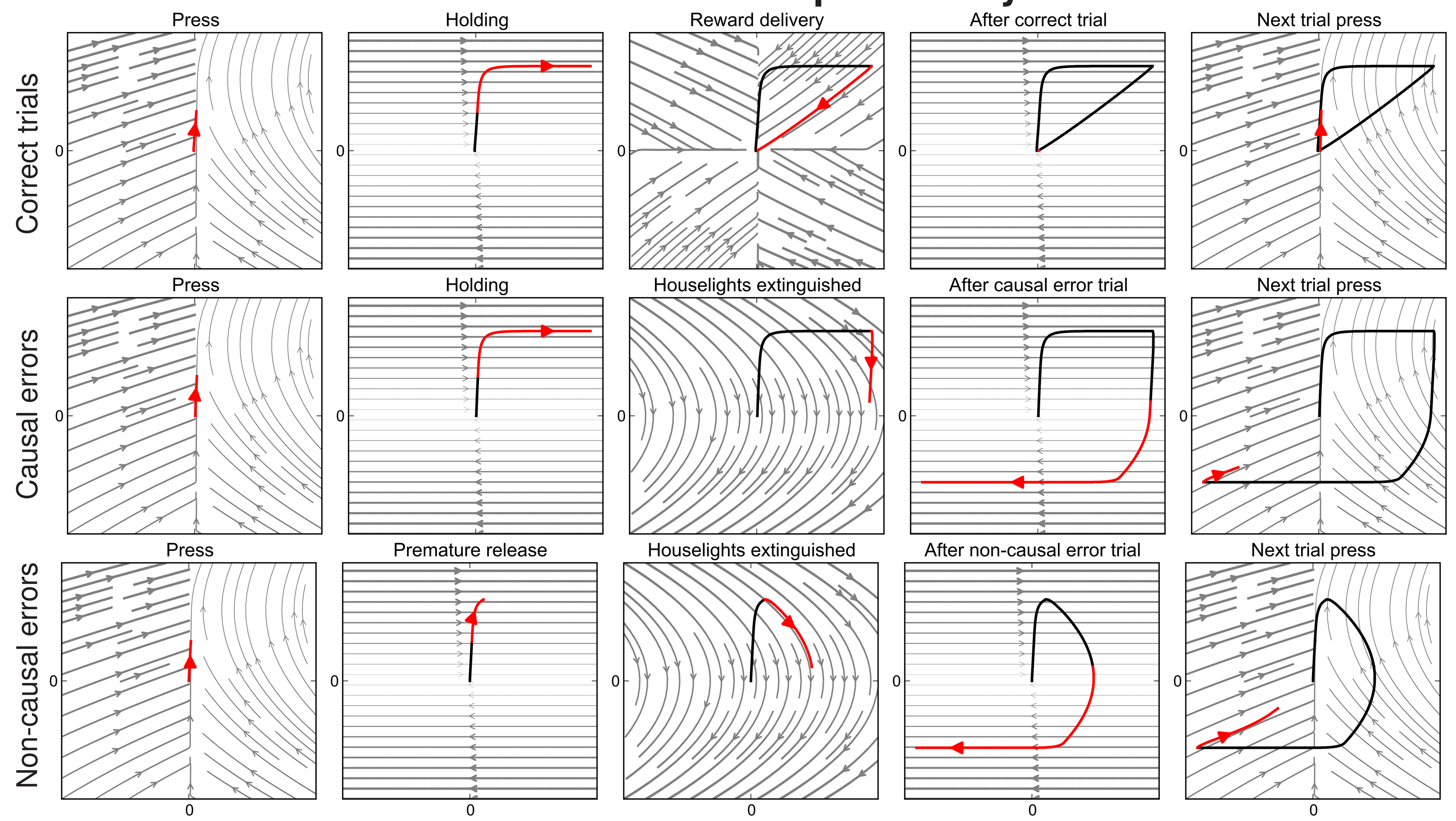
Two-dimensional state space analysis

The dynamics of the modified double-integrator model (bottom-left panel) are captured by the following two-dimensional non-linear dynamical system.

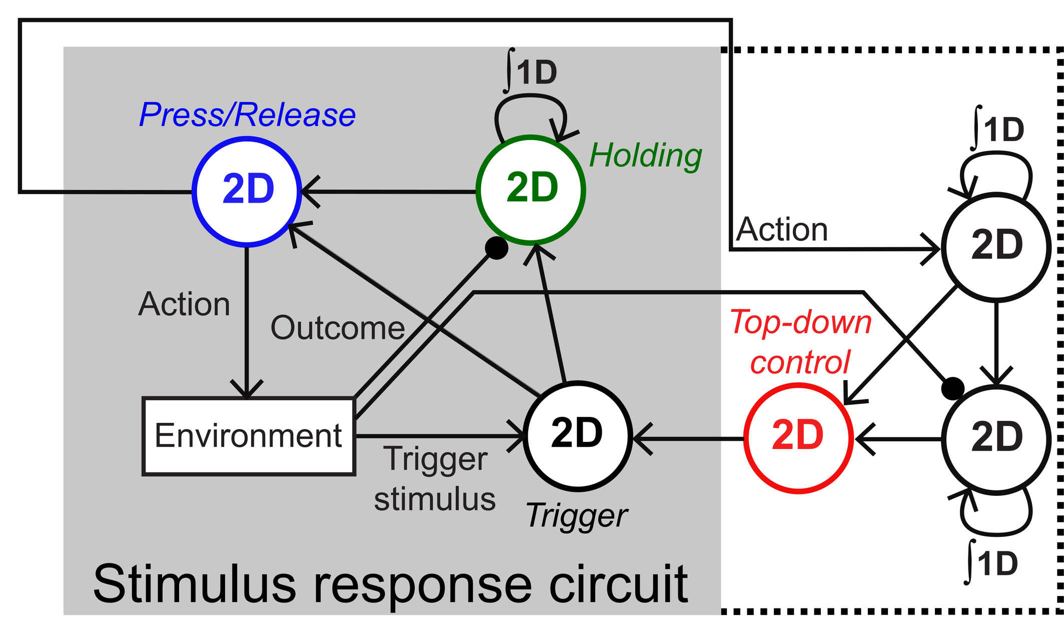
$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}\beta R & 0\\ \alpha & \beta R\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}1 & -1\\ 0 & 0\end{bmatrix}\begin{bmatrix}A\\ P\end{bmatrix}$$

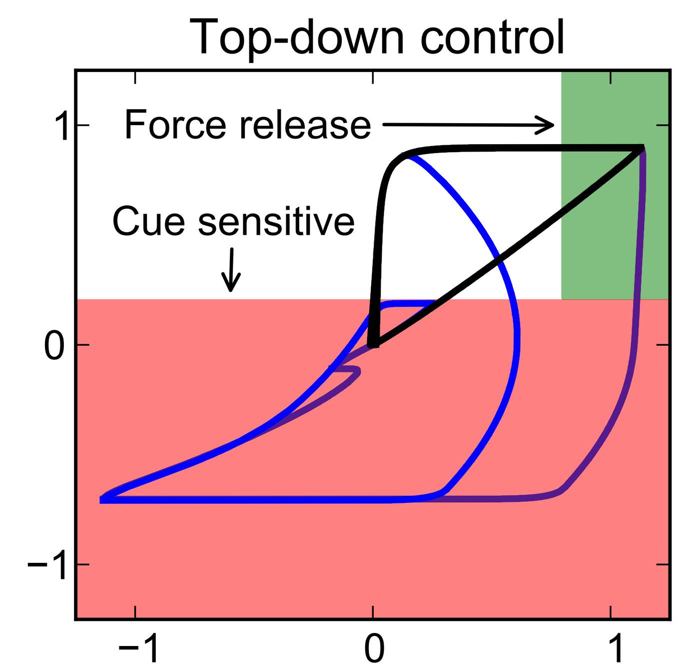
- x is the current state,
- R is a reward value,
- A is the action (i.e., press),
- P is a penalty value,
- $\alpha > 0$ is a parameter representing the strength of the connection between the two integrators, and
- $\beta < 0$ is a parameter representing how much control the reward exerts on the system.

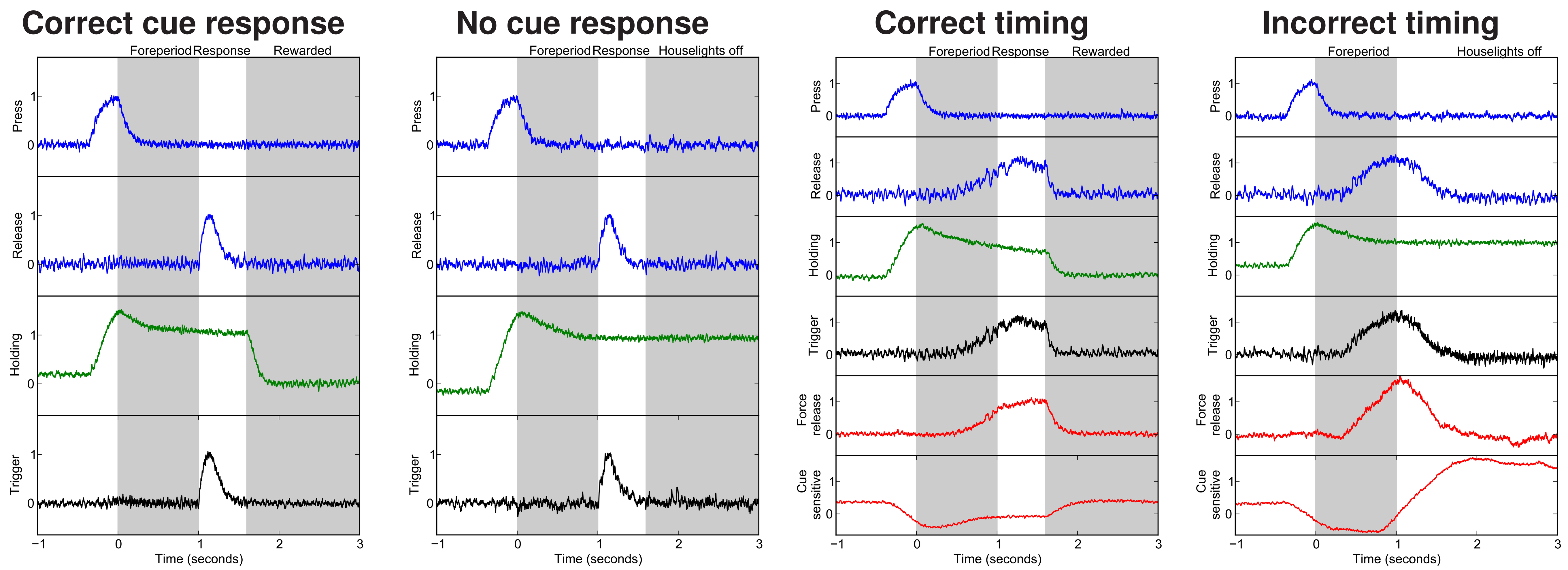
This results in the dynamics to the right in the three possible trial outcomes.

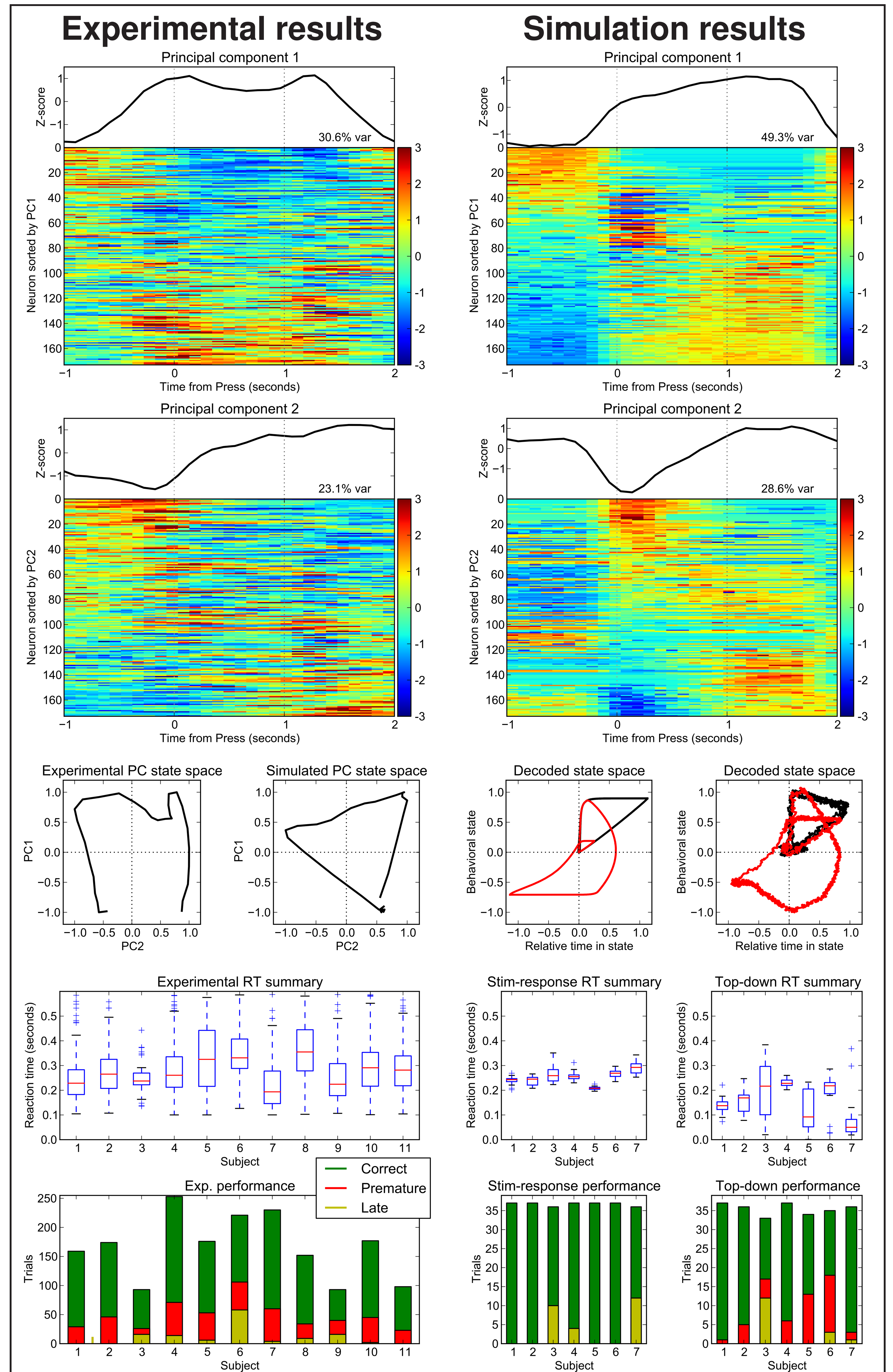


The cyclic nature of the system when performing correctly allows it to be used for top-down control. Using the same NEF methods as the original model, we built a circuit that can reliably respond to the stimulus. The addition of top-down control by the adapted double-integrator model enables the system to switch between a stimulus-dependent strategy and a timing strategy based on the outcome of the previous trial.









Summary

1. Model captures features of the neural data (e.g., principal components).
2. Model is linked to a simple two-dimensional dynamical system.
3. Model switches strategy based on previous outcomes.
4. Model is able to achieve low reaction times with more errors using timing.

Conclusion

Examining the state-space of the experimental and simulated data after dimension reduction led to a model that can be manipulated neurally and analyzed behaviorally.

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