

Model description and simulation protocol

Coupling and redundancy shape shock persistence in a computational model of social coordination

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This ODD-style protocol [1–3] documents the executable model and simulation experiment. It specifies the 120 independent base matrices, repeated coupling conditions, counterfactual measurement, and validation grouping used in the accompanying article.

S1 Purpose and modelling scope

The model is designed to test whether dependence becomes a shock-persistence liability when a multivariate system loses differentiated response modes. It is a mechanism-discovery model, not a calibrated representation of a person, community, organization, market, or country. Its target pattern is conditional: highly redundant structures should show longer endogenous counterfactual decay only when recurrent coupling is sufficiently strong and the shock excites a shared mode.

The model's empirical status is generative. It provides sufficient-condition evidence inside a controlled virtual experiment and generates external hypotheses for economic and social networks. Model purpose, scope, and boundary are stated explicitly because simulation validity is always fitness-for-purpose rather than a single universal property.

S2 Entities state variables and scales

The model contains one stylized multivariate unit with five continuous state variables. It also contains a five-dimensional memory vector and a five-dimensional exogenous input vector. Time is discrete and dimensionless. Each run has 260 steps; the shock begins at step 130. The state and memory are initialized at zero and bounded through the hyperbolic tangent. Table S1 summarizes the entities, state variables, scales, and interpretive roles.

Table S1 Entities, state variables, and interpretation

Entity / object	Symbol	Range or structure	Role
State vector	x_t	5×1 ; each component in $[-1,1]$	Stylized emotional, conformity, critical-reasoning, prosocial, and external-influence response channels.
Memory vector	m_t	5×1 ; bounded	Latent persistence channel influenced by prior memory and state.
Exogenous input	u_t	5×1 ; Gaussian AR(1) or white noise	Common stochastic environment shared by shock and control trajectories.
Topology matrix	A	5×5 ; spectral radius normalized to 1	Organizational geometry shared by input, recurrence, and memory channels.
Counterfactual pair	Shock/control	Two trajectories per condition	Identical except for the programmed perturbation.
Observation	D_k	Non-negative Euclidean distance	Deviation of shocked state from matched no-shock trajectory.

S3 Process overview and scheduling

At each time step, the model computes perceived input, updates memory, and then updates the bounded state. At the shock time, the shocked trajectory receives an additive perturbation before the regular update. The control trajectory follows the identical input sequence without the perturbation. Scheduling is synchronous and deterministic conditional on matrices, input stream, and shock specification. The exact within-step scheduling order is summarized in Table S2.

$$p_t = W_{in} u_t$$

$$m_t = \tanh(W_{self} m_{t-1} + 0.1 x_{t-1})$$

$$x_t = \tanh(W_{rec} x_{t-1} + p_t + 0.2 m_t)$$

Table S2 One-step scheduling pseudocode

Order	Operation
1	Read the shared exogenous input u_t .
2	For the shocked trajectory, add amplitude $\times$ direction to x_{t-1} if the forcing window is active.
3	Compute perceived input $p_t = W_{in} u_t$.
4	Update memory m_t .
5	Update state x_t .
6	Store shock and control states.
7	Compute $D_k = \ x_k^{shock} - x_k^{control}\ _2$ from the shock time onward.

S4 Design concepts

The model design concepts and their implementation are summarized in Table S3.

Table S3 ODD design concepts and their implementation

Design concept	Implementation
Basic principles	Nonlinear recurrent dynamics, bounded states, multivariate covariance geometry, matched counterfactuals, and base-matrix-level uncertainty.
Emergence	Shock persistence emerges from the interaction of topology, coupling intensity, stochastic input, shock direction, magnitude, and duration; it is not directly programmed.
Adaptation	No learning, optimization, or adaptive rewiring occurs. The word adaptation is therefore not used as an observed model outcome.
Objectives	The modeled unit has no utility function or explicit goal.
Sensing	The state receives a linearly transformed exogenous input through W_{in} .
Interaction	Interactions occur among the five state dimensions through W_{rec} and among memory dimensions through W_{self} . There are no separate social agents.
Stochasticity	Topology seeds, input innovations, and random shock direction are generated from stable hashed seeds.
Collectives	Topology families are experimental classes, not emergent collectives.

Design concept	Implementation
Observation	Baseline organization metrics, counterfactual impact, normalized post-forcing AUC, recovery times, and predictive validation metrics are recorded.

S5 Initialization and input data

State and memory start at zero. Twenty independently seeded matrices are generated per family and normalized to spectral radius one. Each is reused at all five coupling levels, giving 120 base matrices and 600 matrix–coupling units. Inputs have innovation SD 0.60 and autocorrelation $\phi = 0$ or 0.70. No external empirical data are used.

The baseline is simulated for all 260 steps before any shock comparison is prepared. Covariance and organization metrics use steps 55–129 to reduce initialization transients. Dominant and weak shock directions are the eigenvectors associated with the largest and smallest regularized baseline covariance eigenvalues.

S6 Submodels

S6.1 Topology generation

Diagonal matrices contain heterogeneous self-couplings without cross-links. Dense heterogeneous matrices combine random signed cross-links with positive diagonal terms. Modular matrices contain two strongly connected groups with sparse bridges. Hub matrices center influence on one dimension. Chain matrices emphasize sequential propagation with weak feedback. Near-rank-one matrices are generated from an outer product plus small noise, producing a dominant shared mode.

S6.2 Structural metrics

Let λ_i be regularized covariance eigenvalues and $p_i = \lambda_i / \sum \lambda_i$. Effective rank is $\exp(-\sum p_i \ln p_i)$, normalized effective rank is $E = \text{effective rank} / 5$, and differentiation is the normalized base-two entropy of p . C is mean absolute off-diagonal correlation. Redundancy $R = C(1-E)$; coordinated differentiation $Q = CE$. Additional measures include participation ratio, total correlation, non-normality, matrix density, and baseline variance.

S6.3 Shock submodel

A shock has magnitude M , unit direction v , and duration $d \in \{1, 8\}$. To match total squared forcing energy, the per-step amplitude is $M/\sqrt{d}$. At each active forcing step, the state receives $(M/\sqrt{d})v$ before the standard update. The three directions are dominant covariance mode, weak covariance mode, and random unit direction.

S6.4 Outcome submodel

The primary outcome is `endogenous_persistence_auc_normalized`. With $k = 0$ at onset and duration d , use D_k for $k = d-1, \dots, 129$. The first observation is the state immediately after the last forcing update, not the next unforced update. Divide by the maximum over that window and integrate with the trapezoidal rule at unit spacing; a zero maximum yields zero AUC. This produces 130 observations at $d = 1$ and 123 at $d = 8$. Secondary outcomes include raw AUC, AUC per magnitude, recovery below 2%, 5%, and 10% of peak for five consecutive steps, and residual distance.

S7 Definitive simulation experiment

The design contains 43,200 paired runs, 2,400 baselines, and 600 matrix–coupling units. Inference and grouped prediction use 120 independent family-by-seed base matrices. Each block contains all five coupling levels and

all 360 associated shock/input conditions. Fig. S1 shows the forcing and observation windows; Fig. S2 shows the within-step update. Table S4 records the parameters.

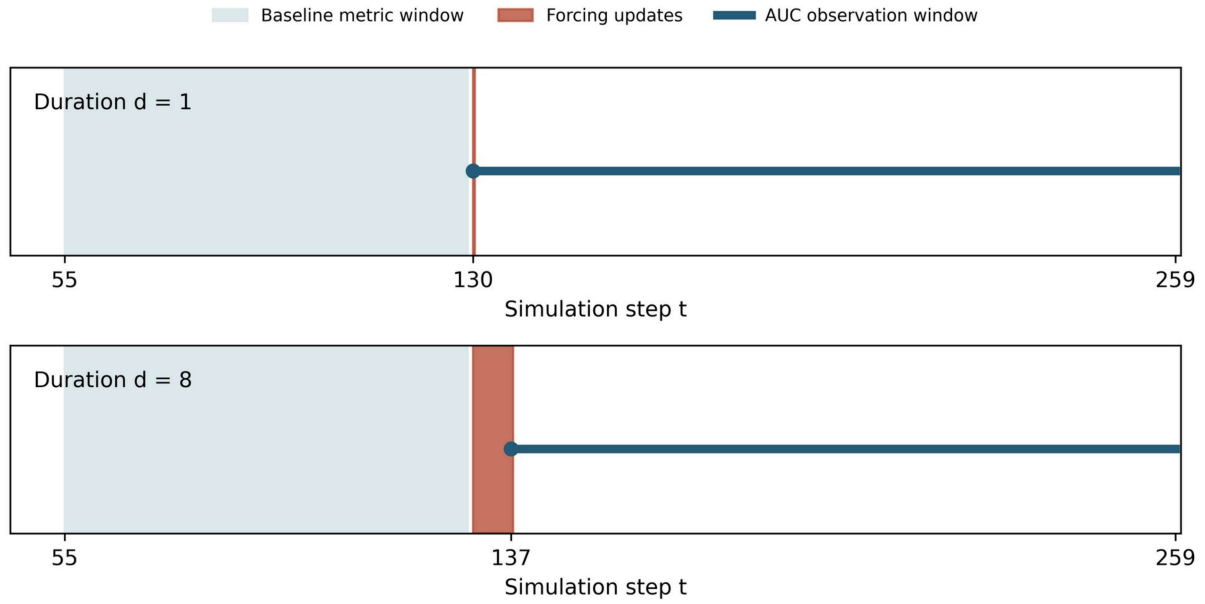


Fig. S1 Timing conventions. The AUC window begins with the stored state after the last forcing update, at $t = 130 + d - 1$. The baseline metric window is $t = 55$ through 129. End-of-forcing distance is included as lag zero

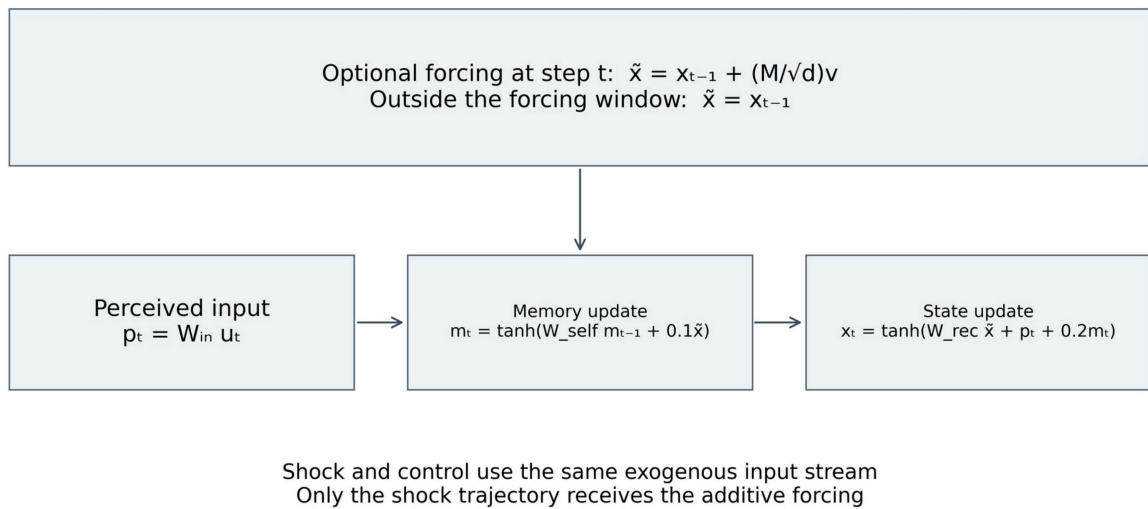


Fig. S2 Exact update order. During forcing, the perturbed previous state enters both the memory and state updates. Outside forcing, the previous state is unchanged before the ordinary recurrence. Both trajectories use the same input sequence

Table S4 Parameter values and ranges

Parameter	Values	Fixed / varied	Rationale
Dimensions	5	Fixed	Minimal multivariate state supporting effective-rank variation.
Time steps	260	Fixed	130 pre-shock and 130 post-onset steps.
Shock time	130	Fixed	Separates baseline from experiment.

Parameter	Values	Fixed / varied	Rationale
Pre-window	55–129	Fixed	Reduces initialization transient.
Input SD	0.60	Fixed	Produces nondegenerate bounded baseline variation.
Input ϕ	0, 0.70	Varied	White versus autocorrelated environment.
W _{in} scale	0.50	Fixed	Input coupling.
W _{self} scale	0.25	Fixed	Memory coupling.
Recurrent ρ	0.20–0.80	Varied	Primary coupling-intensity manipulation.
Topology families	6	Varied	Structural diversity.
Topology seeds	20 per family, reused across ρ	Varied	120 independent base matrices.
Shock magnitude	0.50, 1.50, 3.00	Varied	Scale sensitivity.
Shock direction	Dominant, random, weak	Varied	Directional resilience.
Shock duration	1, 8	Varied	Energy-matched forcing geometry.

S8 Statistical analysis

Bootstrap intervals resample base matrices. Within a family-by-coupling stratum, the 20 seeds are the units; pooled summaries retain all coupling values within each family-by-seed block. Cluster-robust regressions use 120 blocks and $\log(1 + \text{normalized AUC})$. Predictors include family effects, standardized coupling and magnitude, duration, input autocorrelation, direction, standardized R, coupling $\times$ R, and R $\times$ direction. Standardization uses population SD. Bootstrap seed is 20260810; B = 2,000 for condition and family-by-coupling summaries and B = 3,000 for family-wide summaries and ratio contrasts.

Five-fold GroupKFold uses family-by-seed groups with `shuffle = True` and `random_state = 20260810`. Every coupling level of a base matrix stays in one fold. Histogram gradient boosting predicts $\log(1 + \text{AUC})$ with `learning_rate = 0.06`, `max_iter = 300`, `max_leaf_nodes = 31`, `min_samples_leaf = 50`, and `l2_regularization = 1.5`. Fold-specific `random_state` is 20260810 + fold index. Leave-one-family-out validation uses `max_iter = 350`, `l2_regularization = 2.0`, and `random_state = 20260810`. Predictions are inverse-transformed and clipped at zero before calculating R^2 , MAE, and RMSE. Four grouped-CV feature sets and three held-out-family feature sets are specified exactly in `analysis_jcss.py`.

S9 Verification sensitivity and reproducibility status

The full simulation was rerun for this submission. Its $43,200 \times 42$ CSV and $43,200 \times 130$ normalized-curve array matched the archived numeric values exactly in the documented environment. Statistical inference and grouped prediction were then rerun with family-by-seed grouping. Online Resource 2 contains the complete code, data, tables, figure source, and verification record. This is a rerun of the supplied implementation, not an independent reimplement. Fixed-coefficient global sensitivity and empirical validation have not been performed.

Table S5 Reproducibility and validation checklist

Item	Status	Artifact / evidence
Executable code	Complete	definitive_monte_carlo_experiment.py
Run-level output	Complete	43,200-row CSV with all parameters, metrics, and identifiers.
Post-forcing curves	Complete	Compressed NPZ array, 43,200 × 130.
Figure source data	Complete	Run-level output and table directory.
Random seeds	Complete	Global seed and stable hash function in code.
Paired counterfactual	Complete	Shared topology, input, and starting state.
Base-matrix uncertainty	Completed	120 clusters; block bootstrap across repeated coupling levels.
Held-out base matrices	Completed	Five-fold grouped CV with every coupling condition kept together.
Held-out family validation	Complete	Leave-one-family-out.
Empirical calibration	Not performed	Required future work.
Independent reimplementation	Not yet performed	Priority next-stage validation.
Persistent repository DOI	Not assigned in this package	All supporting material is supplied in Online Resource 2.

S10 Minimum independent reimplementation test

An independent implementation should examine the monotonic coupling gradient, near equality of near-rank-one and diagonal persistence at $\rho = 0.20$, a high-coupling ratio near 1.55, the positive coupling-by-R interaction, and the ordering of direction means. It should also reproduce complete-base-matrix grouping and compare fold-level run scores with aggregated display scores. Deviations should prompt inspection of seeds, update order, energy matching, outcome indexing, and grouping before substantive interpretation.

S11 References

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