Conserving Coherence Under Constraint

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Abstract

Organisms often respond to energy constraints, time pressure, or imminent threat by limiting behavioral options, lowering metabolic demands, and increasing their level of coordinated action. Although these responses can be viewed as an impairment, we propose that they can be adaptive responses which occur as the costs of coordinating complexity exceed an organism's capabilities at any given time. Accordingly, selection favors mechanisms that conserve the coherence of function by reducing the number of control inputs and reorganizing coupling among the components that remain. We propose that these transitions share a diagnostic signature that encompasses reduced degrees of freedom, reorganized coupling, and stabilization of protected variables. We formalize this as a capacity–demand framework and articulate four named, testable hypotheses that specify when and how simplification and recovery should occur across biological scales. This perspective generates testable predictions about threshold-driven emergency modes, asymmetric recovery from emergency modes, and anthropogenic disturbance driving the simplification of function.

Keywords: adaptive simplification, coordination capacity, regime shift, dimensionality reduction, hysteresis, dormancy, torpor, collective behavior, coherence

Introduction

When constraints are low, flexibility can enhance fitness/performance. However, under constraints (e.g., food shortages, extreme environmental conditions and/or predation) many organisms will reduce complexity by adopting fixed behavioral patterns and/or becoming immobile (quiescent) or will become highly synchronized with one another (collective) (Geiser 2021; Roelofs 2017). New tracking and machine-learning tools now make these shifts measurable across scales (Pereira et al. 2022).

Historically, simplification has often been interpreted as dysfunction. However, across many biological systems, simplification in function can act as a regulated survival mechanism that allows organisms to remain viable near the boundaries of their functional capacities. The primary issue confronting an organism when functioning near the boundary of its functional capacity is maintaining coordination among components, not maximizing its operational complexity. Sampling the environment extensively when energy is very low can lead to starvation. Delaying response to an immediate threat can result in death. Therefore, the goal is to have enough coordination among the components of an organism to permit it to survive.

We refer to this pattern as the conservation of coherence (see Glossary). When coordination capacity is limited, selection should favor mechanisms to preserve coordinated function and thereby limit the degrees of freedom (behavioral, physiological, interactional) that need to be managed at one time (even at the expense of flexibility). This affords a simple evolutionary prediction grounded in the economics of behavioral and physiological coordination, that is applicable across levels of ecological organization and taxonomic groups. When demands exceed capacity, biological systems will tend to simplify to maintain coherent function because incoherence risks mortality.

Related frameworks and the novelty of conservation of coherence

There are several other theoretical frameworks which have explored how organisms maintain stability and act under uncertainty as demand increases. State-dependent decision theory models threshold-dependent behavioral switches as a function of resource state, risk, and expected fitness returns (Lima & Bednekoff 1999; Ydenberg & Dill 1986). Critical Transition Theory studies how nonlinear systems provide insight into the abrupt transitions between different states in a system and the processes that result in these transitions along with the early warning signs of these transitions (Dakos et al. 2024; Scheffer et al. 2001; Scheffer et al. 2009). An organism's robustness/resilience refers to its ability to withstand disturbances and recover from them. Typically, this involves several properties including modularity and redundancy (Crespi et al. 2021; Kitano 2004). The emphasis of allostasis is on controlled adjustments to mediators or to set points. This type of response enables organisms to adapt to acute stressors and provides shorter term stability. Although the process may be successful for coping with acute stressors, prolonged activation can have cumulative costs (McEwen & Wingfield 2003; Word et al. 2022). Predictive Processing and the Free Energy Principle offer a complementary perspective that is computational in nature. These frameworks view both perception and action as forms of inference which are aimed at minimizing prediction errors, formally quantified as free energy (Friston 2010a; Friston et al. 2010; Hodson et al. 2024) within the constraints of time and energy. Table 1 compares these frameworks with conservation of coherence and highlights its unique observable predictions.

Table 1. Related frameworks for stability and control under constraint

Framework	Key mechanisms	What it does not specify
State-dependent Decision Theory	Threshold-dependent behavioral switches as a function of resource state, risk, and expected fitness returns	Restructuring of coordination architecture among remaining active components
Critical Transition Theory	Nonlinear threshold-driven regime shifts with early warning signals and hysteresis	Whether the transition involves dimensionality compression, coupling tightening, or both
Resilience/Robustness	Buffering, redundancy, and modularity limit effects of perturbations	Why constrained systems converge on tighter coupling rather than maintaining modular independence
Allostasis	Regulated shifts in mediators/set points to meet varying demands; repeated activation carries cumulative costs (allostatic load)	Pattern of coupling reorganization among system components at the transition
Predictive Processing / Free Energy Principle	Perception and action as inference minimizing prediction error; constraints favor less exploratory policies	Coupling reorganization at organismal/group levels or hysteresis in recovery
Conservation of Coherence	Capacity–demand trigger for simplified, tightly coordinated regimes preserving core function	Uniquely predicts co-occurrence of dimensionality reduction, coupling reorganization, and protected variable stabilization (joint signature) at switching points, it also predicts that recovery is asymmetric, with hysteresis proportional to the depth, duration, and severity of the triggering event

When demand exceeds capacity

We do not suggest that there is only one mechanism of preserving coherence - whether through physical processes, neural control, or simple interaction rules. These examples represent convergent functional solutions shaped by similar constraints and thus are not examples of mechanistic homologies. The framework would be challenged if systems routinely remained complex after coordination limits were exceeded without a rise in coordination failures, or if simplification occurred without the joint signature. Importantly, conservation of coherence does not predict that all stress responses involve simplification; systems with sufficient reserve capacity, redundant modules, or low coordination costs may buffer perturbations without reducing dimensionality. Furthermore, a mere reduction in activity level without restructuring of component interactions would not constitute evidence for this framework.

The pattern of simplified, tightly coordinated behavior predicted by this framework can be seen in the collective escape behavior in starlings when under attack by peregrine falcons. Starlings will revert to a small number of coordinated escape modes (e.g., flash expansions, blackening, splits, waves). Whether these modes also involve moment-to-moment reductions in the dimensionality of individual trajectories remains an open and testable question (Storms et al. 2019). A direct means to test this would be to track individual bird movements in three dimensions before and during predator attacks. The question is whether the flock shifts to fewer independent movement patterns at the same moment that individual birds become more tightly coupled with one another.

Why coherence is important

We define coherence as the ability of functioning elements (e.g., cells, organs, behavioral components, or groups) to work together in real time in order to support continued function. Coherence is a function of timing and coupling between the various elements or parts of an organism; thus, it does not depend upon the performance of individual parts alone. Biological robustness relies on decoupling and modularity to buffer against perturbation (Kitano 2004). In contrast, coherence conservation entails a narrowing of active components paired with a strengthening of the coupling among the critical components that persist.

When the coherence of a system changes, that change becomes visible in the number of effective degrees of freedom the system is utilizing at any point in time. Degrees of freedom refer to how many ways a system can change independently of one another. Under constraint, effective degrees of freedom decrease as components become more tightly coupled or linked. Higher degrees of freedom can afford more complex and flexible performance. However, they come at a cost. More sensors, more computation, and more control are needed to manage them (Bernstein

1967; Bialek 2022). The challenge of managing multiple independent variables has been formally recognized in motor coordination research, where it is known as the degrees of freedom problem (Morasso 2022). Biological systems routinely solve this problem by coupling their components together in ways that constrain the number of dimensions that need to be independently controlled. This allows them to achieve reliable performance under constraint (Latash 2024). In ecological terms, the degrees of freedom problem maps onto familiar trade-offs. A forager must simultaneously track predators, monitor patch quality, and coordinate with group members. The coordination challenge scales with the number of independent decisions required per unit of time. The degree of coherence is reflected in the data by changes in the dimensionality of an organism's behavior, such as its movement patterns, interaction patterns, or physiological states (Bialek 2022) (see Box 1).

Box 1: A diagnostic checklist for identifying coherence-preserving regime shifts

Dimensionality: determine the number of dimensions required to describe organisms’ behaviors or physiological states within a particular time scale (e.g., principal component analysis of animal movement, covariance or factor structure of physiological states, order or dispersion of subjects in groups).

Coupling: monitor for reorganization of the coupling structure of a system undergoing a simplification regime shift (i.e., which links strengthen/weaken), including stronger coordination among elements of the active subset, and/or suppression/loosening of other linkages.

Variables protected during regime shift: determine which variables remain within a narrow range during a regime shift (i.e., body temperature maintains its range; position does not significantly move).

Thresholds/hysteresis: use change point methods or segmented regression to identify the thresholds where regime shift (see Glossary) occurs and where there are different thresholds for entry vs exit from a given regime.

Inter-scale comparisons: Using the same measures to measure coherence at the individual level and group level to see whether simplification at the individual level enables coherence to emerge at the group level (e.g., individual freezing reduce an individual’s degrees of freedom, and through this the group becomes more coordinated and therefore has greater polarization).

When coherence is maintained, animals may limit their movement to a few stereotyped patterns, reduce head and body motion, or they may use a limited number of habitual reflexes (Meier et al. 2022; Roelofs 2017; Taylor et al. 2023). Groups of animals can align in terms of speed and direction to facilitate group coordination (Storms et al. 2019). Such adjustments are typically temporary and reversible. However, if the cost of switching between states is high, recovery will be disproportionately expensive. This produces a form of asymmetry, as seen in the energetic cost of torpor arousal (Geiser et al. 2014) and hysteresis in ecosystem regime shifts (Scheffer et al. 2001).

What are the economic costs of coordination?

Maintaining coherence is governed by available resources. From cells to brains, metabolic supply constrains how much sensing, signaling, and computation can be sustained. The cost of neural signaling is significant as it requires a continued expenditure of ATP to maintain ion gradients, generate action potentials, and send synaptic signals (Padamsey & Rochefort 2023; Rae et al. 2024).

When resources are limited, animals alter movement, exploration, social coordination, and defensive responses. The energetic landscape framework shows that animals traveling with limited resources will either reduce how far they travel or utilize a form of locomotion that uses significantly less energy than other forms of locomotion (Cordes et al. 2025; Shepard et al. 2013; Wilson et al. 2012).

Time is another constraint. There is little time to compute flexible, context-sensitive responses when faced with imminent threat. Under imminent threat, defensive responses often shift toward fewer, tightly coordinated modes. Each stage prioritizes coherence of action/function to avoid catastrophic error (Mobbs et al. 2015; Roelofs & Dayan 2022).

Group coordination increases the costs associated with coordination and therefore favors the utilization of simpler rules of interaction in larger groups of animals, and results in tighter group cohesion or dispersal when the cost of flexible coordination of the behaviors of individual members of the group exceeds the benefits. This allows group members to avoid collisions, maintain cohesion, and to track neighbors. However, responses may also include fission or dispersal when alignment costs exceed benefits. Such evidence suggests that groups may preserve coherence either by aligning more tightly or dispersing when coordination costs are too high (Couzin 2009; Sumpter 2010).

Simplification as a regime shift

In ecological terms, a regime shift occurs when an organism's coordination demand exceeds its coordination capacity, triggering a rapid switch in how it regulates function. However, this often occurs at the expense of higher complexity behaviors like reproduction or exploration. Behavioral ecologists have documented numerous examples of state-dependent thresholds in the literature (Lima & Bednekoff 1999; Ydenberg & Dill 1986). The idea of coherence conservation adds a unique "signature" to this study area. However, under this framework, simply decreasing the amount of behavior or energy usage does not indicate a system is displaying this signature.

Simpler systems of organization do not equate to being passive systems. Freezing can allow for greater operational efficiency and preparation for an activity. Torpor states have active regulation through the use of neural circuitry. Dormant microorganisms retain the ability to maintain viable cell function at a reduced level of activity and continue to possess enough sensory capacity to activate an action when reactivated (Bradley 2025; Geiser 2021; Hrvatin et al. 2020; Roelofs 2017). These are simply alternative control methods, not malfunctions.

Additionally, regime shifts typically have recovery costs associated with them. Entering a simplified regime can have switching costs (lost time, missed opportunities, physiological reconfiguration), and exiting may require rebuilding capacity. Within a given episode, entry and exit thresholds can differ (e.g., hysteresis). Systems can enter the simplified mode at higher demand than the demand level at which they re-expand. Hysteresis can make a given state resistant to reversal, but it can also delay recovery after extended periods of disturbance (Dakos et al. 2024; Scheffer et al. 2001).

Common signatures across biological systems

The same pattern emerges across biological domains. From an ecological perspective, these transitions are significant because they alter how organisms interact with their environment, allocate time and energy, and respond to competitors, predators, and conspecifics. Often systems will transition to lower cost, lower dimensional states that stabilize their most critical variables when capacity limits are reached (see Table 2).

Table 2. How constrained regimes simplify

Biological Level	Common constraints	Coherence preserving regime	How the regime simplifies	Example Studies
Cells / Microbes	Starvation, antibiotics, oxidative stress	Dormant states, quiescent states, persister states	Biosynthetic activity and growth decrease; remaining metabolism consolidates around survival functions	Bradley 2025; Niu et al. 2024; McDonald et al. 2024
Plants / Invertebrates	Seasonal changes, desiccation or drought, decreased temperature, threat from predators	Seed dormancy, diapause, tonic immobility	Development and activity are arrested; resources directed to protective structures or states. Under threat, the range of behaviors will collapse to a single defensive state	Taylor et al. 2023; Baskin & Baskin 2014; Denlinger 2002; Sakai 2021
Endotherms	Food shortage, decreased temperature, energy deficit	Torpor, hibernation	Metabolic rate and body temperature reduced; thermoregulation narrows to a defended setpoint	Geiser 2021; Hrvatin et al. 2020; Shankar et al. 2023

Vertebrates	Immediate danger with limited time to respond	Freezing, tonic immobility	Range of behavioral options narrows to a few defensive responses; coordination tightens around threat monitoring	Roelofs 2017; Mobbs et al. 2015; Roelofs & Dayan 2022; Carli & Farabollini 2022
Animal groups	Predation, external disruption, social information overload	Alignment, clustering, reduction in task repertoire	Individual behavioral variability decreases; synchrony and polarization increase among group members	Couzin 2009; Sumpter 2010; Herbert-Read et al. 2011

The lower dimensional state can occur at many scales. Cells become dormant or persistent; plants, insects and other invertebrates cease development, and endotherms will decrease their metabolic activity by entering torpor or hibernation (Baskin & Baskin 2014; Bradley 2025; Denlinger 2002; Geiser 2021; Letten et al. 2024). Invertebrates also display defensive states such as tonic immobility (Sakai 2021; Taylor et al. 2023). Vertebrates defend against predators through freezing and tonic immobility (Carli & Farabollini 2022; Roelofs 2017; Roelofs & Dayan 2022). In addition, all members in a group will define tighter rules of interaction with each other and subsequently cluster or polarize (Couzin 2009; Herbert-Read et al. 2011; Sumpter 2010). All of these states can be described by the joint signature (Table 2).

Evolutionary consequences

If conserving coherence is adaptive, selection should influence both entry into simplified states and recovery from them. Thus, the threshold for entering simplified states should vary with internal state (e.g., energy, health, developmental stage) and external conditions (e.g., threat level, temperature, group density). We predict that populations will evolve differences in when they simplify and how extreme those simplified states may become, based on how often demand exceeds capacity. This reframes behavioral flexibility as beneficial yet costly (Auld et al. 2010; Piersma & van Gils 2010). Organisms that are near their energetic limits may opt for quick entry into simple states (e.g., torpor or habitual behavior), while less constrained organisms will have sufficient energy resources to allow them to spend longer amounts of time learning or exploring.

The conservation of coherence framework also can predict why individuals within the same species differ in how they respond to similar constraints. The point at which an organism enters a simplified regime, and how quickly it makes that transition, are determined by two things: how much coordination capacity the organism has available, and the coordination demand placed on it. The various factors that can influence the capacity-demand balance include energetic reserves, environmental volatility, time-pressure, and individual differences in stress sensitivity and risk tolerance. These differences can be viewed as reflecting alternative strategies to manage coherence shaped by environmental and individual variability, rather than being characterized as just noise (Biro & Stamps 2010; Dall et al. 2004; Sih et al. 2004).

Anthropogenic disturbances can interfere with the natural processes involved in the dynamics described above. Human disruption of the natural environment can force other species into states of heightened vigilance which can limit their ability to find food, explore, and reproduce (Rahman & Candolin 2022; Smith et al. 2021). While some studies have suggested that chronic anthropogenic disturbance can cause long-term changes in the behavior of some non-human species (Gaynor et al. 2019; Lee et al. 2024), direct empirical tests of hysteresis in behavioral dimensionality (where the threshold for entering a simplified regime differs from the threshold for re-expanding) are currently outstanding. Such tests would help identify when adaptive simplification becomes an ecological trap (Robertson & Hutto 2006; Schlaepfer et al. 2002).

Under chronic anthropogenic stress, recovery may become slower or fail altogether. Several plausible mechanisms could drive this. Accumulated allostatic load may degrade the physiological capacity to re-expand behavioral complexity (McEwen & Wingfield 2003).

Persistent environmental cues may prevent organisms from detecting that conditions have improved. The chronic stress that drives prolonged simplification may simultaneously degrade the neural and social structures needed to re-expand (Girotti et al. 2024; Woo et al. 2021). As a result, systems may remain in low-flexibility states, which can have subsequent impacts on their mobility, learning, social interactions, and ultimately on the larger ecological dynamics (Gaynor et al. 2019; Lee et al. 2024; Sih et al. 2023; Uchida et al. 2024).

A concrete example illustrates the conservation implications. Ground-nesting shorebirds at beaches with high recreational disturbance spend more time in vigilance states and less time foraging and incubating (Burger 1994). The conservation of coherence framework predicts not simply that these birds are “more stressed” but that birds at high-disturbance sites should show measurably compressed behavioral dimensionality (fewer distinct behavioral modes in time budgets) and tighter coupling of remaining behaviors to disturbance cues compared to birds at well-protected sites. Critically, the framework also predicts that if disturbance is removed, recovery of normal behavioral repertoires should be asymmetric - slower than the initial compression. If confirmed, this hysteresis would mean that management closures need to account for behavioral recovery time, not just the removal of direct physical threats to nests and chicks.

Testing coherence conservation

Conservation of coherence yields four named, testable hypotheses:

H1 (Coupling–Compression Signature Hypothesis): As coordination demand approaches or exceeds coordination capacity, effective degrees of freedom that are available at a given time should compress along with coupling among the remaining active components reorganizing and tightening. Simultaneously, critical protected variables remain stable. The aforementioned joint signature can be tested by combining latent-variable dimensionality estimates with time-varying coupling metrics in multivariate behavioral, physiological, or interaction datasets (Box 1).

H2 (Coordination Threshold Hypothesis): The stimulus to simplify is not any single stressor but rather an imbalance between what the system needs to coordinate and the capacity it has to coordinate at any given moment. Stress and energy shortages can be contributors to the imbalance, but they are not necessarily required. The critical trigger is that coordination demand exceeds what the system can manage. As such, increased demands on coordination (e.g. time constraints, informational load, group density), can push thresholds to an earlier point of simplification than what would be expected even when there is only a small amount of energy savings. In contrast, added reserve capacity should enable the organism to maintain its original level of coordination longer.

H3 (Hysteretic Re-expansion Hypothesis): There are costs associated with switching into a simplified regime and rebuilding coordination capacity after exiting said regime. When these costs are present, recovery from a simplified regime should require more favorable conditions than entry. The system simplifies at one threshold. It does not re-expand until conditions improve well beyond that point. The re-expansion of dimensionality and coupling should be slower than the initial compression. The degree of asymmetry should scale with the depth and duration of simplification. This can be quantified by comparing entry versus recovery trajectories. We predict that events of simplification that are brief and shallow in nature (e.g., momentary freezing) should not display much evidence of hysteresis. On the other hand, long-duration events of significant simplification (e.g., extended torpor episodes or persistent reduction in behavioral complexity) are predicted to demonstrate considerable hysteresis. Hysteresis can also emerge from a different source. The triggering event itself may damage the system's coordination apparatus. This damage can be neurological, social, or physiological (Girotti et al. 2024; Woo et al. 2021). In such scenarios, the prolongation of asymmetry does not really depend on the duration of the simplified state. Even a brief episode is predicted to produce prolonged asymmetry if the infrastructure needed for re-expansion has been compromised.

H4 (Cross-level Emergence Hypothesis): The coherence signature does not need to be present at all scales at the same time. When one level of organization simplifies, another level may simultaneously show increased coherence. For example, individual animals may show reduced dimensionality while the group as a whole becomes more polarized or synchronized. Individual simplification can actually enable coherence to emerge at a higher level of organization. The failure to find the signature at one scale does not rule out its presence at another. Thus, testing this hypothesis would require analyzing the same metrics at both the individual and group scales concurrently (see Box 1), which would allow for evaluating independently-predicted coherence at each scale.

Worked example: applying H1–H4 to torpor

Torpor in small endotherms provides an ideal system for testing all four hypotheses. Continuous physiological monitoring is feasible in these animals. The transitions between active states and torpid states are both discrete and repeatable. This makes it possible to observe the same process multiple times within a single individual. Testing H1 (Coupling-Compression Signature) can be accomplished by collecting continuous, multivariate physiological data (heart rate, metabolic rate, body temperature, breathing rate, and activity) with implanted logger devices and then computing effective dimensionality (e.g., PCA or factor analysis) as the organism is transitioning into torpor. The prediction is as follows. When an animal enters torpor, the number of latent modes that are needed to represent the animals physiological state will decrease. The remaining active variables (body temperature and breathing) should become more tightly correlated. The framework would be challenged if metabolic rate decreased without a concurrent decrease in multivariate dimensionality or without tighter coupling among remaining variables.

In order to test H2 (Coordination Threshold), one would manipulate coordination demand independent of energy. Potential experiments include exposure of torpor-prone subjects to unpredictability in terms of environmental disturbances (intermittent noise/light), with ambient temperature and food levels maintained at a consistent level throughout the study. The framework predicts in this instance, that coordination demand, not energy shortage, drives simplification. If this is correct, these disturbances should cause the animals to enter torpor sooner, despite no changes in their energy status. Barratt et al. (2025) showed that perceived predation risk alone increased torpor depth and duration in wild superb fairy-wrens. It remains to be tested whether this response reflects a form of compensation for reduced foraging intake to avoid predation or a direct response to increased coordination demand.

To test H3 (Hysteretic Re-expansion), one would compare the rate of physiological simplification during torpor entry against the rate of re-expansion during arousal using the same multivariate metrics. The prediction is that arousal should be slower than entry into torpor. It should also require more favorable conditions (Figure 1). The degree of this asymmetry should increase as torpor bouts become longer or deeper. There are publicly available datasets that can provide an immediate opportunity to test this. For example, the Chmura et al. (2023) arctic ground squirrel body temperature archive contains 306 hibernation seasons from 199 individuals.

H4 (Cross-level Emergence) could be tested in colonial hibernators by measuring whether individual physiological simplification co-occurs with increased synchrony among colony members in torpor bout timing.

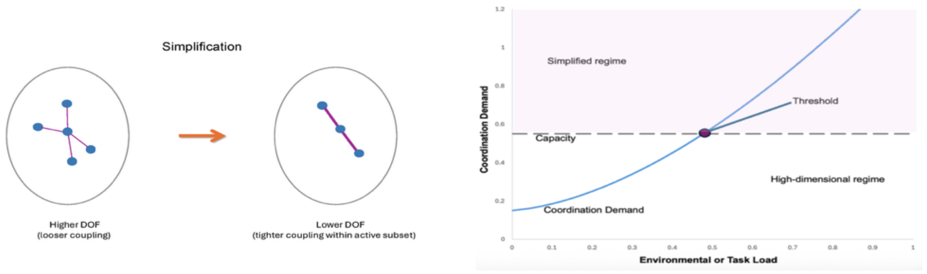
Figure Legends

Figure 1 | Capacity-demand mismatch leads to coherence-conserving simplification.

(A) Simplification is predicted to lead to a joint signature. Effective degrees of freedom will compress while the coupling among the remaining active components reorganizes and tightens. Other degrees of freedom are either suppressed or decoupled (H1).

(B) Coordination demand increases as either environmental or task loads increase. When coordination demand exceeds coordination capacity, the system can then transition into a simplified regime (H2).

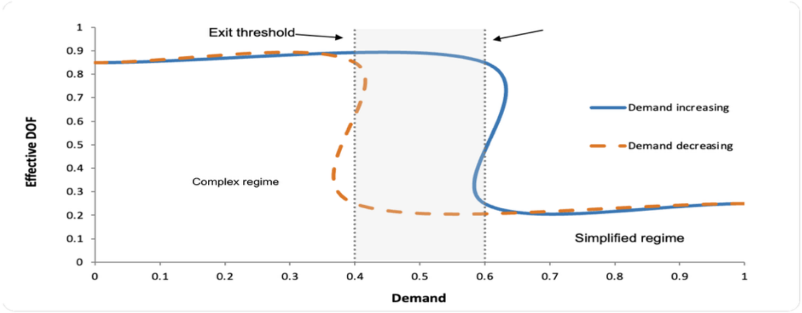
(C) When switching regimes and rebuilding impose costs, the thresholds for entry and exit differ. This produces hysteresis - meaning recovery to a more complex regime is slower than the transition into the simplified regime (H3). DOF, degrees of freedom.



(A) H1: Coupling-compression signature

(B) H2: Coordination threshold

(C) H3: Hysteretic re-expansion



Evaluating support across biological scales

There is variation in the strength of evidence regarding the complete joint signature across biological scales. There is extensive documentation that global suppression of biosynthetic activity and priming for stress tolerance are associated with microbial persistence/dormancy (Bradley 2025; Hossain et al. 2023; Niu et al. 2024). The consolidation of metabolism around core survival functions in Persister cells is consistent with dimensionality reduction (McDonald et al. 2024). However, explicit multivariate analyses of coupling reorganization among physiological or molecular variables during the dormancy transition remain rare. Formal tests of hysteresis in the transition between active and dormant states are largely absent as well. This is a clear opportunity for applying the conservation of coherence framework to transcriptomic or metabolomic time series data.

In plant and invertebrate diapause and dormancy, development and activity arrest while resources are redirected to protective structures (Baskin & Baskin 2014; Denlinger 2002). Tonic immobility in invertebrates collapses the behavioral repertoire to a single defensive state (Sakai 2021; Taylor et al. 2023). These cases are consistent with dimensionality reduction, but coupling reorganization has not been explicitly measured. Protected variable stabilization (structural integrity, metabolic viability) is implied but not formally quantified in most studies.

The most compelling evidence to support a common joint signature would be torpor and hibernation. Active regulation by identified neural circuits drives torpor entry (Hrvatin et al. 2020). During torpor, three main physiological parameters become tightly coupled (Geiser 2021). Geiser et al. (2014) compared torpor with pathological hypothermia in similar-sized mammals. Torpor displayed coordinated reduction in metabolic rate and body temperature with body temperature defended at a lowered set point. Hypothermia did not show this, despite similar reductions in both variables. This is consistent with the framework's prediction that coherent simplification produces a distinguishable signature. The same study showed that metabolic rate and body temperature follow different trajectories during entry versus arousal, consistent with recovery costs predicted by H3. Despite this evidence, relatively little research is available regarding whether the collapse in dimensionality of high-dimensional behavioral or physiological repertoires occurs at the same transition point. As a result, this leaves the full H1 signature partially tested.

During both tonic immobility and freezing in vertebrates, the range of defensive behaviors diminishes dramatically to include only a few coordinated defensive responses (Carli & Farabollini 2022; Roelofs & Dayan 2022). At the same time, autonomic functions become highly correlated and tightly linked around threat monitoring (Roelofs 2017; Roelofs & Dayan 2022). However, to confirm the full H1 signature, all three components must be shown to emerge together at the same transition point. This has not been formally tested. Evidence for hysteresis in recovery from freezing states also remains limited.

Collective behavior research has examined group responses to predator attacks. Research shows that when predators attack, groups consistently show increased synchronization in addition to increased group polarization (Couzin 2009; Herbert-Read et al. 2011; Sumpter 2010). Increased synchronization and group polarization are both consistent signs of increased or tighter coupling under the framework. However, Storms et al. (2019) identified several different escape patterns from starling flocks. These findings could be interpreted by some researchers as a maintained repertoire of escape behaviors instead of an example of dimensionality compression. This ambiguity further illustrates the importance of performing a dimensionality analysis on the trajectories of individual animals within a group, rather than measuring the degree of polarized behavior at the group level. Notably, diversity across escape motifs is compatible with the framework. The key consideration is what happens within any single motif. If the number of independent movement dimensions drops and the coordination between individuals tightens, then the joint signature is present. The number of different motifs the flock uses over the course of an encounter is not relevant. What really matters is what occurs inside each one.

What would falsify the framework

Two scenarios would falsify the framework. The first: organisms routinely exceed their coordination capacity with no increase in failure rates and no reduction in complexity. The second: the three components of the joint signature (dimensionality compression, coupling reorganization, and protected variable stabilization) are consistently found to occur independently rather than co-occurring at the same transition. On the other hand, the fact that an organism exhibits lower levels of activity, lower rates of metabolism, or lower levels of diversity in its behavior but has undergone no changes in coupling does not provide evidence for coherence conservation.

Discussion

We have suggested that “emergency modes” across biology may be viewed as coherence-preserving regime shifts. When an organism’s ability to coordinate complex behavior is limited, it reduces the number of possible options for action and reorganizes coupling among the remaining options. This may explain why structurally similar emergency responses appear across such diverse biological systems, e.g., bacterial dormant states, freezing, torpor, habitual control, and flocking. For ecology specifically, this framework provides a unifying logic for phenomena that are currently explained by separate bodies of ecological theory, including state-dependent behavior, critical transitions, energy landscapes, and collective movement, by identifying a common operational signature that connects them.

Considering emergency responses as regulated rather than pathological creates new considerations regarding when limits become too restrictive, when recovery occurs, and when repetitive activation of emergency responses could be detrimental. For conservation practitioners, this framework suggests that management strategies should aim to preserve recovery windows rather than simply minimizing disturbance intensity, because even moderate chronic stressors may prevent the re-expansion of complexity if they eliminate the time or energy required for recovery. This has direct implications for ecological management. Disturbance thresholds should be defined not only by population-level metrics but also by behavioral dimensionality measures that capture the coordination state of individuals and groups. Future work should attempt to clarify when hysteresis shifts from an adaptive buffer to an evolutionary constraint. It remains to be determined how selection distributes coherence across organizational levels during simplification. Furthermore, the variation in individual energy reserves and experience may shape both the initiation and recovery from a state of simplification, especially given novel anthropogenic stressors that may reduce or eliminate the windows of recovery on which these evolved mechanisms depend.

The presented work views emergency modes as shifts between regimes of function. Each regime shift carries a joint signature of coupling reorganization and compression of dimensionality (H1). Furthermore, entry into a new regime occurs when demands exceed current available capacity (a threshold that can be dissociated from energetic savings) (H2). Recovery can exhibit hysteresis by way of requiring more favorable conditions for exit from said regime than were needed for entry (H3). Additionally, individual simplification can enable coherence to emerge at higher organizational levels (H4). Collectively, H1 through H4 provide testable predictions for future comparisons and experimental design. The major point of distinction is that all three (dimensionality compression, coupling reorganization and protected variable stabilization) must occur at the exact same switching point. Merely documenting a decline in some level of function or activity is not sufficient evidence for the conservation of coherence.

Glossary

Conservation of coherence: when demand on an organism exceeds its coordination capacity, the organism maintains coherent function by reducing its degrees of freedom, tightening coordination among the remaining active components, and stabilizing critical protected variables.

Coordination Capacity: the energetic, information processing/neural, and temporal resources available to an organism for coordinating its behavior at any given point in time.

Coupling: The strength of the interaction between components of a system. An organism maintains its coherence by increasing the connection between active components and decreasing or eliminating the connection to other less important components; thus, changing their stability and interdependence.

Degrees of freedom: the number of independent ways a system can vary. Effective degrees of freedom decrease under constraint as components become more tightly coupled.

Hysteresis: an asymmetry between entry and exit conditions, such that the demand or capacity required to enter a regime differs from that required to leave it.

Protected variables: variables maintained within a narrow range during a regime shift (e.g., body temperature, oxygen delivery, spatial position), often at the expense of other degrees of freedom.

Regime shift: a rapid, nonlinear transition between distinct states of organization. This transition is triggered when a system crosses a critical threshold.

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