

Interrogating theoretical models of neural computation with deep inference
Sean R. Bittner¹, Agostina Palmigiano¹, Alex T. Piet^{2,3,4}, Chunyu A. Duan⁵, Carlos D. Brody^{2,3,6},
Kenneth D. Miller¹, and John P. Cunningham⁷.

¹Department of Neuroscience, Columbia University,

²Princeton Neuroscience Institute,

³Princeton University,

⁴Allen Institute for Brain Science,

⁵Institute of Neuroscience, Chinese Academy of Sciences,

⁶Howard Hughes Medical Institute,

⁷Department of Statistics, Columbia University

¹ 1 Abstract

² A cornerstone of theoretical neuroscience is the circuit model: a system of equations that captures
³ a hypothesized neural mechanism. Such models are valuable when they give rise to an experimen-
⁴ tally observed phenomenon – whether behavioral or in terms of neural activity – and thus can offer
⁵ insights into neural computation. The operation of these circuits, like all models, critically depends
⁶ on the choices of model parameters. When analytic derivation of the relationship between model pa-
⁷ rameters and computational properties is intractable, approximate inference and simulation-based
⁸ techniques are relied upon for scientific insight. We bring the use of deep generative models for
⁹ probabilistic inference to bear on this problem, learning distributions of parameters that produce
¹⁰ the specified properties of computation. By learning parameter distributions that produce compu-
¹¹ tations – an emergent property, we introduce a novel methodology that is particularly well-suited
¹² to the stochastic dynamical systems models predominant in our field of theoretical neuroscience.
¹³ We motivate this methodology with a worked example analyzing sensitivity in the stomatogastric
¹⁴ ganglion. We then use it to reveal the key factors of variability in a model of primary visual cortex,
¹⁵ gain a mechanistic understanding of rapid task switching in superior colliculus models, and scale
¹⁶ inference of large low-rank RNN’s exhibiting stable amplification. While much use of deep learning
¹⁷ in theoretical neuroscience focuses on drawing analogies between optimized neural architectures
¹⁸ and the brain, this work illustrates how we can further leverage the power of deep learning towards
¹⁹ solving inverse problems in theoretical neuroscience.

²⁰ **2 Introduction**

²¹ The fundamental practice of theoretical neuroscience is to use a mathematical model to understand
²² neural computation, whether that computation enables perception, action, or some intermediate
²³ processing [1]. A neural computation is systematized with a set of equations – the model – and
²⁴ these equations are motivated by biophysics, neurophysiology, and other conceptual considerations.

²⁵ The function of this system is governed by the choice of model parameters, which when configured
²⁶ in a particular way, give rise to a measurable signature of a computation. The work of analyzing a
²⁷ model then requires solving the inverse problem: given a computation of interest, how can we reason
²⁸ about these particular parameter configurations? The inverse problem is crucial for reasoning about
²⁹ likely parameter values, uniquenesses and degeneracies, and predictions made by the model.

³⁰ Consider the idealized practice: one carefully designs a model and analytically derives how model
³¹ parameters govern the computation. Seminal examples of this gold standard (which often adopt
³² approaches from statistical physics) include our field’s understanding of memory capacity in asso-
³³ ciative neural networks [2], chaos and autocorrelation timescales in random neural networks [3],
³⁴ the paradoxical effect [4], and decision making [5]. Unfortunately, as circuit models include more
³⁵ biological realism, theory via analytical derivation becomes intractable. Alternatively, we can gain
³⁶ insight into these complex models by identifying all of the parameters consistent with the emer-
³⁷ gent phenomena of interest. By examining the structure of the full space of possible parameters,
³⁸ scientists can reason about the sensitivity and robustness of the model with respect to different
³⁹ parameter combinations [6, 7, 8, 9, 10].

⁴⁰ The preferred formalism for parameter identification in science, statistical inference, has been used
⁴¹ to great success in neuroscience through the stipulation of statistical generative models [11, 12,
⁴² 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25] (see review, [26]). However, most neural circuit
⁴³ models in theoretical neuroscience stipulate a noisy system of differential equations that can only
⁴⁴ be sampled or realized through forward simulation; they lack the explicit likelihood central to the
⁴⁵ probabilistic modeling toolkit. Therefore, the most popular approaches to the inverse problem have
⁴⁶ been likelihood-free methods such as approximate Bayesian computation (ABC) [27, 28], in which
⁴⁷ a set of reasonable parameters estimates is obtained via simulation and rejection.

⁴⁸ Of course, the challenge of doing inference in complex models has arisen in many scientific fields.
⁴⁹ In response, the machine learning community has made remarkable progress in recent years, via
⁵⁰ the use of deep neural networks as a powerful inference engine: a flexible function family that can

51 map observations back to probability distributions quantifying the likely parameter configurations.
52 One celebrated example of this approach from machine learning, of which we draw key inspiration
53 for this work, is the variational autoencoder (VAE) [29, 30], which uses a deep neural network to
54 induce an (approximate) posterior distribution on hidden variables in a latent variable model, given
55 data. Indeed, these tools have been used to great success in neuroscience as well, in particular for
56 interrogating parameters (sometimes treated as hidden states) in models of both cortical population
57 activity [31, 32, 33, 34] and animal behavior [35, 36, 37]. These works have used deep neural
58 networks to expand the expressivity and accuracy of statistical models of neural data [26].

59 Existing approaches to the inverse problem in theoretical neuroscience fall short in three key ways.
60 First, theoretical models of neural computation aim to reflect a complex biological reality, and as
61 a result, such models lack tractable likelihoods. Neuroscientists therefore resort to using approx-
62 imate Bayesian computation, which requires a rejection heuristic, scales poorly, and only obtains
63 sets of non-rejected parameters lacking probabilities. Second, is the undesirable trade-off between
64 the flexibility and sampling speed of the approximated posterior distributions. Sampling-based
65 approaches to statistical inference (e.g. ABC and Markov chain Monte Carlo (MCMC)) have flexi-
66 bility in approximation, but must be executed continually for increasing samples. While variational
67 approaches often result in fast sampling and sensitivity measurements post-optimization, existing
68 approaches have relied on simplified classes of distributions. These simple distributions (e.g. mean-
69 field gaussians) restrict the flexibility of the posterior approximation. And third, one can never
70 assume what inferred model parameters may predict. This is well understood when considering
71 Box’s loop and the role of posterior predictive checks in the development and critique of scientific
72 models [38, 39]. Uncertainty about the properties of inferred model predictions introduce a con-
73 ceptual degree of freedom to the inverse problem that may be unnecessary and undesirable given
74 the scientific motivation.

75 To address these three challenges, we developed an inference methodology – ‘emergent property
76 inference’ – which learns a distribution over parameter configurations in a theoretical model. This
77 distribution has two critical properties: *(i)* it is chosen such that draws from the distribution (pa-
78 rameter configurations) correspond to systems of equations that give rise to a specified emergent
79 property (a set of constraints); and *(ii)* it is chosen to have maximum entropy given those con-
80 straints, such that we identify all likely parameters and can use the distribution to reason about
81 parametric sensitivity and degeneracies [40]. First, we use stochastic gradient techniques in the
82 spirit of likelihood-free variational inference [41] to enable inference in likelihood-free models of

83 neural computation. Second, we stipulate a bijective deep neural network that induces a flexible
84 family of probability distributions over model parameterizations with a probability density we can
85 calculate [42, ?, 43], which confers fast sampling and sensitivity measurements. Third, we quantify
86 the notion of emergent properties as a set of moment constraints on datasets generated by the
87 model. Thus, an emergent property is not a single data realization, but a phenomenon or a feature
88 of the model, which is ultimately the object of interest in theoretical neuroscience. Conditioning
89 on an emergent property requires a variant of deep probabilistic inference methods, which we have
90 previously introduced [44]. Taken together, emergent property inference (EPI) provides a method-
91 ology for inferring parameter configurations consistent with a particular emergent phenomena in
92 theoretical models. We use a classic example of parametric degeneracy in a biological system, the
93 stomatogastric ganglion [45], to motivate and clarify the technical details of EPI.

94 Equipped with this methodology, we then investigated three models of current importance in the-
95 oretical neuroscience. These models were chosen to demonstrate generality through ranges of bi-
96 ological realism (from conductance-based biophysics to recurrent neural networks), neural system
97 function (from pattern generation to decision making), and network scale (from four to hundreds
98 of neurons). First, we use EPI to understand the characteristics of noise that govern Fano factor
99 in a stochastic four neuron-type model of primary visual cortex. Second, we discover connectivity
100 patterns in superior colliculus resilient to optogenetic perturbation by using EPI to condition on
101 rapid task switching. The novel scientific insights offered by EPI contextualize and clarify the
102 previous studies exploring these models [46, 47]. Third, we emphasize the methodological advance-
103 ment of EPI by inferring high-dimensional distributions of RNN connectivities exhibiting stable
104 amplification. These results point to the value of deep inference for the interrogation of biologically
105 relevant models.

106 3 Results

107 3.1 Motivating emergent property inference of theoretical models

108 Consideration of the typical workflow of theoretical modeling clarifies the need for emergent prop-
109 erty inference. First, one designs or chooses an existing model that, it is hypothesized, captures
110 the computation of interest. To ground this process in a well-known example, consider the stom-
111 atogastric ganglion (STG) of crustaceans, a small neural circuit which generates multiple rhythmic
112 muscle activation patterns for digestion [48]. Despite full knowledge of STG connectivity and a

precise characterization of its rhythmic pattern generation, biophysical models of the STG have complicated relationships between circuit parameters and neural activity [45, 7]. A subcircuit model of the STG [49] is shown schematically in Figure 1A, and note that the behavior of this model will be critically dependent on its parameterization – the choices of conductance parameters $\mathbf{z} = [g_{el}, g_{synA}]$. Specifically, the two fast neurons ($f1$ and $f2$) mutually inhibit one another, and oscillate at a faster frequency than the mutually inhibiting slow neurons ($s1$ and $s2$). The hub neuron (hub) couples with either the fast or slow population or both.

Second, once the model is selected, one defines the emergent phenomena of scientific interest. In the STG example, we are concerned with neural spiking frequency, which emerges from the dynamics of the circuit model 1B. An interesting emergent property of this stochastic model is when the hub neuron fires at an intermediate frequency between the intrinsic spiking rates of the fast and slow populations. This emergent property is shown in Figure 1C at an average frequency of 0.55Hz.

Third, parameter analyses ensue: brute-force parameter sweeps, ABC sampling, and sensitivity analyses are all routinely used to reason about what parameter configurations lead to an emergent property. In this last step lies the opportunity for a precise quantification of the emergent property as a statistical feature of the model. Once we have such a methodology, we can infer a probability distribution over parameter configurations that produce this emergent property.

Before presenting technical details (in the following section), let us understand emergent property inference schematically: EPI (Fig. 1D) takes, as input, the model and the specified emergent property, and as its output, produces the parameter distribution EPI (Fig. 1E). This distribution – represented for clarity as samples from the distribution – is then a scientifically meaningful and mathematically tractable object. In the STG model, this distribution can be specifically queried to reveal the prototypical parameter configuration for network syncing (the mode; Figure 1E yellow star), and how network syncing decays based on changes away from the mode. The eigenvectors (of the Hessian of the distribution at the mode) quantitatively formalize the robustness of unified intermediacy (Fig. 1B solid (v_1) and dashed (v_2) black arrows). Indeed, samples equidistant from the mode along these EPI-identified dimensions of sensitivity (v_1) and degeneracy (v_2) agree with error contours (Fig. 1B contours) and have diminished or preserved network syncing, respectively (Fig. 1F activity traces, Fig. S TODO) (see Section 5.2.1).

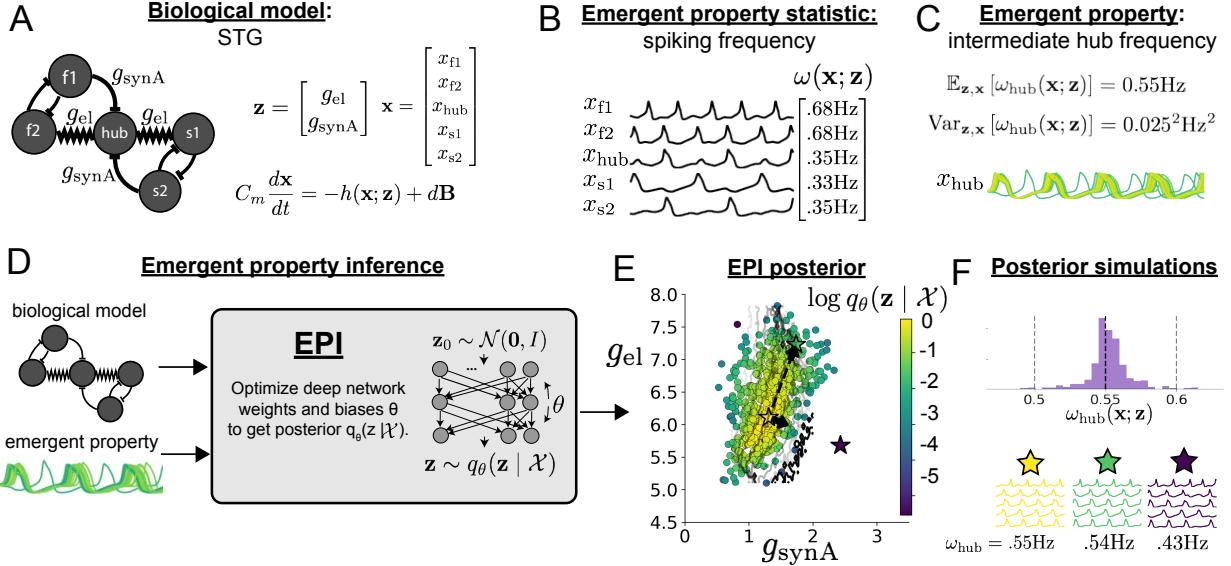


Figure 1: Emergent property inference (EPI) in the stomatogastric ganglion. **A.** Conductance-based biophysical model of the STG subcircuit. In the STG model, jagged connections indicate electrical coupling having electrical conductance g_{el} . Other connections in the diagram are inhibitory synaptic projections having strength g_{synA} onto the hub neuron, and $g_{synB} = 5\text{nS}$ for mutual inhibitory connections. Parameters are represented by the vector \mathbf{z} and membrane potentials by the vector \mathbf{x} . The evolution of this model's activity $\mathbf{x}(t)$ is predicated by differential equations. **B.** Spiking frequency $\omega(\mathbf{x}; \mathbf{z})$ is an emergent property statistic. Spiking frequency is measured from simulated activity of the STG model at parameter choices of $g_{el} = 4.5\text{nS}$ and $g_{synA} = 3\text{nS}$. **C.** The emergent property of intermediate hub frequency, in which the hub neuron fires at a rate between the fast and slow frequencies. Simulated activity traces are colored by log probability density of their generating parameters in the EPI-inferred distribution (Panel E). **D.** For a choice of model and emergent property, emergent property inference (EPI) learns a distribution of the model parameters $\mathbf{z} = [g_{el}, g_{synA}]$ producing intermediate hub frequency. Deep probability distributions map a simple random variable \mathbf{z}_0 through a deep neural network with weights and biases $\boldsymbol{\theta}$ to parameters $\mathbf{z} = g_{\boldsymbol{\theta}}(\mathbf{z}_0)$ distributed as $q_{\boldsymbol{\theta}}(\mathbf{z} | \mathcal{X})$. In EPI optimization, stochastic gradient steps in $\boldsymbol{\theta}$ are taken such that entropy is maximized, and the emergent property \mathcal{X} is produced. **E.** The EPI distribution of STG model parameters producing intermediate hub frequency. Samples are colored by log probability density. Distribution contours of hub neuron frequency from mean of .55 Hz are shown at levels of .525, .53,575 Hz (dark to light gray away from mean). Frequencies are averages over the stochasticity of the model. Eigenvectors of the Hessian at the mode of the inferred distribution are indicated as \mathbf{v}_1 (solid) and \mathbf{v}_2 (dashed) with lengths scaled by the square root of the absolute value of their eigenvalues. Simulated activity is shown for three samples (stars). **F** Simulations from parameters in E. (Top) The predictive distribution of the posterior obeys the constraints stipulated by the emergent property. The black and gray dashed lines show the mean and two standard deviations according the emergent property, respectively. (Bottom) Simulations at the starred parameter values.

142 **3.2 A deep generative modeling approach to emergent property inference**

143 Emergent property inference (EPI) systematizes the three-step procedure of the previous section.
 144 First, we consider the model as a coupled set of differential equations [49]. In the running STG
 145 example, the model activity $\mathbf{x} = [x_{f1}, x_{f2}, x_{hub}, x_{s1}, x_{s2}]$ is the membrane potential for each neuron,
 146 which evolves according to the biophysical conductance-based equation:

$$C_m \frac{d\mathbf{x}(t)}{dt} = -h(\mathbf{x}(t); \mathbf{z}) + d\mathbf{B} \quad (1)$$

147 where $C_m = 1\text{nF}$, and \mathbf{h} is a sum of the leak, calcium, potassium, hyperpolarization, electrical, and
 148 synaptic currents, all of which have their own complicated dependence on \mathbf{x} and $\mathbf{z} = [g_{el}, g_{synA}]$,
 149 and $d\mathbf{B}$ is white gaussian noise (see Section 5.2.1).

150 Second, we define the emergent property, which as above is “intermediate hub frequency” (Figure
 151 1C). Quantifying this phenomenon is straightforward: we stipulate that the hub neuron’s spiking
 152 frequency – denoted $\omega_{hub}(\mathbf{x})$ is close to an intermediate frequency of 0.55Hz. Mathematically, we
 153 achieve this via constraints on the mean and variance of the hub neuron spiking frequency.

$$\begin{aligned} \mathcal{X} &: \mathbb{E}_{\mathbf{z}, \mathbf{x}} [f(\mathbf{x}; \mathbf{z})] \triangleq \mathbb{E}_{\mathbf{z}, \mathbf{x}} [\omega_{hub}(\mathbf{x}; \mathbf{z})] = [0.55] \triangleq \boldsymbol{\mu} \\ \text{Var}_{\mathbf{z}, \mathbf{x}} [f(\mathbf{x}; \mathbf{z})] &\triangleq \text{Var}_{\mathbf{z}, \mathbf{x}} [\omega_{hub}(\mathbf{x}; \mathbf{z})] = [0.025^2] \triangleq \boldsymbol{\sigma}^2. \end{aligned} \quad (2)$$

154 The emergent property statistic $f(\mathbf{x}; \mathbf{z}) = \omega_{hub}(\mathbf{x}; \mathbf{z})$ along with its constrained mean $\boldsymbol{\mu}$ and variance
 155 $\boldsymbol{\sigma}^2$ define the emergent property denoted \mathcal{X} .

156 Third, we perform emergent property inference: we find a distribution over parameter configura-
 157 tions \mathbf{z} , and insist that samples from this distribution produce the emergent property; in other
 158 words, they obey the constraints introduced in Equation 2. This distribution will be chosen from a
 159 family of probability distributions $\mathcal{Q} = \{q_{\boldsymbol{\theta}}(\mathbf{z}) : \boldsymbol{\theta} \in \Theta\}$, defined by a deep generative distribution
 160 of the normalizing flow class [42, ?, 43] – neural networks which transform a simple distribution
 161 into a suitably complicated distribution (as is needed here). This deep distribution is represented
 162 in Figure 1C (see Section 5.1). Then, mathematically, we must solve the following optimization
 163 program:

$$\begin{aligned} q_{\boldsymbol{\theta}}(\mathbf{z} | \mathcal{X}) &= \underset{\boldsymbol{\theta} \in \mathcal{Q}}{\operatorname{argmax}} H(q_{\boldsymbol{\theta}}(\mathbf{z})) \\ \text{s.t. } \mathcal{X} : \mathbb{E}_{\mathbf{z}, \mathbf{x}} [f(\mathbf{x}; \mathbf{z})] &= \boldsymbol{\mu}, \text{Var}_{\mathbf{z}, \mathbf{x}} [f(\mathbf{x}; \mathbf{z})] = \boldsymbol{\sigma}^2 \end{aligned} \quad (3)$$

164 where $f(\mathbf{x}, \mathbf{z})$, $\boldsymbol{\mu}$, and $\boldsymbol{\sigma}$ are defined as in Equation 10. According to the emergent property of
165 interest, $f(\mathbf{x}, \mathbf{z})$ may contain multiple statistics, in which case the mean and variance vectors $\boldsymbol{\mu}$
166 and $\boldsymbol{\sigma}^2$ match this dimension. Finally, we recognize that many distributions in \mathcal{Q} will respect
167 the emergent property constraints, so we select that which has maximum entropy. This principle,
168 captured in Equation 3 by the primal objective H , identifies parameter distributions with minimal
169 assumptions beyond some chosen structure [50, 51, 44, 52]. Such a normative principle of maximum
170 entropy, which is also that of Bayesian inference, naturally fits with our scientific objective of
171 reasoning about parametric sensitivity and robustness. The recovered distribution of EPI is as
172 variable as possible along each parametric manifold such that it produces the emergent property.

173 EPI optimizes the weights and biases $\boldsymbol{\theta}$ of the deep neural network (which induces the probability
174 distribution) by iteratively solving Equation 3. The optimization is complete when the sampled
175 models with parameters $\mathbf{z} \sim q_{\boldsymbol{\theta}}(z | \mathcal{X})$ produce activity consistent with the specified emergent
176 property (Fig. S4). Such convergence is evaluated with a hypothesis test that the means and
177 variances of each emergent property statistic are not different than their constrained values (see
178 Section 5.1.3). Further validation of EPI is available in the supplementary materials, where we
179 analyze a simpler model for which ground-truth statements can be made (Section 5.1.4).

180 In relation to broader methodology, inspection of the EPI objective reveals a natural relationship
181 to posterior inference. Specifically, EPI executes a novel variant of Bayesian inference with a
182 uniform prior and a gaussian likelihood on the emergent property statistic (see Section 5.1.5).
183 A key advantage of EPI over established Bayesian inference is that the predictions made by the
184 inferred distribution are constrained to produce the specified emergent property. Equipped with
185 this method, we may examine structure in posterior distributions or make comparisons between
186 posteriors conditioned at different levels of the same emergent property statistic. In Sections 3.3
187 and 3.4, we prove out the value of EPI by using it to investigate and produce novel insights into
188 two prominent models in neuroscience. Subsequently in Section 3.5, we show EPI’s superiority in
189 parameter scalability and fidelity of the posterior predictive distribution by conditioning on stable
190 amplification in low-rank RNNs.

191 **3.3 EPI reveals how noise across neural population types governs Fano factor
192 in a stochastic inhibition stabilized network**

193 Dynamical models of excitatory (E) and inhibitory (I) populations with supralinear input-output
194 function have succeeded in explaining a host of experimentally documented phenomena. In a regime

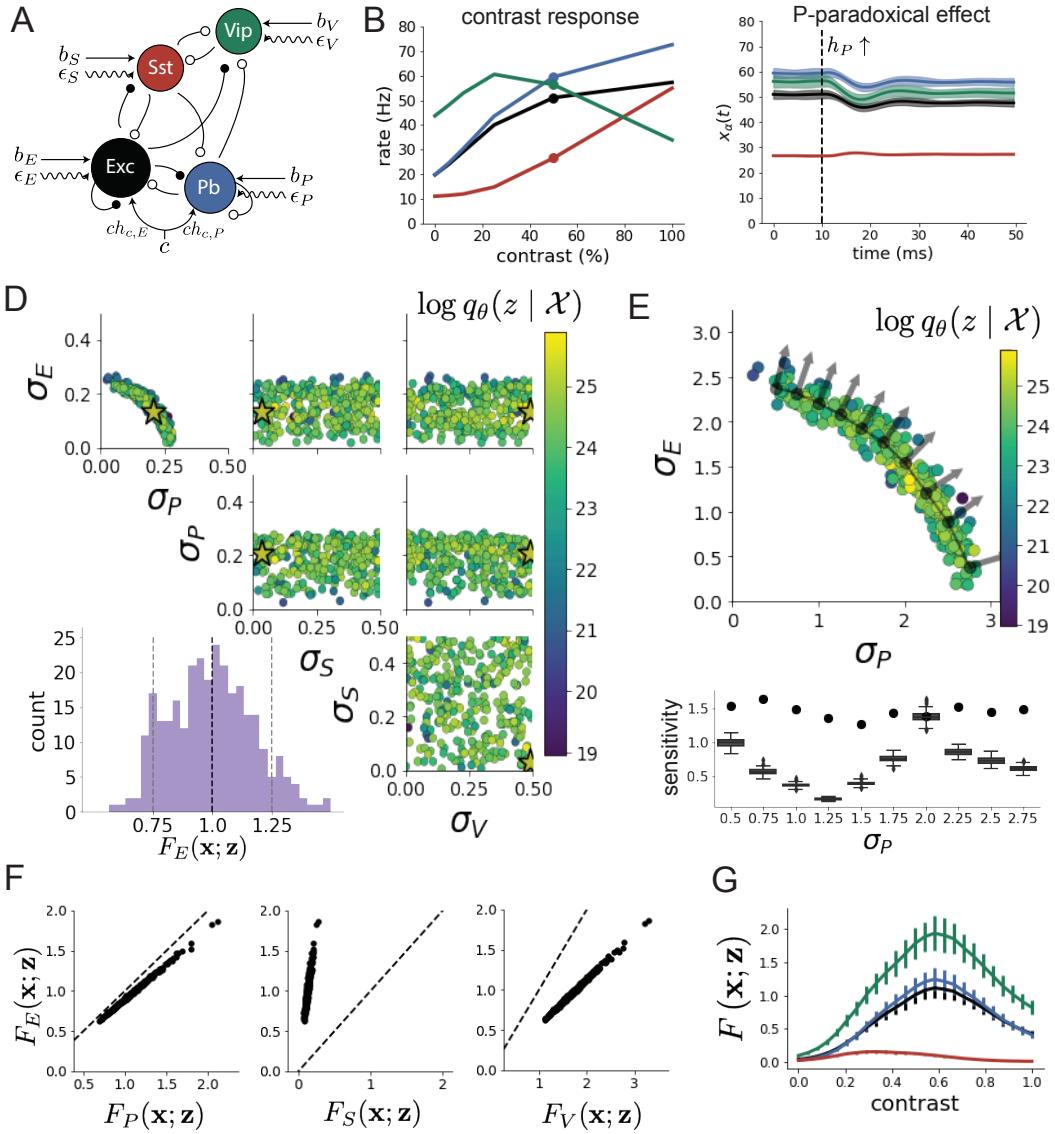


Figure 2: Emergent property inference of a stochastic stabilized supralinear network. **A.** Four-population model of primary visual cortex with excitatory (black), parvalbumin (blue), somatostatin (red), and VIP (green) neurons (excitatory and inhibitory projections filled and unfilled, respectively). Some neuron-types largely do not form synaptic projections to others ($|W_{\alpha_1, \alpha_2}| < 0.025$). Each neural population receives a baseline input \mathbf{h}_b , and the E- and P-populations also receive a contrast-dependent input \mathbf{h}_b . Additionally, each neural population receives a slow noisy input ϵ . **B.** Responses of the deterministic model ($\epsilon = \mathbf{0}$) to varying contrasts. The response at 50% contrast (dots) is the focus of our analysis. **C.** Paradoxical response of the stochastic model to a small increase in input to the P-population. **D.** EPI posterior of noise parameters \mathbf{z} conditioned on realistic E-population Fano factors. The posterior predictive distribution is shown on the bottom-left, and the mode of the distribution is starred. **E.** (Top) Enlarged visualization of the $\sigma_E - \sigma_P$ marginal distribution of the posterior. Each gray dot is a choice of σ_P , for which a constrained mode $z^*(\sigma_P, P)$ is chosen. The arrows show the most sensitive dimensions of the Hessian evaluated at these modes. (Bottom) Such sensitive dimensions of the Hessian (dots) are significantly more sensitive than randomly chosen dimensions (box and whiskers). **F.** The Fano factor of the E-population is strongly correlated with each other neuron-type population. **G.** Mean and standard deviation (across EPI posterior) of Fano factor of each neuron-type population at each level of contrast.

195 characterized by inhibitory stabilization of strong recurrent excitation, these models give rise to
 196 paradoxical responses [4], selective amplification [53, 54], surround suppression [55] and normal-
 197 ization [56]. Despite their strong predictive power, E-I circuit models rely on the assumption that
 198 inhibition can be studied as an indivisible unit. However, experimental evidence shows that inhibi-
 199 tion is composed of distinct elements – parvalbumin (P), somatostatin (S), VIP (V) – composing
 200 80% of GABAergic interneurons in V1 [57, 58, 59], and that these inhibitory cell types follow
 201 specific connectivity patterns (Fig. 2A) [60]. Recent theoretical advances [46, 61, 62], have only
 202 started to address the consequences of this multiplicity in the dynamics of V1, strongly relying on
 203 linear theoretical tools. Here, we use EPI to characterize the properties of slow noise in a stochastic
 204 version of this model, which result in biologically realistic responses.

205 We considered the contrast response of a nonlinear dynamical V1 circuit model (Fig. 2A) with
 206 a state comprised of each neuron-type population’s rate $\mathbf{x} = [x_E, x_P, x_S, x_V]^\top$. Each population
 207 receives recurrent input $W\mathbf{x}$ from synaptic projections of effective connectivity W and an external
 208 input \mathbf{h} , which determine the population rate via nonlinearity $\phi = []_+^2$ (see Section 5.2.2). The
 209 circuit model evolves from an initial condition $\mathbf{x}(0) \sim \mathcal{U}([10, 25])$ with time constant $\tau = 1\text{ms}$
 210 according to a contrast-dependent input \mathbf{h} and slow noise ϵ of time constant $\tau_{\text{noise}} = 5\text{ms}$. This
 211 model is the stochastic stabilized supralinear network (SSSN) [63] generalized to have inhibitory
 212 multiplicity

$$\tau \frac{d\mathbf{x}}{dt} = -\mathbf{x} + \phi(W\mathbf{x} + \mathbf{h} + \epsilon). \quad (4)$$

213 As contrast increases, input to the E- and P-populations increases relative to a baseline input \mathbf{h}_b
 214 via \mathbf{h}_c

$$\mathbf{h} = \mathbf{h}_b + c\mathbf{h}_c, \quad (5)$$

215 where $h_{c,E}, h_{c,P} > 0$ and $h_{c,S}, h_{c,V} = 0$. In this analysis, we fixed W, \mathbf{h}_b , and \mathbf{h}_c to values fit to
 216 mean contrast responses in mice with the deterministic model [64] ($\epsilon = \mathbf{0}$, Fig. 2B, see Section
 217 5.2.2). At all contrasts, the E-population of this SSSN is unstable without recurrent inhibitory
 218 feedback. At 50% contrast, only the P-population exhibits the paradoxical effect (2C, Fig. 9), so
 219 the network is P-stabilized.

220 The slow noise of the SSSN is an Ornstein-Uhlenbeck process

$$\tau_{\text{noise}} d\epsilon_\alpha = -\epsilon_\alpha dt + \sqrt{2\tau_{\text{noise}}} \sigma_\alpha dB, \quad (6)$$

221 parameterized by σ_α , which can be different for each neuron type,

$$\mathbf{z} = [\sigma_E, \sigma_P, \sigma_S, \sigma_V]^\top. \quad (7)$$

222 For this SSSN, we are interested in the parameters of slow noise that produce realistic stochastic
 223 fluctuations. Here, we quantify this emergent property as having an excitatory population Fano
 224 factor near 1:

$$\begin{aligned} \mathcal{X} : \mathbb{E}_{\mathbf{z}} [F_E(\mathbf{x}; \mathbf{z})] &= 1 \\ \text{Var}_{\mathbf{z}} [F_E(\mathbf{x}; \mathbf{z})] &= 0.125^2, \end{aligned} \quad (8)$$

225 where $F_\alpha(\mathbf{x}; \mathbf{z})$ is the Fano factor of the α -population.

226 We ran EPI to obtain a posterior $q_{\theta}(\mathbf{z} | \mathcal{X})$, where each parameter \mathbf{z} produces biologically realistic
 227 levels of E-population variability (Fig. 2D). From the marginal distribution of σ_E and σ_P (Fig.
 228 2D, top-left), we can see that $F_E(\mathbf{x}; \mathbf{z})$ is sensitive to the combination of σ_E and σ_P . In fact, the
 229 posterior obtained through EPI offers exactly how this sensitivity changes along this ridge of the
 230 posterior (Fig. 2E). σ_S and σ_V are degenerate with respect to $F_E(\mathbf{x}; \mathbf{z})$ evidenced by the uniform
 231 distribution in those dimensions of the posterior (Fig. 2D, bottom-right). Together, this posterior
 232 indicates a parametric manifold of degeneracy with respect to Fano factor: the ridge visualized in
 233 the σ_E - σ_P marginal (Fig. 10) and the dimensions of σ_S and σ_V .

234 Greater σ_E and σ_P confer greater Fano factor, and the Fano factors of each neuron-type are
 235 strongly correlated across the posterior (Fig 2F), showing that Fano factor of each neuron-type
 236 can be modulated globally via σ_E and σ_P . Furthermore, across the entire posterior distribution of
 237 noise parameterizations, we find that when contrast is increased above 50%, variability is quenched
 238 for all neuron types (Fig 2G). In summary, we used EPI to obtain a posterior of SSSNs producing
 239 realistic Fano factors, which allowed degenerate manifold identification via sample visualization,
 240 fast sensitivity measurements via Hessian evaluation, and predictions of variability quenching.

241 3.4 EPI identifies neural mechanisms of flexible task switching

242 In a rapid task switching experiment [65], rats were explicitly cued on each trial to either orient
 243 towards a visual stimulus in the Pro (P) task or orient away from a visual stimulus in the Anti
 244 (A) task (Fig. 3A). Neural recordings in the midbrain superior colliculus (SC) exhibited two
 245 populations of neurons that simultaneously represented both task context (Pro or Anti) and motor
 246 response (contralateral or ipsilateral to the recorded side): the Pro/Contra and Anti/Ipsi neurons
 247 [47]. Duan et al. proposed a model of SC that, like the V1 model analyzed in the previous section, is
 248 a four-population dynamical system. We analyzed this model, where the neuron-type populations
 249 are functionally-defined as the Pro- and Anti-populations in each hemisphere (left (L) and right

250 (R)), their connectivity is parameterized geometrically (Fig. 3B). The input-output function of
 251 this model is chosen such that the population responses $\mathbf{x} = [x_{LP}, x_{LA}, x_{RP}, x_{RA}]^\top$ are bounded
 252 from 0 to 1 as a function ϕ of a dynamically evolving internal variable \mathbf{u} . The model responds to
 253 the side with greater Pro neuron activation; e.g. the response is left if $x_{LP} > x_{RP}$ at the end of
 254 the trial. The dynamics evolve with timescale $\tau = 0.09$ governed by connectivity weights W

$$\begin{aligned}\tau \frac{d\mathbf{u}}{dt} &= -\mathbf{u} + W\mathbf{x} + \mathbf{h} + d\mathbf{B} \\ \mathbf{x} &= \phi(\mathbf{u})\end{aligned}\tag{9}$$

255 with white noise of variance 0.2^2 . The input \mathbf{h} is comprised of a cue-dependent input to the Pro
 256 or Anti populations, a stimulus orientation input to either the Left or Right populations, and
 257 a choice-period input to the entire network (see Section 5.2.3). Here, we use EPI to determine
 258 the changes in network connectivity $\mathbf{z} = [sW, vW, dW, hW]^\top$ resulting in execution of rapid task
 259 switching behavior.

260 We define rapid task switching behavior as accurate execution of each task. Inferred models should
 261 not exhibit fully random responses (50%), or perfect performance (100%), since perfection is never
 262 attained by even the best trained rats. We formulate rapid task switching as an emergent property
 263 by stipulating that the average accuracy in the Pro task $p_P(\mathbf{x}, \mathbf{z})$ and Anti task $p_A(\mathbf{x}, \mathbf{z})$ be 75%
 264 with variance $5\%^2$.

$$\begin{aligned}\mathcal{X} : \mathbb{E}_{\mathbf{z}} \begin{bmatrix} p_P(\mathbf{x}; \mathbf{z}) \\ p_A(\mathbf{x}; \mathbf{z}) \end{bmatrix} &= \begin{bmatrix} 75\% \\ 75\% \end{bmatrix} \\ \text{Var}_{\mathbf{z}} \begin{bmatrix} p_P(\mathbf{x}; \mathbf{z}) \\ p_A(\mathbf{x}; \mathbf{z}) \end{bmatrix} &= \begin{bmatrix} 5\%^2 \\ 5\%^2 \end{bmatrix}\end{aligned}\tag{10}$$

265 A variance of $5\%^2$ performance in each task will confer a posterior producing performances ranging
 266 from about 65% – 85%, allowing us to examine the properties of connectivity that yield better
 267 performance.

268 We ran EPI to obtain SC model connectivity parameters \mathbf{z} producing rapid task switching (Fig.
 269 3C). Some parameters were predictive of accuracy while others were not (Fig. 11), and often
 270 had different effects on p_P and p_A . To make sense of this inferred distribution, we took the
 271 eigendecomposition of the symmetric connectivity matrices $W = V\Lambda V^{-1}$, which results in the
 272 same basis vectors \mathbf{v}_i for all W parameterized by \mathbf{z} (Fig. 12A). These basis vectors have intuitive
 273 roles in processing for this task, and are accordingly named the *all* mode - all neurons co-fluctuate,
 274 *side* mode - one side dominates the other, *task* mode - the Pro or Anti populations dominate the

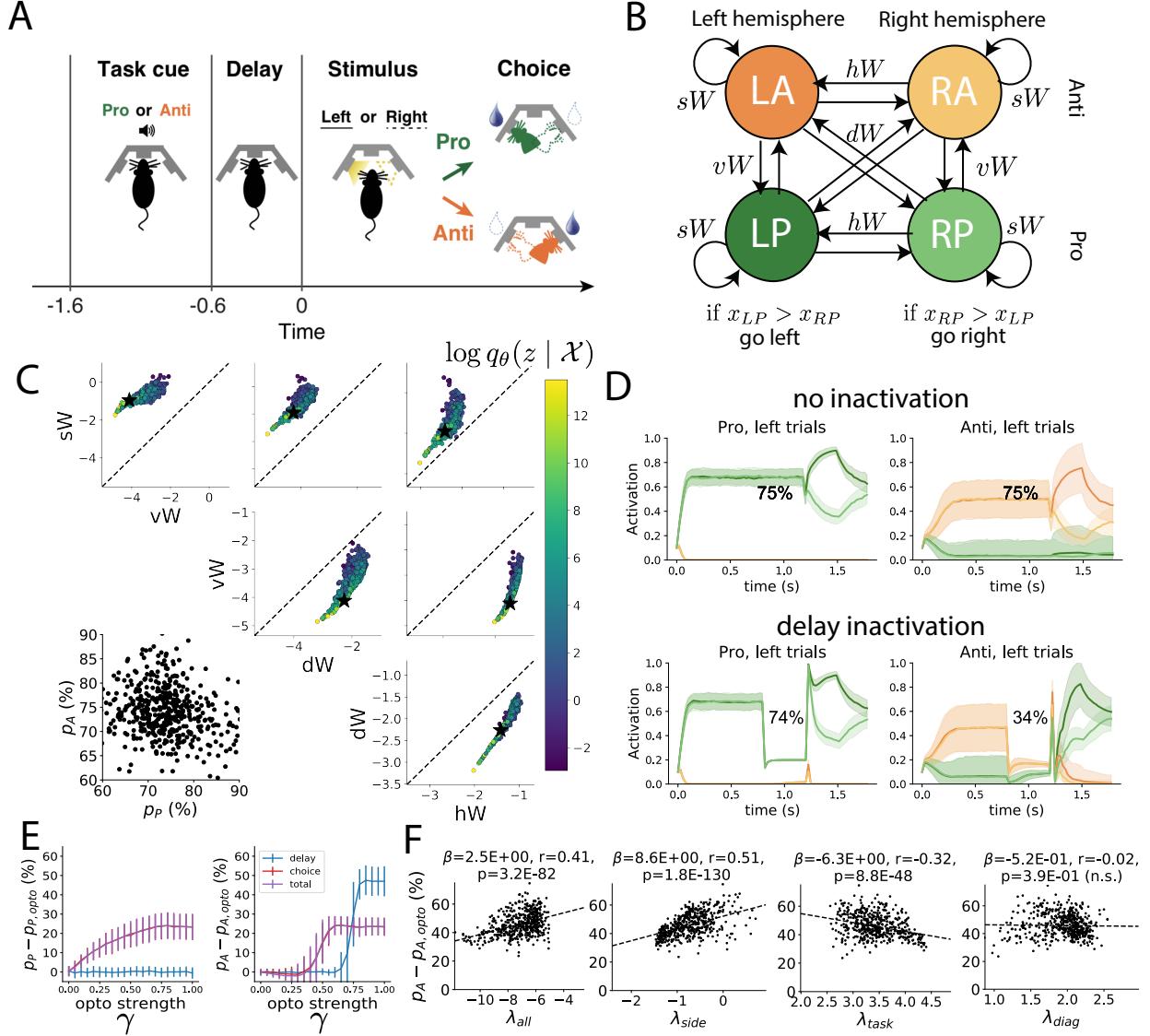


Figure 3: **A.** Rapid task switching behavioral paradigm (see text). **B.** Model of superior colliculus (SC). Neurons: LP - left pro, RP - right pro, LA - left anti, RA - right anti. Parameters: sW - self, hW - horizontal, vW - vertical, dW - diagonal weights. Subscripts P and A of connectivity weights indicate Pro or Anti populations. **C.** The EPI parameter distribution of rapid task switching networks. Black star indicates parameter choice of simulations (D). **D.** Simulations of an SC network from the EPI distribution with 75% accuracy in each task. Top row shows no inactivation during Pro and Anti trials, and bottom row shows simulations with delay period inactivation (optogenetic strength $\gamma = 0.7$). Shading indicates standard deviation across trials. **E.** Difference in performance of each task during inactivation. Inactivation level γ scales from no inactivation (0) to full inactivation (1). We compare delay period inactivation $1.2 < t < 1.5$ (blue), choice period inactivation $1.5 < t$ (red), and total inactivation $0 \leq t \leq 1.8$ (purple). **F.** The effect of delay period inactivation on Anti accuracy versus dynamics eigenvalues.

275 other, and *diag* mode - Pro- and Anti-populations of opposite hemispheres dominate the opposite
276 pair.

277 Greater λ_{task} , λ_{side} , and λ_{diag} all produce greater Pro accuracy. This shows that strong task
278 representations and hemispheric

279

280 dominance in the dynamics result in better execution of the Pro task. By visualizing these four
281 variables together by p_A (Fig. 13B), we see that low λ_{task} and λ_{diag} producing strong Anti accuracy
282 also have high λ_{side} and λ_{all} . Thus, stronger hemispheric dominance, relaxed task and diag mode
283 dynamics, and slower circuit-wide decay result in greater Anti accuracy.

284 In agreement with experimental results from Duan et al., we found that inactivation above nominal
285 strength during the delay period consistently decreased performance in the Anti task, but had no
286 consistent effect on the Pro task (Fig. 3E) e.g. (Fig. 3D, bottom). This difference in resiliency
287 across tasks to delay perturbation is a prediction made by the inferred EPI distribution, rather
288 than an emergent property that was conditioned upon. Even though p_P and p_A are anticorrelated
289 in the EPI posterior ($r = -0.15$, $p = 3.68 \times 10^{-12}$), greater p_P and p_A both result in decreased
290 resiliency to delay perturbation in the Anti task (Fig. 14). Ultimately, lower λ_{side} and λ_{all} and
291 greater λ_{task} produce networks more robust to delay perturbation in the Anti task (Fig. 3F)).

292 In summary, we used EPI to obtain the full distribution of connectivities that execute rapid task
293 switching. This posterior revealed the mechanisms leading to greater accuracy in each task as well
294 as those increasing resiliency to perturbation in the Anti task. Importantly, every connectivity
295 from this inferred distribution predicts fragility and robustness of performance in the Anti and Pro
296 tasks, respectively. EPI allows us to conclude that since *all* parameters of this model producing
297 rapid task switching make such an experimentally verified prediction, we have a well-chosen model.

298 3.5 EPI scales well to high-dimensional parameter spaces

299 Here, we are interested in the scalability of EPI in number of parameters ($|\mathbf{z}|$). We consider rank-2
300 RNN with N neurons of connectivity

$$W = UV^\top + g\chi \quad (11)$$

301 and dynamics

$$\tau \dot{\mathbf{x}} = -\mathbf{x} + W\mathbf{x} \quad (12)$$

302 where $U = [\mathbf{u}_1 \ \mathbf{u}_2]$, $V = [\mathbf{v}_1 \ \mathbf{v}_2]$, $\mathbf{u}_1, \mathbf{u}_2, \mathbf{v}_1, \mathbf{v}_2 \in [-1, 1]^N$, and $g = 0.01$.

303 We want to learn distributions of connectivity that produce stable amplification. Two conditions
 304 are both necessary and sufficient for RNNs to exhibit stable amplification [?]. These conditions are
 305 inequalities on $\text{real}(\lambda_1)$ and λ_1^s the maximal real eigenvalue of W and the maximum eigenvalue of
 306 $W^s = \frac{W+W^\top}{2}$, respectively.

307 In our analysis, we seek to condition rank-2 networks of increasing size on a regime of stable ampli-
 308 fication. Networks with $\text{real}(\lambda_1) = 0.5 \pm 0.5$ and $\lambda_1^s = 1.5 \pm 0.5$ will yield moderate amplification.
 309 EPI can naturally condition on this emergent property

$$\begin{aligned} \mathcal{X} : \mathbb{E}_{\mathbf{z}, \mathbf{x}} \begin{bmatrix} \text{real}(\lambda_1) \\ \lambda_1^s \end{bmatrix} &= \begin{bmatrix} 0.5 \\ 1.5 \end{bmatrix} \\ \text{Var}_{\mathbf{z}, \mathbf{x}} \begin{bmatrix} \text{real}(\lambda_1) \\ \lambda_1^s \end{bmatrix} &= \begin{bmatrix} 0.25^2 \\ 0.25^2 \end{bmatrix}. \end{aligned} \quad (13)$$

310 In contrast, SNPE cannot condition on the variance of observations across posterior. Thus, we
 311 condition on an observation x_0 located at the mean of our desired emergent property.

$$x_0 = \begin{bmatrix} \text{real}(\lambda_1) \\ \lambda_1^s \end{bmatrix} = \begin{bmatrix} 0.5 \\ 1.5 \end{bmatrix} \quad (14)$$

312 ABC methods define tolerance ϵ and distance for observed data x_0 . Here, we chose $\epsilon = 0.5$, an $l - 2$
 313 distance, and the same choice for x_0 as in Equation 14.

314 EPI is capable of scaling to higher dimensional parameter spaces than ABC and SNPE. EPI consis-
 315 tently produces the same posterior predictive distribution independent of the dimensionality. SMC
 316 produces a limited variety of parameters due to the nature of its proposal generation algorithm,
 317 yet all parameters obtained produce stable amplification. SNPE's posterior predictive distribution
 318 is not necessarily close to the conditioning point, and is very dependent on dimensionality.

319 4 Discussion

320 NOTE: This is the old discussion section. I will rewrite this based on our discussion of
 321 the rest of the draft.

322 In neuroscience, machine learning has primarily been used to reveal structure in neural datasets
 323 [11, 12, 13, 14, 16, 18, 20, 22, 23, 24, 25] (see review, [26]). Such careful inference procedures

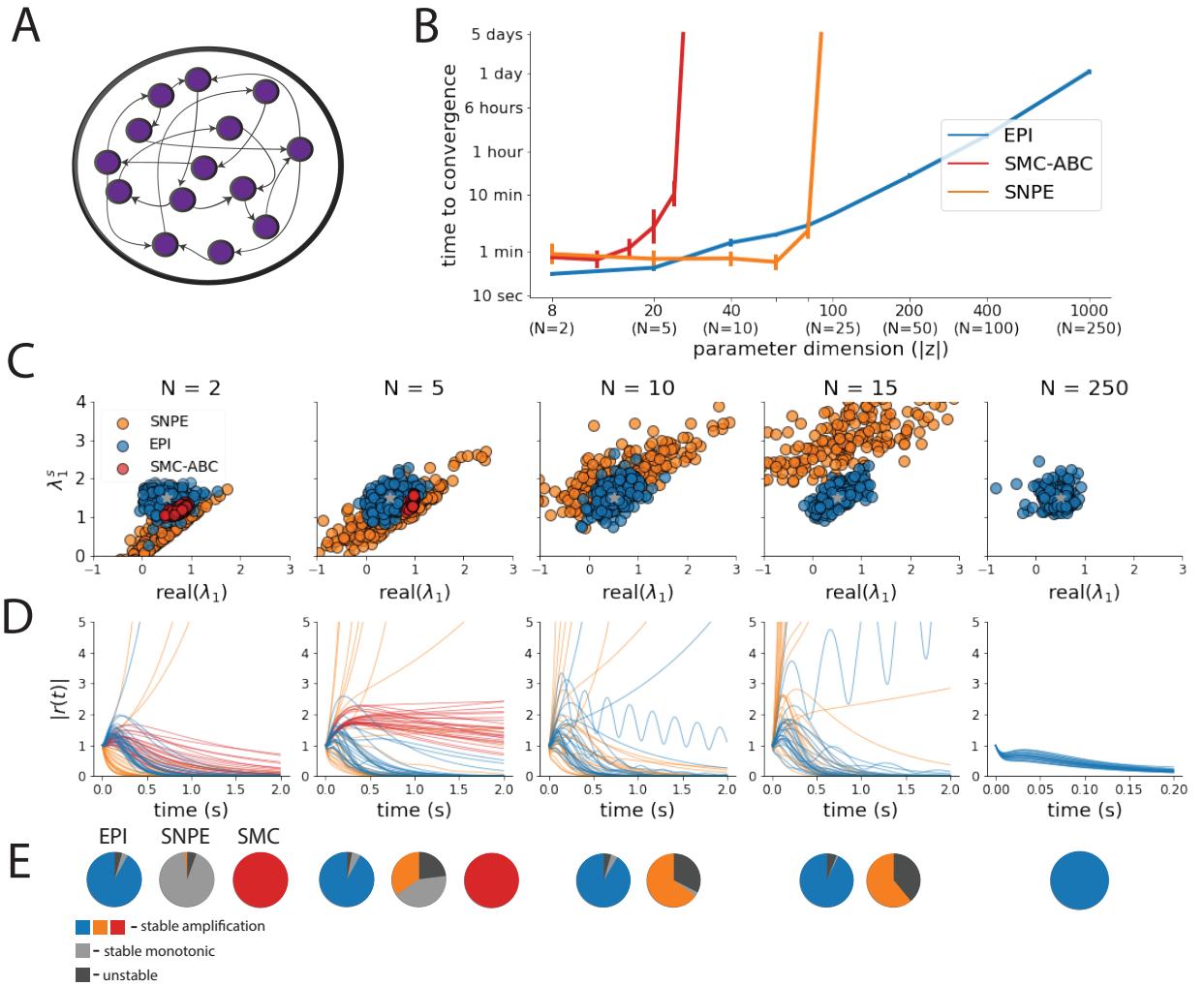


Figure 4: **A.** Recurrent neural network. **B.** EPI scales with z to high dimensions. Convergence definitions: EPI (blue) - satisfies all moment constraints, SNPE (orange)- produces at least $2/n_{\text{train}}$ parameter samples are in the bounds of emergent property (mean ± 0.5), and SMC-ABC (red) - 100 particles with $\epsilon < 0.5$ are produced. **C.** Posterior predictive distributions of EPI (blue), SNPE (orange), and SMC-ABC (red). Gray star indicates emergent property mean, and gray dashed lines indicate two standard deviations corresponding to the variance constraint. For $N \leq 6$ where SMC-ABC converges, samples are not diverse (path degeneracies). For $N \geq 25$, SNPE does not produce a posterior approximation yielding parameters with simulations near x_0 . **D.** Simulations of network parameters resulting from each method ($\tau = 100\text{ms}$). Each trace corresponds to simulation of one z . **E.** Ratio of obtained samples producing stable amplification.

324 are developed for these statistical models allowing precise, quantitative reasoning, which clarifies
325 the way data informs beliefs about the model parameters. However, these statistical models lack
326 resemblance to the underlying biology, making it unclear how to go from the structure revealed by
327 these methods, to the neural mechanisms giving rise to it. In contrast, theoretical neuroscience has
328 focused on careful mechanistic modeling and the production of emergent properties of computation.
329 The careful steps of *i.*) model design and *ii.*) emergent property definition, are followed by *iii.)*
330 practical inference methods resulting in an opaque characterization of the way model parameters
331 govern computation. In this work, we replaced this opaque procedure of parameter identification
332 in theoretical neuroscience with emergent property inference, opening the door to careful inference
333 in careful models of neural computation.

334 Biologically realistic models of neural circuits often prove formidable to analyze. Two main factors
335 contribute to the difficulty of this endeavor. First, in most neural circuit models, the number
336 of parameters scales quadratically with the number of neurons, limiting analysis of its parameter
337 space. Second, even in low dimensional circuits, the structure of the parametric regimes governing
338 emergent properties is intricate. For example, these circuit models can support more than one
339 steady state [66] and non-trivial dynamics on strange attractors [67].

340 In Section 3.3, we advanced the tractability of low-dimensional neural circuit models by showing
341 that EPI offers insights about cell-type specific input-responsivity that cannot be afforded through
342 the available linear analytical methods [46, 61, 62]. By flexibly conditioning this V1 model on
343 different emergent properties, we performed an exploratory analysis of a *model* rather than a
344 dataset, generating a set of testable hypotheses, which were proved out. Furthermore, exploratory
345 analyses can be directed towards formulating hypotheses of a specific form. For example, model
346 parameter dependencies on behavioral performance can be assessed by using EPI to condition on
347 various levels of task accuracy (See Section 3.4). This analysis identified experimentally testable
348 predictions (proved out *in-silico*) of patterns of effective connectivity in SC that should be correlated
349 with increased performance.

350 In our final analysis, we presented a novel procedure for doing statistical inference on interpretable
351 parameterizations of RNNs executing simple tasks. Specifically, we analyzed RNNs solving a pos-
352 terior conditioning problem in the spirit of [68, 69]. This methodology relies on recently extended
353 theory of responses in random neural networks with low-rank structure [70]. While we focused
354 on rank-1 RNNs, which were sufficient for solving this task, this inference procedure generalizes
355 to RNNs of greater rank necessary for more complex tasks. The ability to apply the probabilistic

356 model selection toolkit to RNNs should prove invaluable as their use in neuroscience increases.
357 EPI leverages deep learning technology for neuroscientific inquiry in a categorically different way
358 than approaches focused on training neural networks to execute behavioral tasks [71]. These works
359 focus on examining optimized deep neural networks while considering the objective function, learn-
360 ing rule, and architecture used. This endeavor efficiently obtains sets of parameters that can be
361 reasoned about with respect to such considerations, but lacks the careful probabilistic treatment of
362 parameter inference in EPI. These approaches can be used complementarily to enhance the practice
363 of theoretical neuroscience.

364 **TODO** *merge this point in*

365 While much research in computational neuroscience has focused on optimizing neural architectures
366 to process information and accomplish tasks [71], structure in parameter space of the set of opti-
367 mized solutions is rarely discussed and lacks a probabilistic treatment. Talk about Wykтор’s work
368 here [72].

369 **Acknowledgements:**

370 This work was funded by NSF Graduate Research Fellowship, DGE-1644869, McKnight Endow-
371 ment Fund, NIH NINDS 5R01NS100066, Simons Foundation 542963, NSF NeuroNex Award, DBI-
372 1707398, The Gatsby Charitable Foundation, Simons Collaboration on the Global Brain Postdoc-
373 toral Fellowship, Chinese Postdoctoral Science Foundation, and International Exchange Program
374 Fellowship. Helpful conversations were had with Francesca Mastrogiovanni, Srdjan Ostojic, James
375 Fitzgerald, Stephen Baccus, Dhruva Raman, Liam Paninski, and Larry Abbott.

376 **Data availability statement:**

377 The datasets generated during and/or analyzed during the current study are available from the
378 corresponding author upon reasonable request.

379 **Code availability statement:**

380 The software written for the current study is available from the corresponding author upon rea-
381 sonable request.

382 **References**

- 383 [1] Larry F Abbott. Theoretical neuroscience rising. *Neuron*, 60(3):489–495, 2008.

- 384 [2] John J Hopfield. Neural networks and physical systems with emergent collective computa-
385 tional abilities. *Proceedings of the national academy of sciences*, 79(8):2554–2558, 1982.
- 386 [3] Haim Sompolinsky, Andrea Crisanti, and Hans-Jurgen Sommers. Chaos in random neural
387 networks. *Physical review letters*, 61(3):259, 1988.
- 388 [4] Misha V Tsodyks, William E Skaggs, Terrence J Sejnowski, and Bruce L McNaughton. Para-
389 doxical effects of external modulation of inhibitory interneurons. *Journal of neuroscience*,
390 17(11):4382–4388, 1997.
- 391 [5] Kong-Fatt Wong and Xiao-Jing Wang. A recurrent network mechanism of time integration
392 in perceptual decisions. *Journal of Neuroscience*, 26(4):1314–1328, 2006.
- 393 [6] WR Foster, LH Ungar, and JS Schwaber. Significance of conductances in hodgkin-huxley
394 models. *Journal of neurophysiology*, 70(6):2502–2518, 1993.
- 395 [7] Astrid A Prinz, Dirk Bucher, and Eve Marder. Similar network activity from disparate circuit
396 parameters. *Nature neuroscience*, 7(12):1345–1352, 2004.
- 397 [8] Pablo Achard and Erik De Schutter. Complex parameter landscape for a complex neuron
398 model. *PLoS computational biology*, 2(7):e94, 2006.
- 399 [9] Timothy O’Leary, Alex H Williams, Alessio Franci, and Eve Marder. Cell types, network
400 homeostasis, and pathological compensation from a biologically plausible ion channel expres-
401 sion model. *Neuron*, 82(4):809–821, 2014.
- 402 [10] Leandro M Alonso and Eve Marder. Visualization of currents in neural models with similar
403 behavior and different conductance densities. *Elife*, 8:e42722, 2019.
- 404 [11] Robert E Kass and Valérie Ventura. A spike-train probability model. *Neural computation*,
405 13(8):1713–1720, 2001.
- 406 [12] Emery N Brown, Loren M Frank, Dengda Tang, Michael C Quirk, and Matthew A Wilson.
407 A statistical paradigm for neural spike train decoding applied to position prediction from
408 ensemble firing patterns of rat hippocampal place cells. *Journal of Neuroscience*, 18(18):7411–
409 7425, 1998.
- 410 [13] Liam Paninski. Maximum likelihood estimation of cascade point-process neural encoding
411 models. *Network: Computation in Neural Systems*, 15(4):243–262, 2004.

- 412 [14] Wilson Truccolo, Uri T Eden, Matthew R Fellows, John P Donoghue, and Emery N Brown.
413 A point process framework for relating neural spiking activity to spiking history, neural
414 ensemble, and extrinsic covariate effects. *Journal of neurophysiology*, 93(2):1074–1089, 2005.
- 415 [15] Elad Schneidman, Michael J Berry, Ronen Segev, and William Bialek. Weak pairwise correla-
416 tions imply strongly correlated network states in a neural population. *Nature*, 440(7087):1007–
417 1012, 2006.
- 418 [16] Shaul Druckmann, Yoav Banitt, Albert A Gidon, Felix Schürmann, Henry Markram, and Idan
419 Segev. A novel multiple objective optimization framework for constraining conductance-based
420 neuron models by experimental data. *Frontiers in neuroscience*, 1:1, 2007.
- 421 [17] Richard Turner and Maneesh Sahani. A maximum-likelihood interpretation for slow feature
422 analysis. *Neural computation*, 19(4):1022–1038, 2007.
- 423 [18] M Yu Byron, John P Cunningham, Gopal Santhanam, Stephen I Ryu, Krishna V Shenoy, and
424 Maneesh Sahani. Gaussian-process factor analysis for low-dimensional single-trial analysis of
425 neural population activity. In *Advances in neural information processing systems*, pages
426 1881–1888, 2009.
- 427 [19] Jakob H Macke, Lars Buesing, John P Cunningham, Byron M Yu, Krishna V Shenoy, and
428 Maneesh Sahani. Empirical models of spiking in neural populations. *Advances in neural
429 information processing systems*, 24:1350–1358, 2011.
- 430 [20] Il Memming Park and Jonathan W Pillow. Bayesian spike-triggered covariance analysis. In
431 *Advances in neural information processing systems*, pages 1692–1700, 2011.
- 432 [21] Einat Granot-Atedgi, Gašper Tkačik, Ronen Segev, and Elad Schneidman. Stimulus-
433 dependent maximum entropy models of neural population codes. *PLoS Comput Biol*,
434 9(3):e1002922, 2013.
- 435 [22] Kenneth W Latimer, Jacob L Yates, Miriam LR Meister, Alexander C Huk, and Jonathan W
436 Pillow. Single-trial spike trains in parietal cortex reveal discrete steps during decision-making.
437 *Science*, 349(6244):184–187, 2015.
- 438 [23] Kaushik J Lakshminarasimhan, Marina Petsalis, Hyeshin Park, Gregory C DeAngelis, Xaq
439 Pitkow, and Dora E Angelaki. A dynamic bayesian observer model reveals origins of bias in
440 visual path integration. *Neuron*, 99(1):194–206, 2018.

- 441 [24] Lea Duncker, Gergo Bohner, Julien Boussard, and Maneesh Sahani. Learning interpretable
442 continuous-time models of latent stochastic dynamical systems. *Proceedings of the 36th International Conference on Machine Learning*, 2019.
- 443
- 444 [25] Josef Ladenbauer, Sam McKenzie, Daniel Fine English, Olivier Hagens, and Srdjan Ostojic.
445 Inferring and validating mechanistic models of neural microcircuits based on spike-train data.
446 *Nature Communications*, 10(4933), 2019.
- 447 [26] Liam Paninski and John P Cunningham. Neural data science: accelerating the experiment-
448 analysis-theory cycle in large-scale neuroscience. *Current opinion in neurobiology*, 50:232–241,
449 2018.
- 450 [27] Scott A Sisson, Yanan Fan, and Mark M Tanaka. Sequential monte carlo without likelihoods.
451 *Proceedings of the National Academy of Sciences*, 104(6):1760–1765, 2007.
- 452 [28] Juliane Liepe, Paul Kirk, Sarah Filippi, Tina Toni, Chris P Barnes, and Michael PH Stumpf.
453 A framework for parameter estimation and model selection from experimental data in systems
454 biology using approximate bayesian computation. *Nature protocols*, 9(2):439–456, 2014.
- 455 [29] Diederik P Kingma and Max Welling. Auto-encoding variational bayes. *International Conference on*
456 *Learning Representations*, 2014.
- 457 [30] Danilo Jimenez Rezende, Shakir Mohamed, and Daan Wierstra. Stochastic backpropagation
458 and variational inference in deep latent gaussian models. *International Conference on*
459 *Machine Learning*, 2014.
- 460 [31] Yuanjun Gao, Evan W Archer, Liam Paninski, and John P Cunningham. Linear dynamical
461 neural population models through nonlinear embeddings. In *Advances in neural information*
462 *processing systems*, pages 163–171, 2016.
- 463 [32] Yuan Zhao and Il Memming Park. Recursive variational bayesian dual estimation for non-
464 linear dynamics and non-gaussian observations. *stat*, 1050:27, 2017.
- 465 [33] Gabriel Barello, Adam Charles, and Jonathan Pillow. Sparse-coding variational auto-
466 encoders. *bioRxiv*, page 399246, 2018.
- 467 [34] Chethan Pandarinath, Daniel J O’Shea, Jasmine Collins, Rafal Jozefowicz, Sergey D Stavisky,
468 Jonathan C Kao, Eric M Trautmann, Matthew T Kaufman, Stephen I Ryu, Leigh R

- 469 Hochberg, et al. Inferring single-trial neural population dynamics using sequential auto-
470 encoders. *Nature methods*, page 1, 2018.
- 471 [35] Alexander B Wiltschko, Matthew J Johnson, Giuliano Iurilli, Ralph E Peterson, Jesse M
472 Katon, Stan L Pashkovski, Victoria E Abraira, Ryan P Adams, and Sandeep Robert Datta.
473 Mapping sub-second structure in mouse behavior. *Neuron*, 88(6):1121–1135, 2015.
- 474 [36] Matthew J Johnson, David K Duvenaud, Alex Wiltschko, Ryan P Adams, and Sandeep R
475 Datta. Composing graphical models with neural networks for structured representations and
476 fast inference. In *Advances in neural information processing systems*, pages 2946–2954, 2016.
- 477 [37] Eleanor Batty, Matthew Whiteway, Shreya Saxena, Dan Biderman, Taiga Abe, Simon Musall,
478 Winthrop Gillis, Jeffrey Markowitz, Anne Churchland, John Cunningham, et al. Behavenet:
479 nonlinear embedding and bayesian neural decoding of behavioral videos. *Advances in Neural
480 Information Processing Systems*, 2019.
- 481 [38] Andrew Gelman and Cosma Rohilla Shalizi. Philosophy and the practice of bayesian statistics.
482 *British Journal of Mathematical and Statistical Psychology*, 66(1):8–38, 2013.
- 483 [39] David M Blei. Build, compute, critique, repeat: Data analysis with latent variable models.
484 2014.
- 485 [40] Mark K Transtrum, Benjamin B Machta, Kevin S Brown, Bryan C Daniels, Christopher R
486 Myers, and James P Sethna. Perspective: Sloppiness and emergent theories in physics,
487 biology, and beyond. *The Journal of chemical physics*, 143(1):07B201_1, 2015.
- 488 [41] Dustin Tran, Rajesh Ranganath, and David Blei. Hierarchical implicit models and likelihood-
489 free variational inference. In *Advances in Neural Information Processing Systems*, pages
490 5523–5533, 2017.
- 491 [42] Danilo Jimenez Rezende and Shakir Mohamed. Variational inference with normalizing flows.
492 *International Conference on Machine Learning*, 2015.
- 493 [43] George Papamakarios, Theo Pavlakou, and Iain Murray. Masked autoregressive flow for
494 density estimation. In *Advances in Neural Information Processing Systems*, pages 2338–2347,
495 2017.
- 496 [44] Gabriel Loaiza-Ganem, Yuanjun Gao, and John P Cunningham. Maximum entropy flow
497 networks. *International Conference on Learning Representations*, 2017.

- 498 [45] Mark S Goldman, Jorge Golowasch, Eve Marder, and LF Abbott. Global structure, ro-
499 bustness, and modulation of neuronal models. *Journal of Neuroscience*, 21(14):5229–5238,
500 2001.
- 501 [46] Ashok Litwin-Kumar, Robert Rosenbaum, and Brent Doiron. Inhibitory stabilization and
502 visual coding in cortical circuits with multiple interneuron subtypes. *Journal of neurophysiology*,
503 115(3):1399–1409, 2016.
- 504 [47] Chunyu A Duan, Marino Pagan, Alex T Piet, Charles D Kopec, Athena Akrami, Alexander J
505 Riordan, Jeffrey C Erlich, and Carlos D Brody. Collicular circuits for flexible sensorimotor
506 routing. *bioRxiv*, page 245613, 2018.
- 507 [48] Eve Marder and Vatsala Thirumalai. Cellular, synaptic and network effects of neuromodula-
508 tion. *Neural Networks*, 15(4-6):479–493, 2002.
- 509 [49] Gabrielle J Gutierrez, Timothy O’Leary, and Eve Marder. Multiple mechanisms switch an
510 electrically coupled, synaptically inhibited neuron between competing rhythmic oscillators.
511 *Neuron*, 77(5):845–858, 2013.
- 512 [50] Edwin T Jaynes. Information theory and statistical mechanics. *Physical review*, 106(4):620,
513 1957.
- 514 [51] Gamaleldin F Elsayed and John P Cunningham. Structure in neural population recordings:
515 an expected byproduct of simpler phenomena? *Nature neuroscience*, 20(9):1310, 2017.
- 516 [52] Cristina Savin and Gašper Tkačik. Maximum entropy models as a tool for building precise
517 neural controls. *Current opinion in neurobiology*, 46:120–126, 2017.
- 518 [53] Mark S Goldman. Memory without feedback in a neural network. *Neuron*, 61(4):621–634,
519 2009.
- 520 [54] Brendan K Murphy and Kenneth D Miller. Balanced amplification: a new mechanism of
521 selective amplification of neural activity patterns. *Neuron*, 61(4):635–648, 2009.
- 522 [55] Hirofumi Ozeki, Ian M Finn, Evan S Schaffer, Kenneth D Miller, and David Ferster. Inhibitory
523 stabilization of the cortical network underlies visual surround suppression. *Neuron*, 62(4):578–
524 592, 2009.

- 525 [56] Daniel B Rubin, Stephen D Van Hooser, and Kenneth D Miller. The stabilized supralinear
526 network: a unifying circuit motif underlying multi-input integration in sensory cortex.
527 *Neuron*, 85(2):402–417, 2015.
- 528 [57] Henry Markram, Maria Toledo-Rodriguez, Yun Wang, Anirudh Gupta, Gilad Silberberg, and
529 Caizhi Wu. Interneurons of the neocortical inhibitory system. *Nature reviews neuroscience*,
530 5(10):793, 2004.
- 531 [58] Bernardo Rudy, Gordon Fishell, SooHyun Lee, and Jens Hjerling-Leffler. Three groups of
532 interneurons account for nearly 100% of neocortical gabaergic neurons. *Developmental neu-*
533 *robiology*, 71(1):45–61, 2011.
- 534 [59] Robin Tremblay, Soohyun Lee, and Bernardo Rudy. GABAergic Interneurons in the Neocor-
535 tex: From Cellular Properties to Circuits. *Neuron*, 91(2):260–292, 2016.
- 536 [60] Carsten K Pfeffer, Mingshan Xue, Miao He, Z Josh Huang, and Massimo Scanziani. Inhi-
537 bition of inhibition in visual cortex: the logic of connections between molecularly distinct
538 interneurons. *Nature Neuroscience*, 16(8):1068, 2013.
- 539 [61] Luis Carlos Garcia Del Molino, Guangyu Robert Yang, Jorge F. Mejias, and Xiao Jing
540 Wang. Paradoxical response reversal of top- down modulation in cortical circuits with three
541 interneuron types. *Elife*, 6:1–15, 2017.
- 542 [62] Guang Chen, Carl Van Vreeswijk, David Hansel, and David Hansel. Mechanisms underlying
543 the response of mouse cortical networks to optogenetic manipulation. 2019.
- 544 [63] Guillaume Hennequin, Yashar Ahmadian, Daniel B Rubin, Máté Lengyel, and Kenneth D
545 Miller. The dynamical regime of sensory cortex: stable dynamics around a single stimulus-
546 tuned attractor account for patterns of noise variability. *Neuron*, 98(4):846–860, 2018.
- 547 [64] Agostina Palmigiano, Francesco Fumarola, Daniel P Mossing, Nataliya Kraynyukova, Hillel
548 Adesnik, and Kenneth Miller. Structure and variability of optogenetic responses identify the
549 operating regime of cortex. *bioRxiv*, 2020.
- 550 [65] Chunyu A Duan, Jeffrey C Erlich, and Carlos D Brody. Requirement of prefrontal and
551 midbrain regions for rapid executive control of behavior in the rat. *Neuron*, 86(6):1491–1503,
552 2015.

- 553 [66] Nataliya Kraynyukova and Tatjana Tchumatchenko. Stabilized supralinear network can give
554 rise to bistable, oscillatory, and persistent activity. *Proceedings of the National Academy of*
555 *Sciences*, 115(13):3464–3469, 2018.
- 556 [67] Katherine Morrison, Anda Degeratu, Vladimir Itskov, and Carina Curto. Diversity of emer-
557 gent dynamics in competitive threshold-linear networks: a preliminary report. *arXiv preprint*
558 *arXiv:1605.04463*, 2016.
- 559 [68] Xaq Pitkow and Dora E Angelaki. Inference in the brain: statistics flowing in redundant
560 population codes. *Neuron*, 94(5):943–953, 2017.
- 561 [69] Rodrigo Echeveste, Laurence Aitchison, Guillaume Hennequin, and Máté Lengyel. Cortical-
562 like dynamics in recurrent circuits optimized for sampling-based probabilistic inference.
563 *bioRxiv*, page 696088, 2019.
- 564 [70] Francesca Mastrogiovanni and Srdjan Ostojic. Linking connectivity, dynamics, and compu-
565 tations in low-rank recurrent neural networks. *Neuron*, 99(3):609–623, 2018.
- 566 [71] Blake A Richards and et al. A deep learning framework for neuroscience. *Nature Neuroscience*,
567 2019.
- 568 [72] Wiktor Młynarski, Michal Hledík, Thomas R Sokolowski, and Gašper Tkačik. Statistical
569 analysis and optimality of neural systems. *bioRxiv*, page 848374, 2020.
- 570 [73] Lawrence Saul and Michael Jordan. A mean field learning algorithm for unsupervised neural
571 networks. In *Learning in graphical models*, pages 541–554. Springer, 1998.
- 572 [74] Nicholas Metropolis, Arianna W Rosenbluth, Marshall N Rosenbluth, Augusta H Teller, and
573 Edward Teller. Equation of state calculations by fast computing machines. *The journal of*
574 *chemical physics*, 21(6):1087–1092, 1953.
- 575 [75] W Keith Hastings. Monte carlo sampling methods using markov chains and their applications.
576 1970.
- 577 [76] Mark Girolami and Ben Calderhead. Riemann manifold langevin and hamiltonian monte
578 carlo methods. *Journal of the Royal Statistical Society: Series B (Statistical Methodology)*,
579 73(2):123–214, 2011.

- 580 [77] Andrew Golightly and Darren J Wilkinson. Bayesian parameter inference for stochastic bio-
581 chemical network models using particle markov chain monte carlo. *Interface focus*, 1(6):807–
582 820, 2011.
- 583 [78] Kyle Cranmer, Johann Brehmer, and Gilles Louppe. The frontier of simulation-based infer-
584 ence. *Proceedings of the National Academy of Sciences*, 2020.
- 585 [79] Mark A Beaumont, Wenyang Zhang, and David J Balding. Approximate bayesian computa-
586 tion in population genetics. *Genetics*, 162(4):2025–2035, 2002.
- 587 [80] Paul Marjoram, John Molitor, Vincent Plagnol, and Simon Tavaré. Markov chain monte carlo
588 without likelihoods. *Proceedings of the National Academy of Sciences*, 100(26):15324–15328,
589 2003.
- 590 [81] Sean R Bittner, Agostina Palmigiano, Kenneth D Miller, and John P Cunningham. Degener-
591 ate solution networks for theoretical neuroscience. *Computational and Systems Neuroscience
592 Meeting (COSYNE), Lisbon, Portugal*, 2019.
- 593 [82] Sean R Bittner, Alex T Piet, Chunyu A Duan, Agostina Palmigiano, Kenneth D Miller,
594 Carlos D Brody, and John P Cunningham. Examining models in theoretical neuroscience
595 with degenerate solution networks. *Bernstein Conference 2019, Berlin, Germany*, 2019.
- 596 [83] Marcel Nonnenmacher, Pedro J Goncalves, Giacomo Bassetto, Jan-Matthis Lueckmann, and
597 Jakob H Macke. Robust statistical inference for simulation-based models in neuroscience. In
598 *Bernstein Conference 2018, Berlin, Germany*, 2018.
- 599 [84] Deistler Michael, , Pedro J Goncalves, Kaan Oecal, and Jakob H Macke. Statistical infer-
600 ence for analyzing sloppiness in neuroscience models. In *Bernstein Conference 2019, Berlin,
601 Germany*, 2019.
- 602 [85] Pedro J Gonçalves, Jan-Matthis Lueckmann, Michael Deistler, Marcel Nonnenmacher, Kaan
603 Öcal, Giacomo Bassetto, Chaitanya Chintaluri, William F Podlaski, Sara A Haddad, Tim P
604 Vogels, et al. Training deep neural density estimators to identify mechanistic models of neural
605 dynamics. *bioRxiv*, page 838383, 2019.
- 606 [86] Jan-Matthis Lueckmann, Pedro J Goncalves, Giacomo Bassetto, Kaan Öcal, Marcel Nonnen-
607 macher, and Jakob H Macke. Flexible statistical inference for mechanistic models of neural
608 dynamics. In *Advances in Neural Information Processing Systems*, pages 1289–1299, 2017.

- 609 [87] George Papamakarios, David Sterratt, and Iain Murray. Sequential neural likelihood: Fast
610 likelihood-free inference with autoregressive flows. In *The 22nd International Conference on*
611 *Artificial Intelligence and Statistics*, pages 837–848. PMLR, 2019.
- 612 [88] Joeri Hermans, Volodimir Begy, and Gilles Louppe. Likelihood-free mcmc with amortized
613 approximate ratio estimators. In *International Conference on Machine Learning*, pages 4239–
614 4248. PMLR, 2020.
- 615 [89] Martin J Wainwright, Michael I Jordan, et al. Graphical models, exponential families, and
616 variational inference. *Foundations and Trends® in Machine Learning*, 1(1–2):1–305, 2008.
- 617 [90] Sean R Bittner and John P Cunningham. Approximating exponential family models (not
618 single distributions) with a two-network architecture. *arXiv preprint arXiv:1903.07515*, 2019.
- 619 [91] Johan Karlsson, Milena Anguelova, and Mats Jirstrand. An efficient method for structural
620 identifiability analysis of large dynamic systems. *IFAC Proceedings Volumes*, 45(16):941–946,
621 2012.
- 622 [92] Ricky TQ Chen, Yulia Rubanova, Jesse Bettencourt, and David K Duvenaud. Neural ordinary
623 differential equations. In *Advances in neural information processing systems*, pages 6571–6583,
624 2018.
- 625 [93] Xuechen Li, Ting-Kam Leonard Wong, Ricky TQ Chen, and David Duvenaud. Scalable
626 gradients for stochastic differential equations. *arXiv preprint arXiv:2001.01328*, 2020.
- 627 [94] Andreas Raue, Clemens Kreutz, Thomas Maiwald, Julie Bachmann, Marcel Schilling, Ursula
628 Klingmüller, and Jens Timmer. Structural and practical identifiability analysis of partially
629 observed dynamical models by exploiting the profile likelihood. *Bioinformatics*, 25(15):1923–
630 1929, 2009.
- 631 [95] Dhruva V Raman, James Anderson, and Antonis Papachristodoulou. Delineating parameter
632 unidentifiabilities in complex models. *Physical Review E*, 95(3):032314, 2017.
- 633 [96] Maria Pia Saccomani, Stefania Audoly, and Leontina D’Angiò. Parameter identifiability of
634 nonlinear systems: the role of initial conditions. *Automatica*, 39(4):619–632, 2003.
- 635 [97] George Papamakarios, Eric Nalisnick, Danilo Jimenez Rezende, Shakir Mohamed, and Bal-
636 aji Lakshminarayanan. Normalizing flows for probabilistic modeling and inference. *arXiv*
637 *preprint arXiv:1912.02762*, 2019.

- 638 [98] Laurent Dinh, Jascha Sohl-Dickstein, and Samy Bengio. Density estimation using real nvp.
639 *Proceedings of the 5th International Conference on Learning Representations*, 2017.
- 640 [99] Durk P Kingma and Prafulla Dhariwal. Glow: Generative flow with invertible 1x1 convolu-
641 tions. In *Advances in neural information processing systems*, pages 10215–10224, 2018.
- 642 [100] Durk P Kingma, Tim Salimans, Rafal Jozefowicz, Xi Chen, Ilya Sutskever, and Max Welling.
643 Improved variational inference with inverse autoregressive flow. *Advances in neural informa-*
644 *tion processing systems*, 29:4743–4751, 2016.
- 645 [101] Diederik P Kingma and Jimmy Ba. Adam: A method for stochastic optimization. *Interna-*
646 *tional Conference on Learning Representations*, 2015.
- 647 [102] David M Blei, Alp Kucukelbir, and Jon D McAuliffe. Variational inference: A review for
648 statisticians. *Journal of the American Statistical Association*, 112(518):859–877, 2017.

649 **5 Methods**

650 **5.1 Emergent property inference (EPI)**

651 Determining the combinations of model parameters that can produce observed data or a desired
652 output is a key part of scientific practice. Solving inverse problems is especially important in
653 neuroscience, since we require complex models to describe the complex phenomena of neural com-
654 putations. While much machine learning research has focused on how to find latent structure
655 in large-scale neural datasets, less has focused on inverting theoretical circuit models conditioned
656 upon the emergent phenomena they produce. Here, we introduce a novel method for statistical
657 inference, which finds distributions of parameter solutions that only produce the desired emer-
658 gent property. This method seamlessly handles neural circuit models with stochastic nonlinear
659 dynamical generative processes, which are predominant in theoretical neuroscience.

660 Consider model parameterization \mathbf{z} , which is a collection of scientifically interesting variables that
661 govern the complex simulation of data \mathbf{x} . For example (see Section 3.1), \mathbf{z} may be the electrical
662 conductance parameters of an STG subcircuit, and \mathbf{x} the evolving membrane potentials of the five
663 neurons. In terms of statistical modeling, this circuit model has an intractable likelihood $p(\mathbf{x} | \mathbf{z})$,
664 which is predicated by the stochastic differential equations that define the model. Even so, we do
665 not scientifically reason about how \mathbf{z} governs all of \mathbf{x} , but rather specific phenomena that are a
666 function of the data $f(\mathbf{x}; \mathbf{z})$. In the STG example, $f(\mathbf{x}; \mathbf{z})$ measures hub neuron frequency from the
667 evolution of \mathbf{x} governed by \mathbf{z} . With EPI, we learn distributions of \mathbf{z} that results in an average and
668 variance of $f(\mathbf{x}; \mathbf{z})$, denoted $\boldsymbol{\mu}$ and $\boldsymbol{\sigma}^2$. We refer to the collection of these statistical moments as an
669 emergent property. Such emergent properties \mathcal{X} are defined through choice of $f(\mathbf{x}; \mathbf{z})$ (which may
670 be one or multiple statistics), $\boldsymbol{\mu}$, and $\boldsymbol{\sigma}^2$

$$\mathcal{X} : \mathbb{E}_{\mathbf{z}, \mathbf{x}} [f(\mathbf{x}; \mathbf{z})] = \boldsymbol{\mu}, \text{Var}_{\mathbf{z}, \mathbf{x}} [f(\mathbf{x}; \mathbf{z})] = \boldsymbol{\sigma}^2. \quad (15)$$

671 Precisely, the emergent property statistics $f(\mathbf{x}; \mathbf{z})$ must have means $\boldsymbol{\mu}$ and variances $\boldsymbol{\sigma}^2$ over the
672 EPI distribution of parameters and stochasticity of the data given the parameters.

673 In EPI, deep probability distributions are used as posterior approximations $q_{\boldsymbol{\theta}}(\mathbf{z} | \mathcal{X})$. In deep
674 probability distributions, a simple random variable $\mathbf{z}_0 \sim q_0(\mathbf{z}_0)$ is mapped deterministically via a
675 sequence of deep neural network layers (g_1, \dots, g_l) parameterized by weights and biases $\boldsymbol{\theta}$ to the
676 support of the distribution of interest:

$$\mathbf{z} = g_{\boldsymbol{\theta}}(\mathbf{z}_0) = g_l(\dots g_1(\mathbf{z}_0)) \sim q_{\boldsymbol{\theta}}(\mathbf{z}). \quad (16)$$

677 Such deep probability distributions embed the posterior distribution in a deep network. Once
 678 optimized, this deep network representation has remarkably useful properties: immediate posterior
 679 sampling, and immediate probability, gradient, and Hessian evaluation at any parameter choice.
 680 Given a choice of model $p(\mathbf{x} \mid \mathbf{z})$ and emergent property of interest \mathcal{X} , $q_{\theta}(\mathbf{z})$ is optimized via
 681 the neural network parameters θ to find a maximally entropic distribution q_{θ}^* within the deep
 682 variational family \mathcal{Q} producing the emergent property \mathcal{X} :

$$q_{\theta}(\mathbf{z} \mid \mathcal{X}) = q_{\theta}^*(\mathbf{z}) = \operatorname{argmax}_{q_{\theta} \in \mathcal{Q}} H(q_{\theta}(\mathbf{z})) \quad (17)$$

s.t. $\mathcal{X} : \mathbb{E}_{\mathbf{z}, \mathbf{x}} [f(\mathbf{x}; \mathbf{z})] = \boldsymbol{\mu}, \operatorname{Var}_{\mathbf{z}, \mathbf{x}} [f(\mathbf{x}; \mathbf{z})] = \boldsymbol{\sigma}^2.$

683 Entropy is chosen as the normative selection principle, since we want the posterior to only contain
 684 structure predicated by the emergent property [50, 51]. This choice of selection principle is also
 685 that of standard Bayesian inference, and we derive an exact relation between EPI and variational
 686 inference (see Section 5.1.5). However, a key difference is that variational inference and other
 687 Bayesian methods do not constrain the predictions of their inferred posteriors. This optimization
 688 is executed using the algorithm of Maximum Entropy Flow Networks (MEFNs) [44].

689 In the remainder of Section 5.1, we will explain the finer details and motivation of the EPI method.
 690 First, we explain related approaches and what EPI introduces to this domain (Section 5.1.1). Sec-
 691 ond, we describe the special class of deep probability distributions used in EPI called normalizing
 692 flows (Section 5.1.2). Next, we explain the constrained optimization technique used to solve Equa-
 693 tion 17 (Section 5.1.3). Then, we demonstrate the details of this optimization in a toy example
 694 (Section 5.1.4). Finally, we establish the known relationship between maximum entropy distribu-
 695 tions and exponential families (Section 5.1.5), which is used to explain the relation between EPI
 696 and variational inference (Section 5.1.6).

697 5.1.1 Related approaches

698 When Bayesian inference problems lack conjugacy, scientists use approximate inference methods
 699 like variational inference (VI) [73] and Markov chain Monte Carlo (MCMC) [74, 75]. After opti-
 700 mization, variational methods return a parameterized posterior distribution, which we can analyze.
 701 Also, the variational approximating distribution class is often chosen such that it permits fast
 702 sampling. In contrast MCMC methods only produce samples from the approximated posterior dis-
 703 tribution. No parameterized distribution is estimated, and additional samples are always generated
 704 with the same sampling complexity. Inference in models defined by systems of differential has been

705 demonstrated with MCMC [76], although this approach requires tractable likelihoods. Advances
706 have leveraged structure in stochastic differential equation models to improve likelihood
707 approximations, thus expanding the domain of applicable models [77].

708 Likelihood-free (or “simulation-based”) inference (LFI) [78] is model parameter inference in the
709 absence of a tractable likelihood function. The most prevalent approach to LFI is approximate
710 Bayesian computation [79], in which satisfactory parameter samples are kept from random prior
711 sampling according to a rejection heuristic. The obtained set of parameters do not have a prob-
712 abilities, and further insight about the model must be gained from examination of the parameter
713 set and their generated activity. Methodological advances to ABC methods have come through
714 the use of Markov chain Monte Carlo (MCMC-ABC) [80] and sequential Monte Carlo (SMC-ABC)
715 [27] sampling techniques. SMC-ABC is considered state-of-the-art ABC, yet this approach still
716 struggles to scale in dimensionality (cf. Fig. 4). Furthermore, once a parameter set has been
717 obtained by SMC-ABC from a finite set of particles, the SMC-ABC algorithm must be run again
718 with a new population of initialized particles to obtain additional samples.

719 For scientific model analysis, we seek a posterior distribution exhibiting the properties of a well-
720 chosen variational approximation: a parametric form conferring analytic calculations, and trivial
721 sampling time. For this reason, ABC and MCMC techniques are unattractive, since they only
722 produce a set of parameter samples and have unchanging sampling rate. EPI executes likelihood-
723 free inference using the MEFN [44] algorithm using a deep variational posterior approximation.
724 The deep neural network of EPI defines the parametric form of the posterior approximation. Fur-
725 thermore, the EPI distribution is constrained to produce an emergent property. In other words,
726 the summary statistics of the posterior predictive distribution are fixed to have certain first and
727 second moments. EPI optimization is enabled using stochastic gradient techniques in the spirit
728 of likelihood-free variational inference [41]. The analytic relationship between EPI and variational
729 inference is explained in Secton 5.1.6.

730 We note that, during our preparation and early presentation of this work [81, 82], another work
731 has arisen with broadly similar goals: bringing statistical inference to mechanistic models of neural
732 circuits ([83, 84, 85]). We are encouraged by this general problem being recognized by others in the
733 community, and we emphasize that these works offer complementary neuroscientific contributions
734 (different theoretical models of focus) and use different technical methodologies (ours is built on
735 our prior work [44], theirs similarly [86]).

736 The method EPI differs from SNPE in some key ways. SNPE belongs to a “sequential” class of

737 recently developed LFI methods in which two neural networks are used for posterior inference.
738 This first neural network is a normalizing flow used to estimate the posterior $p(\mathbf{z} | \mathbf{x})$ (SNPE)
739 or the likelihood $p(\mathbf{x} | \mathbf{z})$ (sequential neural likelihood (SNL [87])). A recent advance uses an
740 unconstrained neural network to estimate the likelihood ratio (sequential neural ratio estimation
741 (SNRE [88])). In SNL and SNRE, MCMC sampling techniques are used to obtain samples from
742 the approximated posterior. This contrasts with EPI and SNPE, which afford a normalizing flow
743 approximation to the posterior, which facilitates immediate measurements of sample probability,
744 gradient, or Hessian for system analysis. The second neural network in this sequential class of
745 methods is the amortizer. This network maps data \mathbf{x} (or statistics $f(\mathbf{x}; \mathbf{z})$ or model parameters \mathbf{z})
746 to the weights and biases of the first neural network. These methods are optimized on a conditional
747 density (or ratio) estimation objective on a sequentially adapting finite sample-based approximation
748 to the posterior.

749 The approximating fidelity of the first neural network in sequential approaches is optimized to
750 generalize across the entire distribution it is conditioned upon. This optimization towards gen-
751 eralization of sequential methods can reduce the accuracy at the singular posterior of interest.
752 Whereas in EPI, the entire expressivity of the normalizing flow is dedicated to learning a single
753 distribution as well as possible. While amortization is not possible in EPI parameterized by the
754 mean parameter μ (due to the inverse mapping problem [89]), we have shown this two-network
755 amortization approach to be effective in exponential family distributions defined by their natural
756 parameterization [90].

757 Structural identifiability analysis involves the measurement of sensitivity and unidentifiabilities in
758 natural models. Around a point, one can measure the Jacobian. One approach that scales well is
759 EAR [91]. A popular efficient approach for systems of ODEs has been neural ODE adjoint [92] and
760 its stochastic adaptation [93]. Casting identifiability as a statistical estimation problem, the profile
761 likelihood can assess via iterated optimization while holding parameters fixed [94]. An exciting
762 recent method is capable of recovering the functional form of such unidentifiabilities away from a
763 point by following degenerate dimensions of the fisher information matrix [95]. Global structural
764 non-identifiabilities can be found for models with polynomial or rational dynamics equations using
765 DAISY [96]. With EPI, we have all the benefits given by a statistical inference method plus the
766 ability to query the gradient or Hessian of the inferred distribution at any chosen parameter value.

767 **5.1.2 Normalizing flows**

768 Deep probability distributions are comprised of multiple layers of fully connected neural networks
 769 (Equation). When each neural network layer is restricted to be a bijective function, the sample
 770 density can be calculated using the change of variables formula at each layer of the network. For
 771 $\mathbf{z}_i = g_i(\mathbf{z}_{i-1})$,

$$p(\mathbf{z}_i) = p(g_i^{-1}(\mathbf{z}_i)) \left| \det \frac{\partial g_i^{-1}(\mathbf{z}_i)}{\partial \mathbf{z}_i} \right| = p(\mathbf{z}_{i-1}) \left| \det \frac{\partial g_i(\mathbf{z}_{i-1})}{\partial \mathbf{z}_{i-1}} \right|^{-1}. \quad (18)$$

772 However, this computation has cubic complexity in dimensionality for fully connected layers. By
 773 restricting our layers to normalizing flows [42, 97] – bijective functions with fast log determinant
 774 Jacobian computations, which confer a fast calculation of the sample log probability. Fast log
 775 probability calculation confers efficient optimization of the maximum entropy objective (see Section
 776 5.1.3). We use the Real NVP [98] normalizing flow class, because its coupling architecture confers
 777 both fast sampling (forward) and fast log probability evaluation (backward). Fast probability
 778 evaluation in turn facilitates fast gradient and Hessian evaluation of log probability throughout
 779 parameter space. Glow permutations were used in between coupling stages [99]. This is in contrast
 780 to autoregressive architectures [43, 100], in which only forward or backward passes are efficient.
 781 Normalizing flow architectures for deep probability distributions used in EPI are specified by the
 782 number of coupling stages, neural network layers and units per layer for conditioning functions.

783 **5.1.3 Augmented Lagrangian optimization**

784 To optimize $q_{\boldsymbol{\theta}}(\mathbf{z})$ in Equation 17, the constrained optimization is executed using the augmented
 785 Lagrangian method. The following objective is minimized:

$$L(\boldsymbol{\theta}; \boldsymbol{\eta}_{\text{opt}}, c) = -H(q_{\boldsymbol{\theta}}) + \boldsymbol{\eta}_{\text{opt}}^\top R(\boldsymbol{\theta}) + \frac{c}{2} \|R(\boldsymbol{\theta})\|^2 \quad (19)$$

786 where $R(\boldsymbol{\theta}) = \mathbb{E}_{\mathbf{z} \sim q_{\boldsymbol{\theta}}} [\mathbb{E}_{\mathbf{x} \sim p(\mathbf{x}|\mathbf{z})} [T(\mathbf{x}; \mathbf{z}) - \boldsymbol{\mu}_{\text{opt}}]]$, $\boldsymbol{\eta}_{\text{opt}} \in \mathbb{R}^m$ are the Lagrange multipliers where
 787 $m = |\boldsymbol{\mu}_{\text{opt}}| = |T(\mathbf{x}; \mathbf{z})|$, and c is the penalty coefficient. These Lagrange multipliers are closely
 788 related to the natural parameters $\boldsymbol{\eta}$ of exponential families (see Section 5.1.6). Deep neural network
 789 weights and biases $\boldsymbol{\theta}$ of the deep probability distribution are optimized according to Equation 19
 790 using the Adam optimizer with learning rate 10^{-3} [101].

791 To take gradients with respect to the entropy $H(q_{\boldsymbol{\theta}}(\mathbf{z}))$, it can be expressed using the reparam-
 792 eterization trick as an expectation of the negative log density of parameter samples \mathbf{z} over the

793 randomness in the parameterless initial distribution $q_0(\mathbf{z}_0)$:

$$H(q_{\theta}(\mathbf{z})) = \int -q_{\theta}(\mathbf{z}) \log(q_{\theta}(\mathbf{z})) d\mathbf{z} = \mathbb{E}_{\mathbf{z} \sim q_{\theta}} [-\log(q_{\theta}(\mathbf{z}))] = \mathbb{E}_{\mathbf{z}_0 \sim q_0} [-\log(q_{\theta}(g_{\theta}(\mathbf{z}_0)))]. \quad (20)$$

794 Thus, the gradient of the entropy of the deep probability distribution can be estimated as an
795 average with respect to the base distribution \mathbf{z}_0 :

$$\nabla_{\theta} H(q_{\theta}(\mathbf{z})) = \mathbb{E}_{\mathbf{z}_0 \sim q_0} [-\nabla_{\theta} \log(q_{\theta}(g_{\theta}(\mathbf{z}_0)))] . \quad (21)$$

796 The lagrangian parameters η_{opt} are initialized to zero and adapted following each augmented
797 Lagrangian epoch, which is a period of optimization with fixed (η_{opt}, c) for a given number of
798 stochastic optimization iterations. A low value of c is used initially, and conditionally increased
799 after each epoch based on constraint error reduction. The penalty coefficient is updated based
800 on the result of a hypothesis test regarding the reduction in constraint violation. The p-value of
801 $\mathbb{E}[|R(\theta_{k+1})|] > \gamma \mathbb{E}[|R(\theta_k)|]$ is computed, and c_{k+1} is updated to βc_k with probability $1 - p$. The
802 other update rule is $\eta_{\text{opt},k+1} = \eta_{\text{opt},k} + c_k \frac{1}{n} \sum_{i=1}^n (T(\mathbf{x}^{(i)}) - \mu_{\text{opt}})$ given a batch size n . Throughout
803 the study, $\beta = 4.0$, $\gamma = 0.25$, and the batch size was a hyperparameter, which varied according to
804 the application of EPI.

805 The intention is that c and η_{opt} start at values encouraging entropic growth early in optimization.
806 With each training epoch in which the update rule for c is invoked by unsatisfactory constraint
807 error reduction, the constraint satisfaction terms are increasingly weighted, resulting in a decreased
808 entropy. This encourages the discovery of suitable regions of parameter space, and the subsequent
809 refinement of the distribution to produce the emergent property (see example in Section 5.1.4). The
810 momentum parameters of the Adam optimizer are reset at the end of each augmented Lagrangian
811 epoch.

812 Rather than starting optimization from some θ drawn from a randomized distribution, we found
813 that initializing $q_{\theta}(\mathbf{z})$ to approximate an isotropic Gaussian distribution conferred more stable, con-
814 sistent optimization. The parameters of the Gaussian initialization were chosen on an application-
815 specific basis. Throughout the study, we chose isotropic Gaussian initializations with mean μ_{init}
816 at the center of the distribution support and some standard deviation σ_{init} , except for one case,
817 where an initialization informed by random search was used (see Section 5.2.1).

818 To assess whether the EPI distribution $q_{\theta}(\mathbf{z})$ produces the emergent property, we defined a hy-
819 pothesis testing convergence criteria. The algorithm has converged when a null hypothesis test of
820 constraint violations $R(\theta)_i$ being zero is accepted for all constraints $i \in \{1, \dots, m\}$ at a significance

821 threshold $\alpha = 0.05$. This significance threshold is adjusted through Bonferroni correction according
 822 to the number of constraints m . The p-values for each constraint are calculated according to
 823 a two-tailed nonparametric test, where 200 estimations of the sample mean $R(\boldsymbol{\theta})^i$ are made from
 824 k resamplings of \mathbf{z} from a finite sample of size n taken at the end of the augmented Lagrangian
 825 epoch.

826 When assessing the suitability of EPI for a particular modeling question, there are some important
 827 technical considerations. First and foremost, as in any optimization problem, the defined emergent
 828 property should always be appropriately conditioned (constraints should not have wildly different
 829 units). Furthermore, if the program is underconstrained (not enough constraints), the distribution
 830 grows (in entropy) unstably unless mapped to a finite support. If overconstrained, there is no pa-
 831 rameter set producing the emergent property, and EPI optimization will fail (appropriately). Next,
 832 one should consider the computational cost of the gradient calculations. In the best circumstance,
 833 there is a simple, closed form expression (e.g. Section 5.2.4) for the emergent property statistic
 834 given the model parameters. On the other end of the spectrum, many forward simulation iterations
 835 may be required before a high quality measurement of the emergent property statistic is available
 836 (e.g. Section 5.2.1). In such cases, backpropagating gradients through the SDE evolution will be
 837 expensive.

838 5.1.4 Example: 2D LDS

839 To gain intuition for EPI, consider a two-dimensional linear dynamical system (2D LDS) model
 840 (Fig. S1A):

$$\tau \frac{d\mathbf{x}}{dt} = A\mathbf{x} \quad (22)$$

841 with

$$A = \begin{bmatrix} a_1 & a_2 \\ a_3 & a_4 \end{bmatrix}. \quad (23)$$

842 To run EPI with the dynamics matrix elements as the free parameters $\mathbf{z} = [a_1, a_2, a_3, a_4]$ (fix-
 843 ing $\tau = 1$), the emergent property statistics $T(\mathbf{x})$ were chosen to contain the first and second
 844 moments of the oscillatory frequency, $\frac{\text{imag}(\lambda_1)}{2\pi}$, and the growth/decay factor, $\text{real}(\lambda_1)$, of the oscil-
 845 lating system. λ_1 is the eigenvalue of greatest real part when the imaginary component is zero, and
 846 alternatively of positive imaginary component when the eigenvalues are complex conjugate pairs.
 847 To learn the distribution of real entries of A that produce a band of oscillating systems around
 848 1Hz, we formalized this emergent property as $\text{real}(\lambda_1)$ having mean zero with variance 0.25², and

849 the oscillation frequency $2\pi\text{imag}(\lambda_1)$ having mean $\omega = 1$ Hz with variance $(0.1\text{Hz})^2$:

$$\mathbb{E}[T(\mathbf{x})] \triangleq \mathbb{E} \begin{bmatrix} \text{real}(\lambda_1) \\ \text{imag}(\lambda_1) \\ (\text{real}(\lambda_1) - 0)^2 \\ (\text{imag}(\lambda_1) - 2\pi\omega)^2 \end{bmatrix} = \begin{bmatrix} 0.0 \\ 2\pi\omega \\ 0.25^2 \\ (2\pi\omega)^2 \end{bmatrix} \triangleq \boldsymbol{\mu}. \quad (24)$$

850

851 Unlike the models we presented in the main text, this model admits an analytical form for the
 852 mean emergent property statistics given parameter \mathbf{z} , since the eigenvalues can be calculated using
 853 the quadratic formula:

$$\lambda = \frac{\left(\frac{a_1+a_4}{\tau}\right) \pm \sqrt{\left(\frac{a_1+a_4}{\tau}\right)^2 + 4\left(\frac{a_2a_3-a_1a_4}{\tau}\right)}}{2}. \quad (25)$$

854 Importantly, even though $\mathbb{E}_{\mathbf{x} \sim p(\mathbf{x}|\mathbf{z})}[T(\mathbf{x})]$ is calculable directly via a closed form function and
 855 does not require simulation, we cannot derive the distribution $q_{\boldsymbol{\theta}}^*$ directly. This fact is due to the
 856 formally hard problem of the backward mapping: finding the natural parameters η from the mean
 857 parameters $\boldsymbol{\mu}$ of an exponential family distribution [89]. Instead, we used EPI to approximate this
 858 distribution (Fig. S1B). We used a real-NVP normalizing flow architecture with four masks, two
 859 neural network layers of 15 units per mask, with batch normalization momentum 0.99, mapped
 860 onto a support of $z_i \in [-10, 10]$. (see Section 5.1.2).

861 Even this relatively simple system has nontrivial (though intuitively sensible) structure in the
 862 parameter distribution. To validate our method, we analytically derived the contours of the prob-
 863 ability density from the emergent property statistics and values. In the a_1 - a_4 plane, the black
 864 line at $\text{real}(\lambda_1) = \frac{a_1+a_4}{2} = 0$, dotted black line at the standard deviation $\text{real}(\lambda_1) = \frac{a_1+a_4}{2} \pm 0.25$,
 865 and the dotted gray line at twice the standard deviation $\text{real}(\lambda_1) = \frac{a_1+a_4}{2} \pm 0.5$ follow the contour
 866 of probability density of the samples (Fig. S2A). The distribution precisely reflects the desired
 867 statistical constraints and model degeneracy in the sum of a_1 and a_4 . Intuitively, the parameters
 868 equivalent with respect to emergent property statistic $\text{real}(\lambda_1)$ have similar log densities.

869 To explain the bimodality of the EPI distribution, we examined the imaginary component of λ_1 .

870 When $\text{real}(\lambda_1) = \frac{a_1+a_4}{2} = 0$, we have

$$\text{imag}(\lambda_1) = \begin{cases} \sqrt{\frac{a_1a_4-a_2a_3}{\tau}}, & \text{if } a_1a_4 < a_2a_3 \\ 0 & \text{otherwise} \end{cases}. \quad (26)$$

871 When $\tau = 1$ and $a_1a_4 > a_2a_3$ (center of distribution above), we have the following equation for the

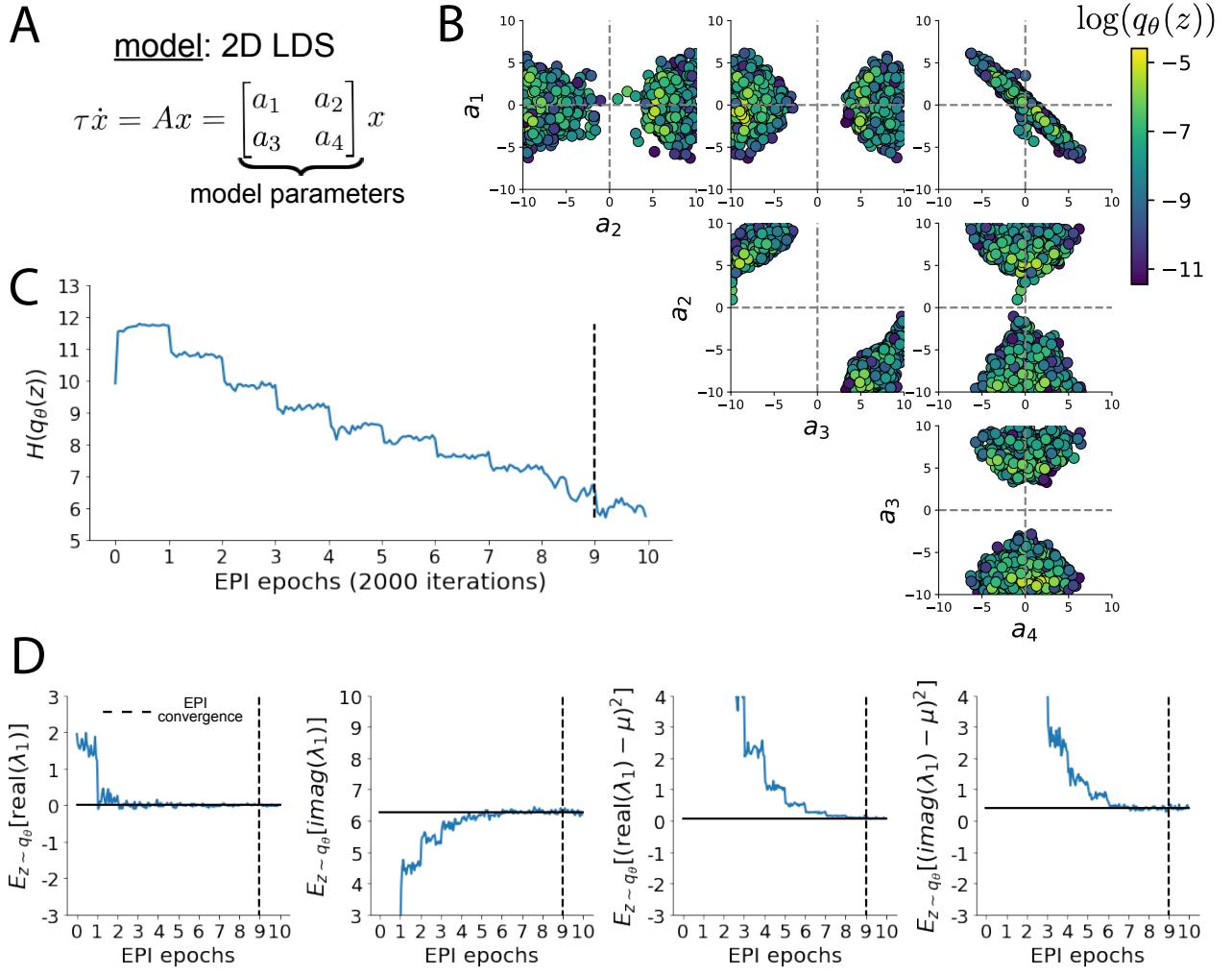


Figure 5: (LDS1): A. Two-dimensional linear dynamical system model, where real entries of the dynamics matrix A are the parameters. B. The EPI distribution for a two-dimensional linear dynamical system with $\tau = 1$ that produces an average of 1Hz oscillations with some small amount of variance. Dashed lines indicate the parameter axes. C. Entropy throughout the optimization. At the beginning of each augmented Lagrangian epoch (2,000 iterations), the entropy dipped due to the shifted optimization manifold where emergent property constraint satisfaction is increasingly weighted. D. Emergent property moments throughout optimization. At the beginning of each augmented Lagrangian epoch, the emergent property moments adjust closer to their constraints.

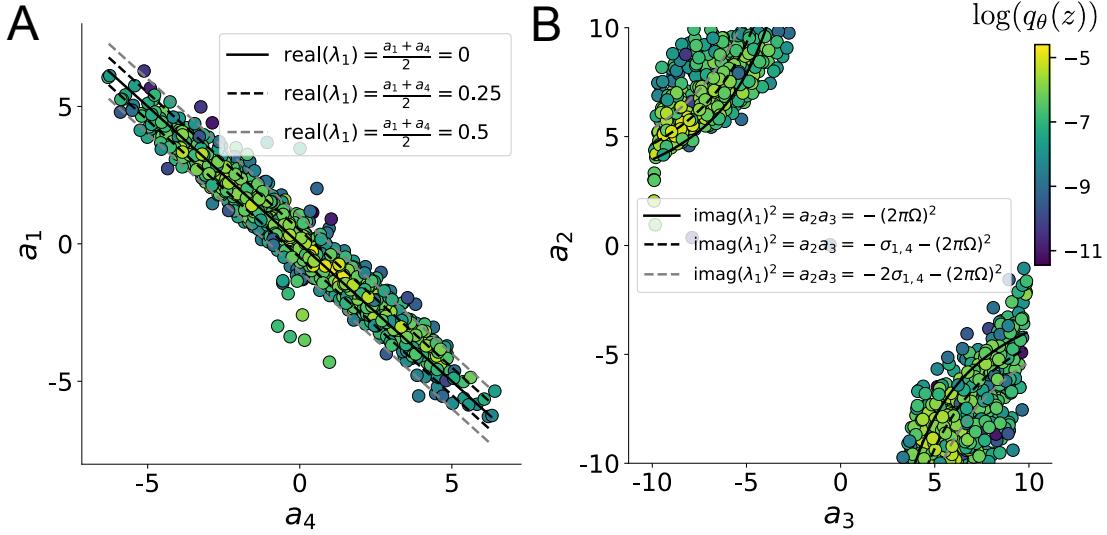


Figure 6: (LDS2): A. Probability contours in the a_1 - a_4 plane were derived from the relationship to emergent property statistic of growth/decay factor $\text{real}(\lambda_1)$. B. Probability contours in the a_2 - a_3 plane were derived from the emergent property statistic of oscillation frequency $2\pi\text{imag}(\lambda_1)$.

872 other two dimensions:

$$\text{imag}(\lambda_1)^2 = a_1 a_4 - a_2 a_3 \quad (27)$$

873 Since we constrained $\mathbb{E}_{\mathbf{z} \sim q_\theta} [\text{imag}(\lambda)] = 2\pi$ (with $\omega = 1$), we can plot contours of the equation
 874 $\text{imag}(\lambda_1)^2 = a_1 a_4 - a_2 a_3 = (2\pi)^2$ for various $a_1 a_4$ (Fig. S2B). With $\sigma_{1,4} = \mathbb{E}_{\mathbf{z} \sim q_\theta} [|a_1 a_4 - E_{q_\theta}[a_1 a_4]|]$,
 875 we show the contours as $a_1 a_4 = 0$ (black), $a_1 a_4 = -\sigma_{1,4}$ (black dotted), and $a_1 a_4 = -2\sigma_{1,4}$ (grey
 876 dotted). This validates the curved structure of the inferred distribution learned through EPI. We
 877 took steps in negative standard deviation of $a_1 a_4$ (dotted and gray lines), since there are few positive
 878 values $a_1 a_4$ in the learned distribution. Subtler combinations of model and emergent property will
 879 have more complexity, further motivating the use of EPI for understanding these systems. As we
 880 expect, the distribution results in samples of two-dimensional linear systems oscillating near 1Hz
 881 (Fig. S3).

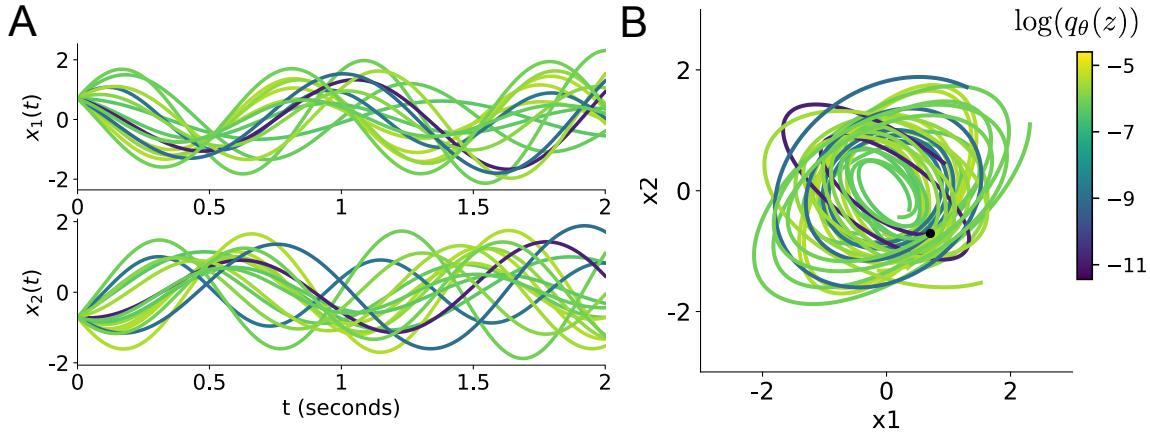


Figure 7: (LDS3): Sampled dynamical systems $\mathbf{z} \sim q_{\theta}(\mathbf{z})$ and their simulated activity from $\mathbf{x}(0) = [\frac{\sqrt{2}}{2}, -\frac{\sqrt{2}}{2}]$ colored by log probability. A. Each dimension of the simulated trajectories throughout time. B The simulated trajectories in phase space.

882 5.1.5 Maximum entropy distributions and exponential families

883 Maximum entropy distributions have a fundamental link to exponential family distributions. A
 884 maximum entropy distribution of form:

$$p^*(\mathbf{z}) = \underset{p \in \mathcal{P}}{\operatorname{argmax}} H(p(\mathbf{z})) \quad (28)$$

s.t. $\mathbb{E}_{\mathbf{z} \sim p} [T(\mathbf{z})] = \boldsymbol{\mu}_{\text{opt}}$.

885 will have probability density in the exponential family:

$$p^*(\mathbf{z}) \propto \exp(\boldsymbol{\eta}^\top T(\mathbf{z})). \quad (29)$$

886 The mappings between the mean parameterization $\boldsymbol{\mu}_{\text{opt}}$ and the natural parameterization $\boldsymbol{\eta}$ are
 887 formally hard to identify [89].

888 In EPI, emergent properties are defined as statistics having a fixed mean and variance as in Equation
 889 2

$$\mathbb{E}_{\mathbf{z}, \mathbf{x}} [f(\mathbf{x}; \mathbf{z})] = \boldsymbol{\mu}, \operatorname{Var}_{\mathbf{z}, \mathbf{x}} [f(\mathbf{x}; \mathbf{z})] = \sigma^2. \quad (30)$$

890 The variance constraint is a second moment constraint on $f(\mathbf{x}; \mathbf{z})$

$$\operatorname{Var}_{\mathbf{z}, \mathbf{x}} [f(\mathbf{x}; \mathbf{z})] = \mathbb{E}_{\mathbf{z}, \mathbf{x}} [(f(\mathbf{x}; \mathbf{z}) - \boldsymbol{\mu})^2] \quad (31)$$

891 As a general maximum entropy distribution (Equation 28), the sufficient statistics vector contains
 892 both first and second order moments of $f(\mathbf{x}; \mathbf{z})$

$$T(\mathbf{x}; \mathbf{z}) = \begin{bmatrix} f(\mathbf{x}; \mathbf{z}) \\ (f(\mathbf{x}; \mathbf{z}) - \boldsymbol{\mu})^2 \end{bmatrix}, \quad (32)$$

893 which are constrained to the chosen means and variances

$$\boldsymbol{\mu}_{\text{opt}} = \begin{bmatrix} \boldsymbol{\mu} \\ \sigma^2 \end{bmatrix}. \quad (33)$$

894 **5.1.6 EPI as variational inference**

895 In Bayesian inference a prior belief about model parameters \mathbf{z} is stated in a prior distribution $p(\mathbf{z})$,
 896 and the statistical model capturing the effect of \mathbf{z} on observed data points \mathbf{x} is formalized in the
 897 likelihood distribution $p(\mathbf{x} | \mathbf{z})$. In Bayesian inference, we obtain a posterior distribution $p(z | \mathbf{x})$,
 898 which captures how the data inform our knowledge of model parameters using Bayes' rule:

$$p(\mathbf{z} | \mathbf{x}) = \frac{p(\mathbf{x} | \mathbf{z})p(\mathbf{z})}{p(\mathbf{x})}. \quad (34)$$

899 The posterior distribution is analytically available when the prior is conjugate with the likelihood.
 900 However, conjugacy is rare in practice, and alternative methods, such as variational inference [102],
 901 are utilized.

902 In variational inference, a posterior approximation $q_{\boldsymbol{\theta}}^*$ is chosen from within some variational family
 903 \mathcal{Q}

$$q_{\boldsymbol{\theta}}^*(\mathbf{z}) = \underset{q_{\boldsymbol{\theta}} \in \mathcal{Q}}{\operatorname{argmin}} KL(q_{\boldsymbol{\theta}}(\mathbf{z}) || p(\mathbf{z} | \mathbf{x})). \quad (35)$$

904 The KL divergence can be written in terms of entropy of the variational approximation:

$$KL(q_{\boldsymbol{\theta}}(\mathbf{z}) || p(\mathbf{z} | \mathbf{x})) = \mathbb{E}_{\mathbf{z} \sim q_{\boldsymbol{\theta}}} [\log(q_{\boldsymbol{\theta}}(\mathbf{z}))] - \mathbb{E}_{\mathbf{z} \sim q_{\boldsymbol{\theta}}} [\log(p(\mathbf{z} | \mathbf{x}))] \quad (36)$$

905

$$= -H(q_{\boldsymbol{\theta}}) - \mathbb{E}_{\mathbf{z} \sim q_{\boldsymbol{\theta}}} [\log(p(\mathbf{x} | \mathbf{z})) + \log(p(\mathbf{z})) - \log(p(\mathbf{x}))] \quad (37)$$

906 Since the marginal distribution of the data $p(\mathbf{x})$ (or ‘evidence’) is independent of $\boldsymbol{\theta}$, variational
 907 inference is executed by optimizing the remaining expression. This is usually framed as maximizing
 908 the evidence lower bound (ELBO)

$$\underset{q_{\boldsymbol{\theta}} \in \mathcal{Q}}{\operatorname{argmin}} KL(q_{\boldsymbol{\theta}} || p(\mathbf{z} | \mathbf{x})) = \underset{q_{\boldsymbol{\theta}} \in \mathcal{Q}}{\operatorname{argmax}} H(q_{\boldsymbol{\theta}}) + \mathbb{E}_{\mathbf{z} \sim q_{\boldsymbol{\theta}}} [\log(p(\mathbf{x} | \mathbf{z})) + \log(p(\mathbf{z}))]. \quad (38)$$

909 Now, consider the setting where we have chosen a uniform prior, and stipulate a mean-field gaussian
 910 likelihood on a chosen statistic of the data $f(\mathbf{x}; \mathbf{z})$

$$p(\mathbf{x} | \mathbf{z}) = \mathcal{N}(f(\mathbf{x}; \mathbf{z}) | \boldsymbol{\mu}_f, \Sigma_f), \quad (39)$$

911 where $\Sigma_f = \text{diag}(\boldsymbol{\sigma}_f^2)$. The log likelihood is then proportional to a dot product of the natural
 912 parameter of this mean-field gaussian distribution and the first and second moment statistics.

$$\log p(\mathbf{x} | \mathbf{z}) \propto \boldsymbol{\eta}_f^\top T(\mathbf{x}, \mathbf{z}), \quad (40)$$

913 where

$$\boldsymbol{\eta}_f = \begin{bmatrix} \frac{\boldsymbol{\mu}_f}{\boldsymbol{\sigma}_f^2} \\ \frac{-1}{2\boldsymbol{\sigma}_f^2} \end{bmatrix}, \text{ and} \quad (41)$$

$$T(\mathbf{x}; \mathbf{z}) = \begin{bmatrix} f(\mathbf{x}; \mathbf{z}) \\ (f(\mathbf{x}; \mathbf{z}) - \boldsymbol{\mu}_f)^2 \end{bmatrix}. \quad (42)$$

914 The variational objective is then

$$\underset{q_\theta \in Q}{\operatorname{argmax}} H(q_\theta) + \boldsymbol{\eta}_f^\top \mathbb{E}_{\mathbf{z} \sim q_\theta} [T(\mathbf{x}; \mathbf{z})] \quad (43)$$

915 Comparing this to the Lagrangian objective (without augmentation) of EPI, we see they are the
 916 same

$$\begin{aligned} q_\theta^*(\mathbf{z}) &= \underset{q_\theta \in Q}{\operatorname{argmin}} -H(q_\theta) + \boldsymbol{\eta}_{\text{opt}}^\top (\mathbb{E}_{\mathbf{z}, \mathbf{x}} [T(\mathbf{x}; \mathbf{z})] - \boldsymbol{\mu}_{\text{opt}}) \\ &= \underset{q_\theta \in Q}{\operatorname{argmin}} -H(q_\theta) + \boldsymbol{\eta}_{\text{opt}}^\top \mathbb{E}_{\mathbf{z}, \mathbf{x}} [T(\mathbf{x}; \mathbf{z})]. \end{aligned} \quad (44)$$

917 where $T(\mathbf{x}; \mathbf{z})$ consists of the first and second moments of the emergent property statistic $f(\mathbf{x}; \mathbf{z})$
 918 (Equation 32). Thus, EPI is implicitly executing variational inference with a uniform prior and a
 919 mean-field gaussian likelihood on the emergent property statistics. The data \mathbf{x} used by this implicit
 920 variational inference program would be that generated by the adapting variational approximation
 921 $\mathbf{x} \sim p(\mathbf{x} | \mathbf{z})q_\theta(\mathbf{z})$, and the likelihood parameters $\boldsymbol{\eta}_f$ of EPI optimization epoch k are predicated
 922 by $\boldsymbol{\eta}_{\text{opt}, k}$. However, in EPI we have not specified a prior distribution, or collected data, which can
 923 inform us about model parameters. Instead we have a mathematical specification of an emergent
 924 property, which the model must produce, and a maximum entropy selection principle. Accordingly,
 925 we replace the notation of $p(\mathbf{z} | \mathbf{x})$ with $p(\mathbf{z} | \mathcal{X})$ conceptualizing an inferred distribution that obeys
 926 emergent property \mathcal{X} (see Section 5.1).

928 **5.2 Theoretical models**

929 In this study, we used emergent property inference to examine several models relevant to theoretical
 930 neuroscience. Here, we provide the details of each model and the related analyses.

931 **5.2.1 Stomatogastric ganglion**

932 We analyze how the parameters $\mathbf{z} = [g_{el}, g_{synA}]$ govern the emergent phenomena of intermediate
 933 hub frequency in a model of the stomatogastric ganglion (STG) [49] shown in Figure 1A with
 934 activity $\mathbf{x} = [x_{f1}, x_{f2}, x_{hub}, x_{s1}, x_{s2}]$, using the same hyperparameter choices as Gutierrez et al.
 935 Each neuron's membrane potential $x_\alpha(t)$ for $\alpha \in \{f1, f2, hub, s1, s2\}$ is the solution of the following
 936 stochastic differential equation:

$$C_m \frac{dx_\alpha}{dt} = -[h_{leak}(\mathbf{x}; \mathbf{z}) + h_{Ca}(\mathbf{x}; \mathbf{z}) + h_K(\mathbf{x}; \mathbf{z}) + h_{hyp}(\mathbf{x}; \mathbf{z}) + h_{elec}(\mathbf{x}; \mathbf{z}) + h_{syn}(\mathbf{x}; \mathbf{z})] + dB. \quad (45)$$

937 The input current of each neuron is the sum of the leak, calcium, potassium, hyperpolarization,
 938 electrical and synaptic currents as well as gaussian noise dB . Each current component is a function
 939 of all membrane potentials and the conductance parameters \mathbf{z} .

940 The capacitance of the cell membrane was set to $C_m = 1nF$. Specifically, the currents are the
 941 difference in the neuron's membrane potential and that current type's reversal potential multiplied
 942 by a conductance:

$$h_{leak}(\mathbf{x}; \mathbf{z}) = g_{leak}(x_\alpha - V_{leak}) \quad (46)$$

$$h_{elec}(\mathbf{x}; \mathbf{z}) = g_{el}(x_\alpha^{post} - x_\alpha^{pre}) \quad (47)$$

$$h_{syn}(\mathbf{x}; \mathbf{z}) = g_{syn}S_\infty^{pre}(x_\alpha^{post} - V_{syn}) \quad (48)$$

$$h_{Ca}(\mathbf{x}; \mathbf{z}) = g_{Ca}M_\infty(x_\alpha - V_{Ca}) \quad (49)$$

$$h_K(\mathbf{x}; \mathbf{z}) = g_KN(x_\alpha - V_K) \quad (50)$$

$$h_{hyp}(\mathbf{x}; \mathbf{z}) = g_hH(x_\alpha - V_{hyp}). \quad (51)$$

943 The reversal potentials were set to $V_{leak} = -40mV$, $V_{Ca} = 100mV$, $V_K = -80mV$, $V_{hyp} = -20mV$,
 944 and $V_{syn} = -75mV$. The other conductance parameters were fixed to $g_{leak} = 1 \times 10^{-4}\mu S$. g_{Ca} ,
 945 g_K , and g_{hyp} had different values based on fast, intermediate (hub) or slow neuron. The fast
 950 conductances had values $g_{Ca} = 1.9 \times 10^{-2}$, $g_K = 3.9 \times 10^{-2}$, and $g_{hyp} = 2.5 \times 10^{-2}$. The intermediate
 951 conductances had values $g_{Ca} = 1.7 \times 10^{-2}$, $g_K = 1.9 \times 10^{-2}$, and $g_{hyp} = 8.0 \times 10^{-3}$. Finally, the
 952 slow conductances had values $g_{Ca} = 8.5 \times 10^{-3}$, $g_K = 1.5 \times 10^{-2}$, and $g_{hyp} = 1.0 \times 10^{-2}$.
 953

954 Furthermore, the Calcium, Potassium, and hyperpolarization channels have time-dependent gating
 955 dynamics dependent on steady-state gating variables M_∞ , N_∞ and H_∞ , respectively:

$$M_\infty = 0.5 \left(1 + \tanh \left(\frac{x_\alpha - v_1}{v_2} \right) \right) \quad (52)$$

$$\frac{dN}{dt} = \lambda_N (N_\infty - N) \quad (53)$$

$$N_\infty = 0.5 \left(1 + \tanh \left(\frac{x_\alpha - v_3}{v_4} \right) \right) \quad (54)$$

$$\lambda_N = \phi_N \cosh \left(\frac{x_\alpha - v_3}{2v_4} \right) \quad (55)$$

$$\frac{dH}{dt} = \frac{(H_\infty - H)}{\tau_h} \quad (56)$$

$$H_\infty = \frac{1}{1 + \exp \left(\frac{x_\alpha + v_5}{v_6} \right)} \quad (57)$$

$$\tau_h = 272 - \left(\frac{-1499}{1 + \exp \left(\frac{-x_\alpha + v_7}{v_8} \right)} \right). \quad (58)$$

962 where we set $v_1 = 0mV$, $v_2 = 20mV$, $v_3 = 0mV$, $v_4 = 15mV$, $v_5 = 78.3mV$, $v_6 = 10.5mV$,
 963 $v_7 = -42.2mV$, $v_8 = 87.3mV$, $v_9 = 5mV$, and $v_{th} = -25mV$.

964 Finally, there is a synaptic gating variable as well:

$$S_\infty = \frac{1}{1 + \exp \left(\frac{v_{th} - x_\alpha}{v_9} \right)}. \quad (59)$$

965 When the dynamic gating variables are considered, this is actually a 15-dimensional nonlinear
 966 dynamical system. Gaussian noise of variance $(1 \times 10^{-12})^2$ amps makes the model stochastic, and
 967 introduces variability in frequency at each parameterization \mathbf{z} .

968 In order to measure the frequency of the hub neuron during EPI, the STG model was simulated for
 969 $T = 300$ time steps of $dt = 25ms$. The chosen dt and T were the most computationally convenient
 970 choices yielding accurate frequency measurement. We used a basis of complex exponentials with
 971 frequencies from 0.0-1.0 Hz at 0.01Hz resolution to measure frequency from simulated time series

$$\Phi = [0.0, 0.01, \dots, 1.0]^\top .. \quad (60)$$

972 To measure spiking frequency, we processed simulated membrane potentials with a relu (spike
 973 extraction) and low-pass filter with averaging window of size 20, then took the frequency with the
 974 maximum absolute value of the complex exponential basis coefficients of the processed time-series.
 975 The first 20 temporal samples of the simulation are ignored to account for initial transients.

976 To differentiate through the maximum frequency identification, we used a soft-argmax Let $X_\alpha \in$
 977 $\mathcal{C}^{|\Phi|}$ be the complex exponential filter bank dot products with the signal $x_\alpha \in \mathbb{R}^N$, where $\alpha \in$
 978 $\{f1, f2, \text{hub}, s1, s2\}$. The soft-argmax is then calculated using temperature parameter $\beta = 100$

$$\psi_\alpha = \text{softmax}(\beta |X_\alpha| \odot i), \quad (61)$$

979 where $i = [0, 1, \dots, 100]$. The frequency is then calculated as

$$\omega_\alpha = 0.01\psi_\alpha \text{Hz}. \quad (62)$$

980 Intermediate hub frequency, like all other emergent properties in this work, is defined by the mean
 981 and variance of the emergent property statistics. In this case, we have one statistic, hub neuron
 982 frequency, where the mean was chosen to be 0.55Hz, and variance was chosen to be $(0.025\text{Hz})^2$ to
 983 capture variation in frequency between 0.5Hz and 0.6Hz (Equation 2). As a maximum entropy dis-
 984 tribution, $T(\mathbf{x}, \mathbf{z})$ is comprised of both these first and second moments of the hub neuron frequency
 985 (as in Equations 32 and 33)

$$T(\mathbf{x}; \mathbf{z}) = \begin{bmatrix} \omega_{\text{hub}}(\mathbf{x}; \mathbf{z}) \\ (\omega_{\text{hub}}(\mathbf{x}; \mathbf{z}) - 0.55)^2 \end{bmatrix}, \quad (63)$$

986

$$\boldsymbol{\mu}_{\text{opt}} = \begin{bmatrix} 0.55 \\ 0.025^2 \end{bmatrix}. \quad (64)$$

987 Throughout optimization, the augmented Lagrangian parameters η and c , were updated after each
 988 epoch of 5,000 iterations(see Section 5.1.3). The optimization converged after five epochs (Fig. S4).

989 For EPI in Fig 1E, we used a real NVP architecture with three coupling layers of affine transfor-
 990 mations parameterized by two-layer neural networks of 25 units per layer. The initial distribution was
 991 a standard isotropic gaussian $z_0 \sim \mathcal{N}(\mathbf{0}, I)$ mapped to a support of $\mathbf{z} = [g_{\text{el}}, g_{\text{synA}}] \in [4, 8] \times [0.01, 4]$.
 992 We did not include $g_{\text{synA}} < 0.01$, since conductances that low make the circuit simulations numeri-
 993 cally unstable. We used an augmented Lagrangian coefficient of $c_0 = 10^5$, a batch size $n = 400$, set
 994 $\nu = 0.25$, and initialized $q_{\theta}(\mathbf{z})$ to produce a gaussian approximation to samples returned from an
 995 initial ABC search. This initialization had much greater entropy and a different emergent property
 996 than the returned EPI posterior.

997 TODO write about specifics of the Hessian analysis.

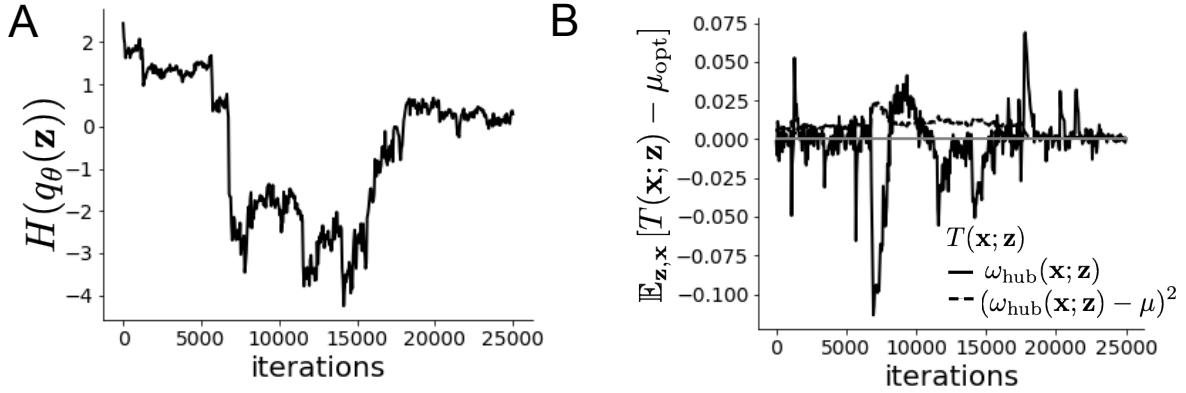


Figure 8: (STG1): EPI optimization of the STG model producing network syncing. A. Entropy throughout optimization. B. The emergent property statistic means and variances converge to their constraints at 25,000 iterations following the fifth augmented Lagrangian epoch.

998 5.2.2 Primary visual cortex

999 Connectivity (W_{fit}) and input ($\mathbf{h}_{b,\text{fit}}$ and $\mathbf{h}_{c,\text{fit}}$) parameters were fit using the deterministic V1 circuit
1000 model [64]

$$W_{\text{fit}} = \begin{bmatrix} W_{EE} & W_{EP} & W_{ES} & W_{EV} \\ W_{PE} & W_{PP} & W_{PS} & W_{PV} \\ W_{SE} & W_{SP} & W_{SS} & W_{SV} \\ W_{VE} & W_{VP} & W_{VS} & W_{VV} \end{bmatrix} = \begin{bmatrix} 2.18 & -1.19 & -.594 & -.229 \\ 1.66 & -.651 & -.680 & -.242 \\ .895 & -5.22 \times 10^{-3} & -1.51 \times 10^{-4} & -.761 \\ 3.34 & -2.31 & -.254 & -2.52 \times 10^{-4} \end{bmatrix}, \quad (65)$$

$$\mathbf{h}_{b,\text{fit}} = \begin{bmatrix} .416 \\ .429 \\ .491 \\ .486 \end{bmatrix}, \quad (66)$$

1001 and

$$\mathbf{h}_{c,\text{fit}} = \begin{bmatrix} .359 \\ .403 \\ 0 \\ 0 \end{bmatrix}. \quad (67)$$

1002 To obtain rates on a realistic scale (100-fold greater), we map these fitted parameters to an equiv-
 1003 alence class

$$W = \begin{bmatrix} W_{EE} & W_{EP} & W_{ES} & W_{EV} \\ W_{PE} & W_{PP} & W_{PS} & W_{PV} \\ W_{SE} & W_{SP} & W_{SS} & W_{SV} \\ W_{VE} & W_{VP} & W_{VS} & W_{VV} \end{bmatrix} = \begin{bmatrix} .218 & -.119 & -.0594 & -.0229 \\ .166 & -.0651 & -.068 & -.0242 \\ .0895 & -5.22 \times 10^{-4} & -1.51 \times 10^{-5} & -.0761 \\ .334 & -.231 & -.0254 & -2.52 \times 10^{-5} \end{bmatrix}, \quad (68)$$

$$\mathbf{h}_b = \begin{bmatrix} h_{b,E} \\ h_{b,P} \\ h_{b,S} \\ h_{b,V} \end{bmatrix} = \begin{bmatrix} 4.16 \\ 4.29 \\ 4.91 \\ 4.86 \end{bmatrix}, \quad (69)$$

1004 and

$$\mathbf{h}_c = \begin{bmatrix} h_{c,E} \\ h_{c,P} \\ h_{c,S} \\ h_{c,V} \end{bmatrix} = \begin{bmatrix} 3.59 \\ 4.03 \\ 0 \\ 0 \end{bmatrix}. \quad (70)$$

1005 Since the E-population of this network increases exponentially in the absense of recurrent inhibitory
 1006 feedback, we may also observe a paradoxical effect in the inhibitory populations (which is present
 1007 in E-I networks). At 50% contrast (Fig. 2B, dots), this network exhibits a paradoxical effect in
 1008 the P-population (Fig. 2C), but no others (Fig. 9). That is, for a small increase in h_P , $\mathbb{E}_t [x_P]$
 1009 decreases.

1010 Fano factor is calculated as the temporal variance divided by the temporal mean following sometime
 1011 t_{ss} following dynamical evolution from the initial state at $\mathbf{x}(t = 0)$.

1012 5.2.3 Superior colliculus

1013 In the model of Duan et al [47], there are four total units: two in each hemisphere corresponding to
 1014 the Pro/Contra and Anti/Ipsi populations. They are denoted as left Pro (LP), left Anti (LA), right
 1015 Pro (RP) and right Anti (RA). Each unit has an activity (x_α) and internal variable (u_α) related
 1016 by

$$x_\alpha = \phi(u_\alpha) = \left(\frac{1}{2} \tanh \left(\frac{u_\alpha - a}{b} \right) + \frac{1}{2} \right) \quad (71)$$

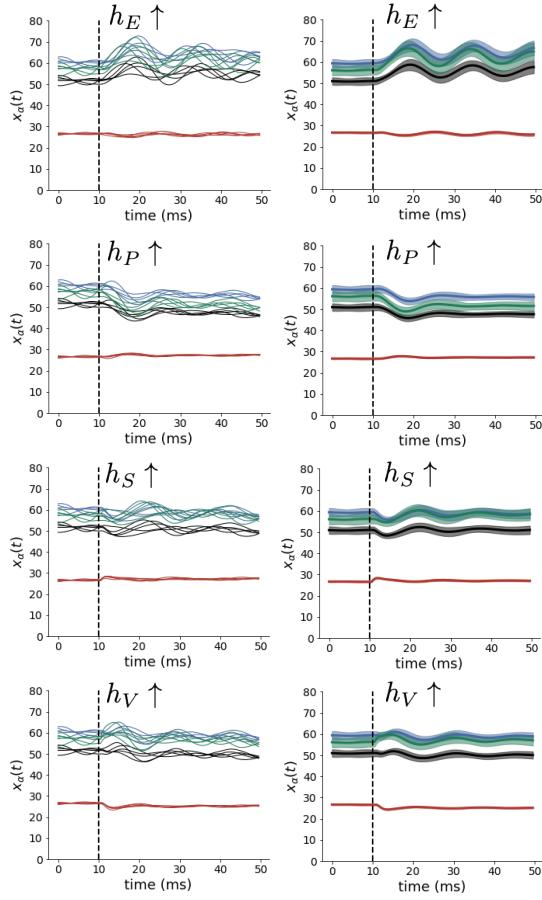


Figure 9: Supplemental Figure: (Left) Simulations for small increases in neuron-type population input. Input magnitudes are chosen so that effect is salient (0.002 for E and P, but 0.02 for S and V). (Right) Average and standard deviation of stochastic fluctuations of responses.

1017 where $\alpha \in \{LP, LA, RA, RP\}$, $a = 0.05$ and $b = 0.5$ control the position and shape of the nonlinearity, respectively. During periods of optogenetic inactivation, activity was decreased proportional
 1018 to the optogenetic strength γ
 1019

$$x_\alpha = (1 - \gamma)\phi(u_\alpha). \quad (72)$$

1020 We order the neural populations of x and u in the following manner

$$\mathbf{x} = \begin{bmatrix} x_{LP} \\ x_{LA} \\ x_{RP} \\ x_{RA} \end{bmatrix} \quad \mathbf{u} = \begin{bmatrix} u_{LP} \\ u_{LA} \\ u_{RP} \\ u_{RA} \end{bmatrix}, \quad (73)$$

1021 which evolve according to

$$\tau \frac{d\mathbf{u}}{dt} = -\mathbf{u} + W\mathbf{x} + \mathbf{h} + d\mathbf{B}. \quad (74)$$

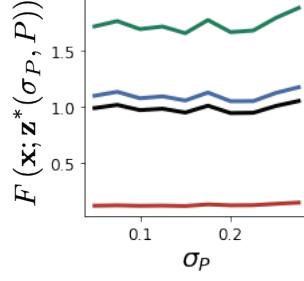


Figure 10: Supplemental Figure: Fano factors along the ridge of the posterior in Fig. 2E.

1022 with time constant $\tau = 0.09s$, step size 24ms and Gaussian noise $d\mathbf{B}$ of variance 0.2. The weight
1023 matrix has 4 parameters sW , vW , hW , and dW :

$$W = \begin{bmatrix} sW & vW & hW & dW \\ vW & sW & dW & hW \\ hW & dW & sW & vW \\ dW & hW & vW & sW \end{bmatrix}. \quad (75)$$

1024 The circuit receives four different inputs throughout each trial, which has a total length of 1.8s.

$$\mathbf{h} = \mathbf{h}_{\text{constant}} + \mathbf{h}_{\text{P,bias}} + \mathbf{h}_{\text{rule}} + \mathbf{h}_{\text{choice-period}} + \mathbf{h}_{\text{light}}. \quad (76)$$

1025 There is a constant input to every population,

$$\mathbf{h}_{\text{constant}} = I_{\text{constant}}[1, 1, 1, 1]^\top, \quad (77)$$

1026 a bias to the Pro populations

$$\mathbf{h}_{\text{P,bias}} = I_{\text{P,bias}}[1, 0, 1, 0]^\top, \quad (78)$$

1027 rule-based input depending on the condition

$$\mathbf{h}_{\text{P,rule}}(t) = \begin{cases} I_{\text{P,rule}}[1, 0, 1, 0]^\top, & \text{if } t \leq 1.2s \\ 0, & \text{otherwise} \end{cases} \quad (79)$$

1028

$$\mathbf{h}_{\text{A,rule}}(t) = \begin{cases} I_{\text{A,rule}}[0, 1, 0, 1]^\top, & \text{if } t \leq 1.2s \\ 0, & \text{otherwise} \end{cases}, \quad (80)$$

1029 a choice-period input

$$\mathbf{h}_{\text{choice}}(t) = \begin{cases} I_{\text{choice}}[1, 1, 1, 1]^\top, & \text{if } t > 1.2s \\ 0, & \text{otherwise} \end{cases}, \quad (81)$$

1030 and an input to the right or left-side depending on where the light stimulus is delivered

$$\mathbf{h}_{\text{light}}(t) = \begin{cases} I_{\text{light}}[1, 1, 0, 0]^\top, & \text{if } 1.2s < t < 1.5s \text{ and Left} \\ I_{\text{light}}[0, 0, 1, 1]^\top, & \text{if } 1.2s < t < 1.5s \text{ and Right} \\ 0, & \text{otherwise} \end{cases}. \quad (82)$$

1031 The input parameterization was fixed to $I_{\text{constant}} = 0.75$, $I_{\text{P,bias}} = 0.5$, $I_{\text{P,rule}} = 0.6$,
1032 $I_{\text{choice}} = 0.25$, and $I_{\text{light}} = 0.5$.

1033 The accuracies of p_P and p_A are calculated as

$$p_P(\mathbf{x}; \mathbf{z}) = \mathbb{E}_{\mathbf{x} \sim p(\mathbf{x}|\mathbf{z})} [\Theta[x_{LP}(t = 1.8s) - x_{RP}(t = 1.8s)]] \quad (83)$$

1034 and

$$p_A(\mathbf{x}; \mathbf{z}) = \mathbb{E}_{\mathbf{x} \sim p(\mathbf{x}|\mathbf{z})} [\Theta[x_{RP}(t = 1.8s) - x_{LP}(t = 1.8s)]] \quad (84)$$

1035 given that the stimulus is on the left side, where Θ is the Heaviside step function.

1036 The Heaviside step function is approximated as

$$\Theta(\mathbf{x}) = \text{sigmoid}(\beta \mathbf{x}), \quad (85)$$

1037 where $\beta = 100$.

1038 As a maximum entropy distribution, $T(\mathbf{x}, \mathbf{z})$ is comprised of both these first and second moments
1039 of the accuracy in each task (as in Equations 32 and 33)

$$T(\mathbf{x}; \mathbf{z}) = \begin{bmatrix} p(\mathbf{x}; \mathbf{z})_P \\ p(\mathbf{x}; \mathbf{z})_A \\ (p(\mathbf{x}; \mathbf{z})_P - 75\%)^2 \\ (p(\mathbf{x}; \mathbf{z})_A - 75\%)^2 \end{bmatrix}, \quad (86)$$

1040

$$\boldsymbol{\mu}_{\text{opt}} = \begin{bmatrix} 75\% \\ 75\% \\ 5\%^2 \\ 5\%^2 \end{bmatrix}. \quad (87)$$

1041 Throughout optimization, the augmented Lagrangian parameters η and c , were updated after each
1042 epoch of 2,000 iterations (see Section 5.1.3). The optimization converged after six epochs (Fig. 15).

1043 For EPI in Fig. 3C, we used a real NVP architecture with three coupling layers of affine transforma-
1044 tions parameterized by two-layer neural networks of 50 units per layer. The initial distribution was

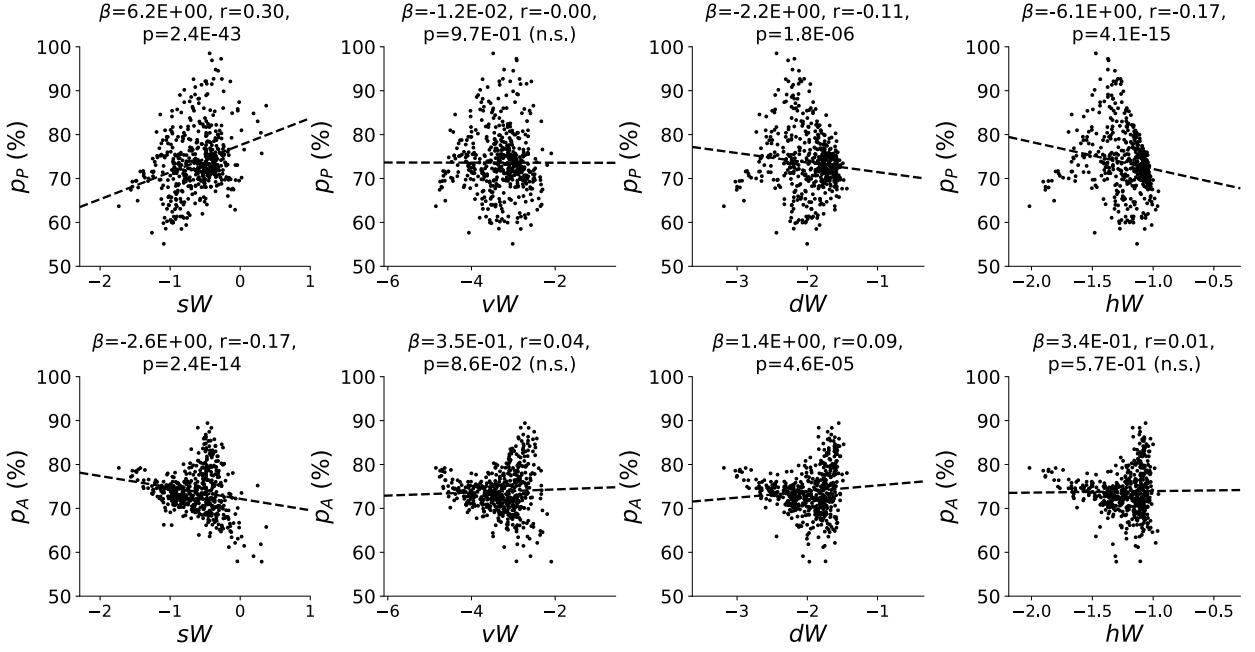


Figure 11: (SC1): Connectivity parameters of EPI distributions versus task accuracies. β is slope coefficient of linear regression, r is correlation, and p is the two-tailed p value.

1045 a standard isotropic gaussian $z_0 \sim \mathcal{N}(\mathbf{0}, I)$ mapped to a support of $\mathbf{z}_i \in [-5, 5]$. We used an aug-
 1046 mented Lagrangian coefficient of $c_0 = 10^2$, a batch size $n = 100$, set $\nu = 0.5$, and initialized $q_{\theta}(\mathbf{z})$
 1047 to produce an isotropic gaussian with mean 0 and variance 2.5^2 . Accuracies were estimated over
 1048 200 trials of random gaussian noise, which was sampled independently for each drawn parameter \mathbf{z}
 1049 and each iteration of the EPI optimization.

1050 5.2.4 Rank-2 RNN

1051 Traditional approaches to likelihood-free inference – approximate Bayesian computation (ABC)
 1052 methods – randomly sample parameters \mathbf{z} until a suitable set is obtained. State-of-the-art ABC
 1053 methods leverage sequential Monte Carlo (SMC) sampling techniques to obtain parameter sets more
 1054 efficiently. To obtain more parameter samples, SMC-ABC must be run from scratch again. ABC
 1055 methods do not confer log probabilities of samples. Like EPI, sequential neural posterior estimation
 1056 (SNPE) uses deep learning to produce flexible posterior approximations. Like traditional Bayesian
 1057 inference methods, SNPE conditions directly on the statistics of data. This differs from EPI, where
 1058 posteriors are conditioned on emergent properties (moment constraints on the posterior predictive
 1059 distribution). Peculiarities of SNPE (density estimation approach, two deep networks) make scaling

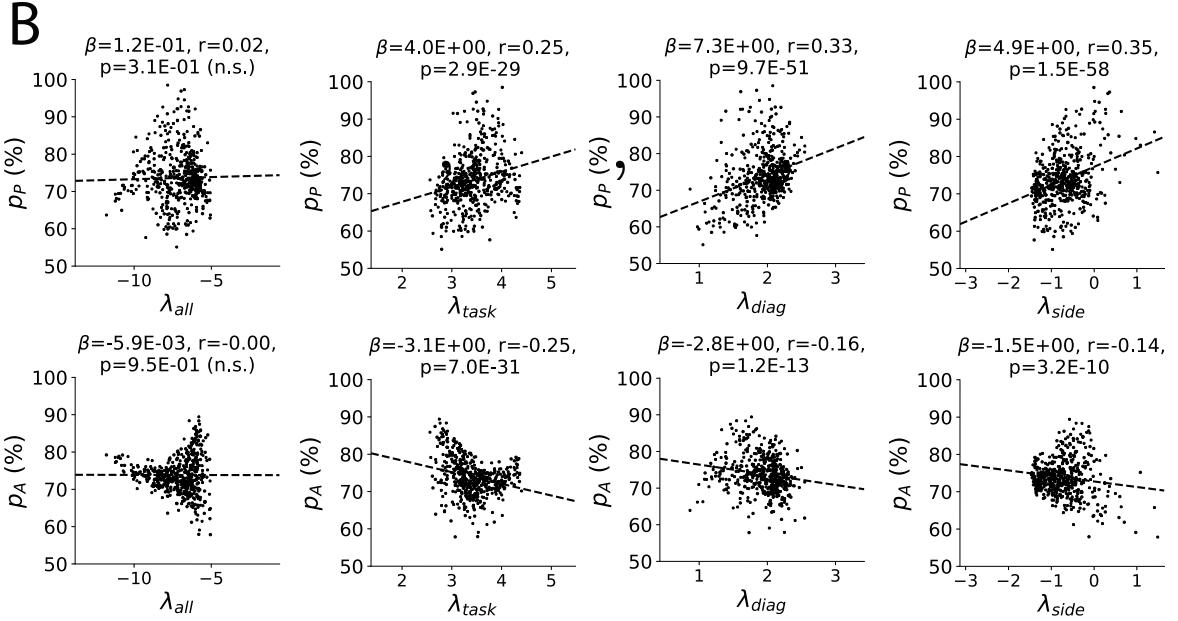
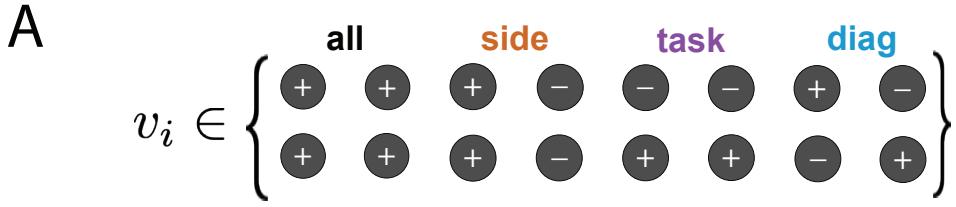


Figure 12: (SC2): A. Invariant eigenvectors of connectivity matrix W . B. Eigenvalues of connectivities of EPI distribution versus task accuracies.

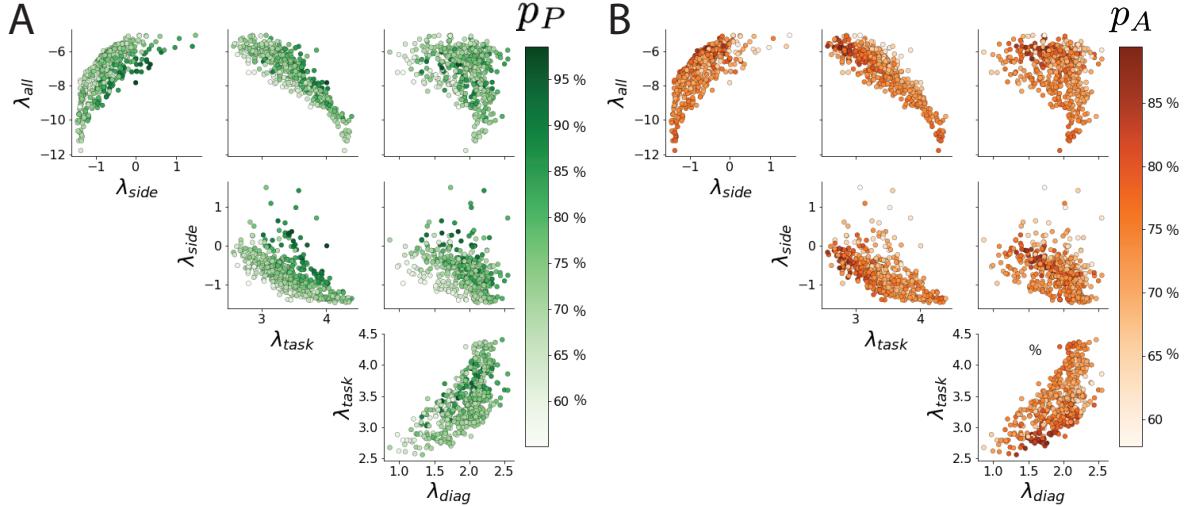


Figure 13: (SC3): A. Connectivity eigenvalues of EPI parameter distribution colored by Pro task accuracy. B. Same for Anti task.

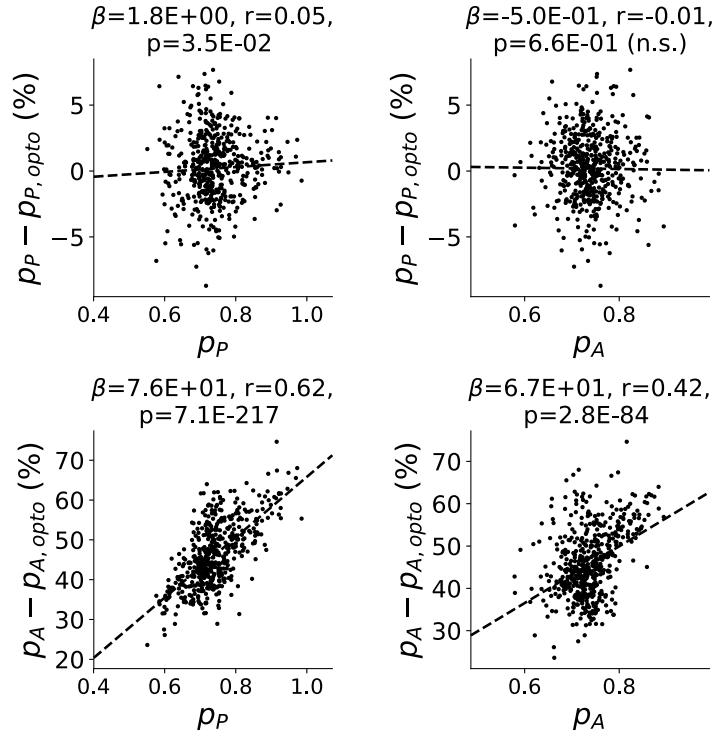


Figure 14: (SC4): Scatters of the effect of delay period inactivation in each task with task accuracy. Plots are shown at an opto strength of 0.8.

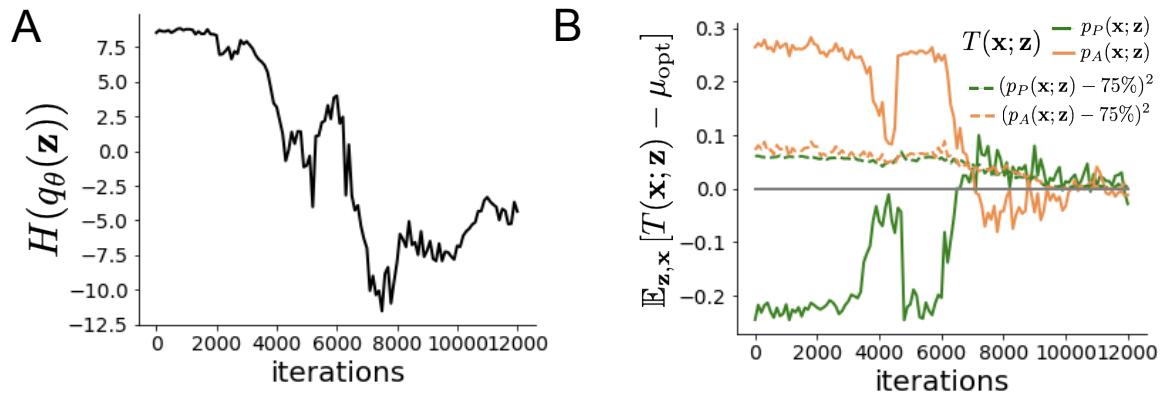


Figure 15: (SC5): EPI optimization of the SC model producing rapid task switching. A. Entropy throughout optimization. B. The emergent property statistic means and variances converge to their constraints at 12,000 iterations following the sixth augmented Lagrangian epoch.

1060 in \mathbf{z} prohibitive.

1061 SMC-ABC has many hyperparameters, of which pyABC selects automatically by running some ini-
1062 tial diagnostics upon initialization. In concurrence with the literature, SMC-ABC fails to converge
1063 around 25-30 dimensions, since its proposal samples never get close enough to the target statis-
1064 tics. We searched over many SNPE hyperparameter choices: $n_{\text{train}} \in [2,000, 10,000, 100,000]$ is the
1065 number of simulations run per training epoch, and $n_{\text{mades}} \in [2, 3]$ is the number of masked autore-
1066 gressive density estimators in the deep parameter distribution architecture. The greater n_{train} , the
1067 longer each epoch will take, but the more likely SNPE may converge during that epoch. Greater
1068 n_{mades} increases the flexibility of the deep parameter distribution of SNPE, but slows optimization.
1069 For the timing plot, we show the fastest among all of these choices, and for the convergence plot,
1070 we show the best convergence among all of these choices. During optimization, we used $n_{\text{atom}}=100$
1071 atomic proposals as is recommended.