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Distributed Decision Making Enables Collective Intelligence in Social Insects Facing Rapid and Unpredictable Environmental Change

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ABSTRACT

Social-insect colonies often act coherently without centralized control, yet coherence alone does not establish collective intelligence. Rapid environmental change creates a harder problem: information must be acquired, filtered, amplified, revised, and sometimes discarded before it becomes obsolete. This perspective develops a proposed behavioral-systems account in which collective performance emerges from the coupling of distributed sensing, local state-dependent processing, recruitment, quorum formation, heterogeneous response thresholds, and corrective feedback. Evidence from ants and honey bees shows that workers can extend group sensing through interaction, alter responses according to physiological and social context, learn components of communication, and combine positive recruitment with inhibitory signals. The same literature also shows limits: stronger activity does not necessarily improve exploitation, consensus can trade quality for cohesion, and heterogeneity is beneficial only conditionally. We therefore argue that collective intelligence should be evaluated as a time-sensitive systems property rather than as an intrinsic attribute of eusociality. The proposed framework predicts that colonies should perform best when information acquisition, amplification, inhibition, and response thresholds remain matched to the rate at which environmental conditions change. Its generality remains to be tested beyond the ant- and honey-bee-dominated evidence base.

Keywords: Collective intelligence, Social insects, Distributed sensing, Recruitment dynamics, Response thresholds, Environmental volatility.

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Introduction

Social-insect colonies solve tasks that exceed the sensory or computational reach of any single worker, but the existence of coordinated group behavior is not itself sufficient evidence of collective intelligence. A useful definition requires an emergent property generated by interactions among components and evaluated against an explicit performance criterion [1]. This distinction matters because colony-level outcomes can be described in terms of mechanism, function, efficiency, robustness, or selection, and these explanatory levels are not interchangeable [2]. A colony that rapidly converges on one option may be cohesive yet inaccurate; another may exploit a familiar resource efficiently while responding poorly when the resource landscape changes.

Environmental volatility makes this inferential problem sharper. Communication is not unconditionally advantageous: theoretical work shows that its value depends on ecological stability and the costs of obtaining information [3]. Temporal decisions also differ from static option choice because delays, commitment,

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irreversibility, and the rate of environmental turnover can alter the value of accumulated social information [4]. These observations suggest that the central problem is not simply whether insects communicate, but whether distributed information remains useful long enough to influence action.

We propose that collective intelligence under rapid and unpredictable change should be treated as a systems property produced by the temporal coordination of six functions: distributed sensing, local information processing, recruitment and amplification, quorum formation, diversity of response thresholds, and error correction. The first five determine what information enters the colony, how strongly it spreads, and when action becomes likely; the sixth determines whether outdated or harmful information can be suppressed or reversed. This is a proposed synthesis, not an empirically validated unitary mechanism. Its strongest direct evidence comes from ants and honey bees, so cross-lineage extension to termites, social wasps, and other eusocial insects should remain a comparative hypothesis.

Distributed sensing

Distributed sensing begins when workers sample different portions of space, resources, nest conditions, or social states and their local encounters alter subsequent movement or activity. In longhorn crazy ants navigating disordered environments, collective interactions allow transported loads and surrounding workers to negotiate obstacles that would be difficult to resolve through a single local viewpoint [5]. The result is not evidence for a colony-wide sensory organ; rather, it demonstrates that coordinated interaction can extend effective task-level sensing beyond the information available to one individual.

Local sensory input is also filtered by immediate social context. Robotic tactile stimulation of worker ants showed that responses to standardized stimulation vary with worker density and behavioral context [6]. Thus, the same nominal signal need not produce a fixed action probability. The sensory substrate itself is taxonomically constrained: comparative analysis across major ant subfamilies indicates deep evolutionary complexity in the olfactory system and cautions against explaining sensory architecture through simple colony-size or social-complexity gradients [7]. Sensory capacity therefore cannot be treated as interchangeable across social-insect lineages.

The transition from sensing to colony activity can depend on encounter dynamics. In harvester ants, returning and outgoing forager encounters have been modeled as a closed-loop excitable system in which local interactions regulate departures [8]. Physiology adds another filter. In desert harvester ants, cuticular-hydrocarbon properties associated with water loss covary with colony differences in water-stress foraging; importantly, the corrected published direction is that risk-averse colonies showed higher alkene abundance than risk-tolerant colonies [9]. This association does not establish hydrocarbons as a causal controller of colony decisions. It instead shows why distributed sensing must include the state of the sensor: workers exposed to the same external environment may differ in what that environment means physiologically.

Local information processing

Distributed sensing becomes behaviorally consequential only when individual workers transform information into action probabilities. Hydration provides a concrete example. Hydrated harvester-ant foragers make more trips, and colonies differ in desiccation sensitivity [10]. Internal physiological state therefore gates whether external information is converted into foraging activity, although individual hydration alone cannot explain the complete colony response.

Local processing may also be socially acquired. Young honey bees deprived of experienced dancers later produced less accurate waggle-dance signals than bees exposed to normal social learning [11]. This finding is specific to honey-bee dance communication and should not be generalized to recruitment mechanisms that rely on pheromonal trails or encounter rates. It nevertheless demonstrates that the quality of information entering a recruitment network can depend on prior social experience.

Mechanistic interpretation must remain multilevel. Recent work on harvester ants links dopaminergic biology to the regulation of foraging under water stress, while also finding that simple differences in dopaminergic neuron number or distribution do not account for colony-level behavioral variation [12]. The implication is not that dopamine is a colony-level controller, but that local decision rules can incorporate neuromodulatory state without being reducible to a single neural variable.

A related conceptual proposal, the Weak Worker Hypothesis, argues that some response-threshold differences may reflect unequal susceptibility to task-relevant stressors rather than abstract threshold values alone [13]. We

use this hypothesis cautiously. It provides one biologically grounded route by which local states could generate heterogeneous task responses, but it is not established as a universal mechanism of division of labor.

Recruitment and information amplification

Recruitment converts local discoveries into socially consequential information, but amplification is not equivalent to indiscriminate positive feedback. Honey-bee stop signals provide active negative feedback capable of suppressing recruitment, showing that information flow can contain inhibitory as well as excitatory components [14]. This makes recruitment better understood as a regulated gain process: information can be strengthened, damped, or redirected depending on the balance of signals.

Information need not pass directly between workers. Agent-based work on leaf-cutter-ant-inspired systems shows that stigmergic environmental traces can produce self-organized division of labor [15]. Such models establish a plausible decentralized information channel, not evidence that all real colonies use identical rules. Direct movement heterogeneity provides another route. In ant foraging systems, differences among workers in movement and responsiveness to social information can increase collective efficiency by distributing search and exploitation across behavioral modes [16]. Yet heterogeneity is not automatically beneficial. In eight ant colonies differing in baseline in-nest activity, recruits from more active colonies were more responsive, but those colonies were not more efficient at exploiting food [17]. Stronger activation therefore does not map monotonically onto colony performance.

We consequently propose a distinction between useful amplification and amplification liability. Useful amplification increases the reach of information while retaining inhibitory or updating routes; amplification liability occurs when recruitment strength outlasts the validity of the information being amplified.

Because recruitment mechanisms differ in whether they rely on direct signaling, environmental traces, worker movement, or inhibitory feedback, prose alone obscures which inference is justified in each case. **Table 1** separates those regimes without assigning an unsupported performance score.

Table 1. Recruitment regimes that separate useful amplification from amplification liability in social-insect collectives

Recruitment with evidential standing	Biological context, recorded evidence, and system-level interpretation	Interpretive limit and decisive check
Positive recruitment with active inhibition **Evidence-supported**	Honey-bee foraging Recruitment and stop signals coexist Gain is regulated rather than purely self-reinforcing	Demonstrated in a specific communication system Proposed test — measure positive and inhibitory channels simultaneously as conditions change
Environmental-trace amplification **Evidence-supported theoretically; empirical transfer unresolved**	Leaf-cutter-ant-inspired task allocation Stigmergic traces alter later task behavior Information can persist outside direct worker contact	Primarily model-based Proposed test — compare environmental-trace persistence with task turnover
Movement-distributed amplification **Evidence-supported conditionally**	Ant foraging Workers differ in movement and social responsiveness Heterogeneity can broaden information acquisition and exploitation	Benefit is task- and environment-dependent Proposed test — compare heterogeneous and experimentally homogenized response structures
High colony activity without higher exploitation efficiency **Evidence-supported boundary**	Ant food recruitment Stronger recruit responsiveness occurs without an efficiency advantage More activation is not equivalent to better collective performance	Limited colony sample and task context Proposed test — separate recruitment responsiveness from outcome measures
Amplification liability **Proposed synthesis**	Rapidly changing environments Persistent recruitment would continue propagating information after local validity declines	Not directly validated as a unitary mechanism Proposed test — manipulate environmental turnover relative to signal persistence

	Information gain may become informational inertia

Quorum and consensus

Quorum and consensus determine when distributed information becomes collective commitment. These processes occur outside foraging: queen supersedure in honey bees has been formulated as a decentralized reproductive decision in which worker responses can accumulate toward colony-level replacement [18]. The model is useful because it broadens the domain of collective decisions, but it should not be treated as prospectively validated.

Consensus is also not synonymous with selecting the best option. In ant emigration experiments with persistent minorities, colonies can resolve conflict through majority concession, sometimes accepting a lower-quality outcome in order to achieve group cohesion [19]. Collective commitment therefore has at least two separable performance dimensions: convergence and option quality.

Theory makes the same point from a different direction. Nonlinear inhibitory responses can accelerate consensus while decreasing best-option accuracy under some conditions [20]. Similarly, models built from simple yes/no decision units show that group performance depends on how response-threshold distributions relate to the distribution of option quality and on the rule used to convert individual responses into a collective decision [21]. These results do not identify a universal optimal quorum. They indicate that thresholds and consensus rules must be interpreted relative to the decision environment.

For rapidly changing environments, the implication is temporal. A low quorum may permit fast response but magnify noisy or transient discoveries; a high quorum may improve filtering but delay action until the underlying condition has changed. We therefore propose that quorum performance should be evaluated by whether commitment time is matched to information lifetime, not by convergence alone.

Diversity of individual thresholds

Variation among workers is often treated as noise around a representative individual, yet collective systems can depend on that variation. Comparative work across acorn ants shows that colony-level activity rhythms can display evolutionary dynamics distinct from the behavior of isolated individuals [22]. This supports a strict level-of-analysis boundary: colony traits cannot always be inferred by averaging individually measured traits.

Within species, response diversity can also persist across time. Five years of field observations of desert harvester ants found repeatable colony differences in how foraging changes with humidity [23]. Those differences demonstrate persistent behavioral plasticity among colonies, but they do not by themselves establish a genetic cause or prove that one response strategy is adaptively superior.

Heterogeneous thresholds can contribute to robustness when their consequences are integrated by feedback. Control-theoretic models of social-insect task allocation show that integral-feedback-like processes can stabilize colony-level allocation despite changing local demand and worker activity [24]. This mechanism is theoretically powerful but should not be described as universally implemented by real colonies.

We therefore treat threshold diversity as a distribution of context-sensitive propensities rather than a fixed catalogue of worker types. Diversity can widen the set of conditions to which at least some workers respond, but excessive sensitivity may amplify noise, whereas overly narrow thresholds may delay response. The resulting prediction is non-monotonic: heterogeneity should improve performance only when its distribution is compatible with task demands, environmental turnover, and corrective feedback. This proposed relationship has no established universal optimum.

The distinction between physiological susceptibility, behavioral responsiveness, colony-level persistence, and feedback compensation is difficult to recover from narrative alone. **Table 2** therefore registers the contexts in which threshold diversity changes system behavior while keeping evidence-supported mechanisms separate from proposed generalization.

Table 2. Context–mechanism–outcome register for response-threshold diversity in distributed social-insect decisions

Mechanism-level interpre within its limit	Biological scale with observed basis	Discriminating check
Physiological-state gating		
Evidence-supported		

Internal state shifts response probability **Colony input is generated by non-equivalent sensors** **Individual state is not sufficient to explain colony policy**	Harvester-ant foragers Hydration changes trip propensity	Proposed test — measure worker state and colony response jointly
Stress-susceptibility threshold ***Proposed in source literature***		
Thresholds may emerge from worker condition **Heterogeneity could allocate susceptible workers earlier** **Hypothesis not universally validated**	Social-insect division of labor Differential vulnerability is hypothesized to trigger task entry	Proposed test — manipulate task-relevant stress while measuring response onset
Movement and social-response heterogeneity ***Evidence-supported conditionally***		
Distributed behavioral modes diversify search and recruitment **Efficiency can increase in specific environments** **Benefit need not be monotonic**	Ant foraging Workers occupy different movement and information-use modes	Proposed test — vary heterogeneity independently of worker number
Colony-level response persistence ***Evidence-supported***		
Response distributions can persist above the individual level **Colonies express distinct environmental reaction patterns** **Genetic and adaptive bases remain unresolved**	Desert harvester ants Colonies differ repeatedly in humidity-linked foraging	Proposed test — replicate across years, populations, and climatic regimes
Threshold-distribution matching ***Evidence-supported theoretically***		
Collective choice depends on distributional fit **Different quorum rules succeed under different conditions** **Transfer from abstract models to insects remains unresolved**	Generic collective-decision models Performance varies with threshold and option distributions	Proposed test — estimate empirical threshold distributions before testing optimality
Feedback-compensated heterogeneity ***Evidence-supported theoretically***		
Feedback can stabilize variable local responses **Robust allocation can persist despite perturbation** **Exact controller not universally demonstrated in colonies**	Social-insect-inspired task-allocation models Accumulated deficits feed back on task activity	Proposed test — perturb task demand and quantify recovery dynamics
Intermediate heterogeneity under volatility ***Proposed synthesis***		
Threshold spread interacts with information lifetime and correction **Too little diversity may delay detection; too much may amplify noise** **Shape and optimum are unknown**	Cross-system synthesis No single study establishes a universal optimum	Proposed test — manipulate environmental turnover and threshold spread factorially

Error correction

Collective intelligence under change requires more than rapid uptake of new information; it also requires mechanisms that suppress, reverse, or spatially isolate information and interactions that have become costly. Experimental work on Lasius niger shows that pathogen exposure can reorganize social interaction networks in ways that reduce transmission [25]. This is direct evidence that a colony can alter its interaction architecture after threat detection, but the result is threat-specific and does not establish that network reconfiguration improves every colony function.

The communication substrate can itself fail. In honey bees, disruption of collective behavior has been associated with reduced interaction efficiency and altered colony-level performance [26]. Because the perturbation was treatment-specific, this finding should not be generalized into a universal mechanism of colony failure. It

nevertheless demonstrates that information processing depends on the integrity of worker interactions rather than only on the quality of individual decisions.

Corrective responses can also be state-specific. In ants, infected worker pupae can generate chemical information that triggers destructive social responses, whereas queen pupae differ because stronger individual immune control changes the conditions under which this colony-level response occurs [27]. Correction therefore depends jointly on signal production, recipient response, caste and physiological state. At a different functional scale, Argentine ants progressively abandon harmful food after adverse experience [28]. This behavioral reversal shows that previously reinforced exploitation can be reduced when its consequences become damaging, without implying a general metacognitive error detector.

We propose that error correction in distributed colonies comprises at least three temporally distinct operations: detecting mismatch between current conditions and previously useful information, limiting further propagation of that information, and reallocating behavior or interactions toward an alternative state. These operations need not share a mechanism. Network restructuring, inhibitory communication, abandonment, and state-dependent removal are different biological processes. Their common systems-level property is that they reduce persistence of a response after its informational value has declined.

Error correction should also be evaluated against overcorrection. Suppressing recruitment too readily can discard valid information, network segregation can reduce useful contacts, and abandonment can terminate exploitation of resources whose short-term costs are tolerable. The criterion is therefore not maximal inhibition but context-appropriate updating. This creates a proposed persistence–reversibility tradeoff: systems that rapidly erase prior collective states may be flexible yet unable to retain information long enough to exploit stable opportunities.

The figure is needed because error correction is distributed across temporal stages and biological levels that cannot be represented faithfully as a single feedback arrow. It therefore separates evidence-supported corrective processes from the proposed integration of those processes into an information-updating architecture.

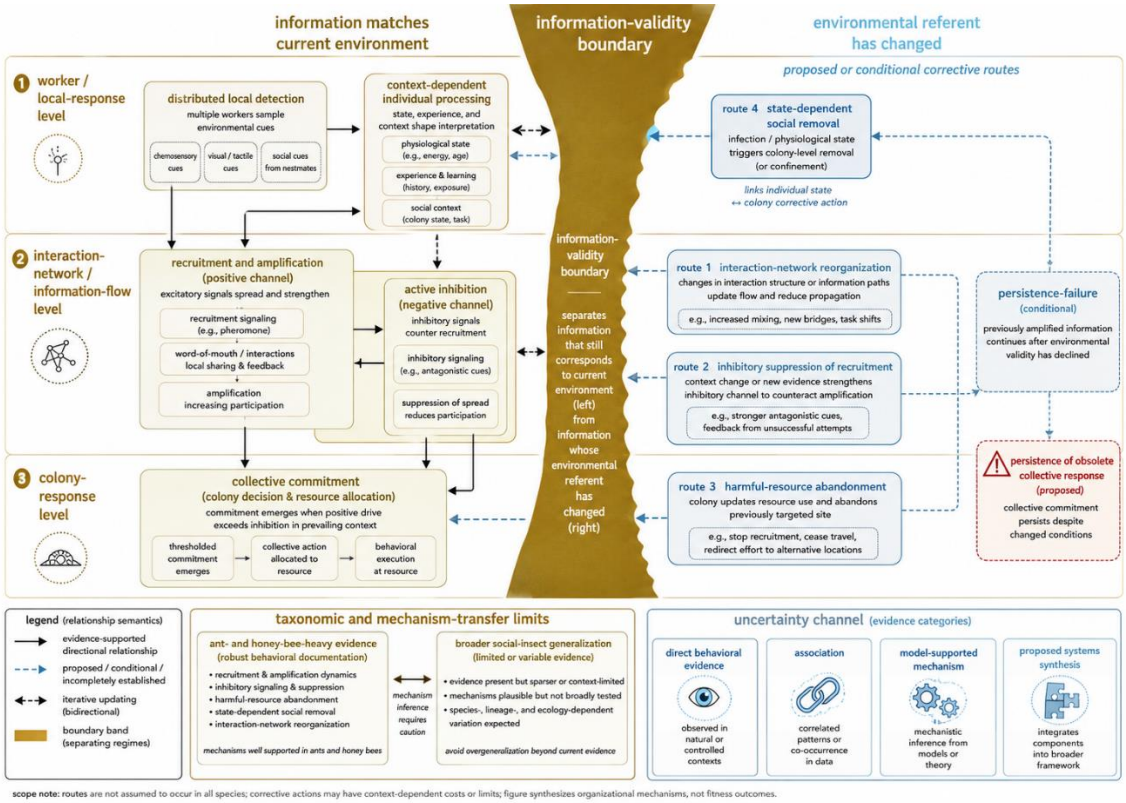


Figure 1. When social information becomes stale: temporal routes from distributed detection to correction and persistence failure

Collective adaptation under volatility

Rapid environmental change does not necessarily reward the strategy that performs best under stable conditions. In ant foraging systems reconstructed with experiment-derived computational replicas, stable environmental

histories favored higher efficiency when conditions matched prior experience, whereas histories with greater fluctuation were associated with greater resilience after conditions shifted [29]. This supports an efficiency–resilience tradeoff at the level studied; it does not demonstrate evolutionary adaptation to volatility.

Mathematical work on harvester-ant foraging likewise shows that recruitment efficiency interacts nonlinearly with environmental variability, so variability can sustain, extend, or disrupt collective activity depending on parameter regime [30]. No universal amount of recruitment or environmental fluctuation follows from that model.

We therefore use "collective adaptation under volatility" in a functional, not evolutionary, sense: the capacity of a colony to alter ongoing collective behavior as conditions change. We propose a timescale-matching principle. Distributed decision systems should be most effective when sensing, amplification, commitment, and correction operate on timescales compatible with environmental turnover. If updating is much slower than change, recruitment can preserve stale information; if commitment is too rapid relative to sampling, transient noise can be amplified. The expected optimum is therefore contextual rather than numerical.

Volatility should not be treated as one environmental variable. Changes differ in frequency, amplitude, spatial extent, predictability and persistence, and these dimensions can expose different bottlenecks in distributed systems. A sudden resource relocation primarily challenges information updating, whereas recurrent desiccation can alter worker physiological state before recruitment changes. Accordingly, behavioral adjustment within a colony is described here as plasticity or resilience unless evolutionary evidence demonstrates adaptation.

The evidence is uneven across the components of this proposed principle. Stable-versus-shifting performance has direct support in ant foraging, while recruitment–variability interactions are strongly developed theoretically. Direct field tests that manipulate environmental turnover while measuring sensing, recruitment, inhibition, commitment, and recovery in the same colonies remain lacking. **Table 3** maps this asymmetry so that evidence coverage is not confused with validation of the integrated proposal.

Table 3. Evidence coverage and validation gaps for time-matched collective responses to environmental volatility

Unresolved link and decisive check	Volatility-related state with evidential standing	Current evidential conte with observed basis
Whether the same relationship holds across tasks and taxa **Replica performance is not evolutionary adaptation** **Compare matched and shifted environments using identical performance currencies**	Stable-history efficiency Evidence-supported in studied system	Ant foraging replicas derived from experiments Familiar conditions can favor efficient exploitation
Mechanisms producing resilience are not uniquely identified **Variable-history advantage is context-specific** **Measure which worker and interaction states change after a shift**	Fluctuation-associated resilience Evidence-supported in studied system	Ant foraging replicas derived from experiments Prior fluctuation can improve response to environmental shifts
Field parameter correspondence is unresolved **Numerical transitions are model-specific** **Manipulate resource turnover and recruitment opportunity independently**	Recruitment–variability interaction Evidence-supported theoretically	Harvester-ant mathematical model Recruitment and variability can interact nonlinearly
Direct demonstration of stale-information dominance is lacking **No universal timescale ratio is established** **Measure environmental turnover, signal persistence, and behavioral reversal together**	Information-lifetime mismatch Proposed synthesis	Cross-section synthesis Component evidence shows signals can persist, be inhibited, or be abandoned
Whether faster correction improves fitness or long-term colony success is untested **Functional adjustment must not be labelled evolutionary adaptation** **Perturb information validity and quantify detection-to-reversal delay**	Time-matched correction Proposed synthesis	Cross-section synthesis Multiple corrective mechanisms can alter ongoing collective responses

Conditions producing collective failure

Collective failure can arise even when every local rule remains functional. In Nylanderia fulva, multi-chamber nest structure restricts pathogen transmission, whereas disruption of that spatial organization increases spread [31]. This demonstrates that colony performance may depend on architecture as well as signaling: removing a structural constraint can degrade a collective defensive function without requiring workers to become individually less competent.

The proposed framework identifies four non-exclusive failure classes. First, sensing failure occurs when sampled information is sparse, biased, or physiologically filtered in ways that no longer represent current conditions. Second, amplification failure occurs when recruitment strengthens transient or obsolete information faster than inhibition can suppress it. Third, commitment failure occurs when quorum dynamics favor speed or cohesion at the expense of decision quality. Fourth, correction failure occurs when interaction networks, inhibitory channels, or behavioral reversal are too slow or too damaged to update the colony. These are proposed analytical classes rather than empirically ranked causes.

Failure is therefore relational. High activity can coexist with no improvement in resource exploitation [17], consensus can be achieved by conceding option quality [19], and strong inhibition can alter speed and accuracy in opposing directions [20]. Similarly, environmental histories that improve matched-condition efficiency can leave systems less resilient after a shift [29]. No single outcome should consequently serve as an invariant measure of collective intelligence.

Comparative predictions

The framework generates comparative predictions that are deliberately qualitative. First, colony-level traits should be measured independently of individual traits because emergent behavior can show evolutionary patterns that differ from isolated-worker behavior [22]. Second, behavioral heterogeneity should be beneficial only over a context-dependent range: movement diversity can improve ant foraging [16], yet greater baseline colony activity need not increase exploitation efficiency [17]. Experiments should therefore manipulate heterogeneity rather than infer its value from worker number or activity alone.

Third, recruitment should become less useful when environmental turnover shortens the lifetime of reliable information below the time required for amplification and commitment. This prediction combines the established ecological conditionality of communication [3] with the temporal nature of collective decisions [4]; the exact crossover point is unknown and should not be assigned without measurement. Fourth, colonies with effective inhibitory or abandonment mechanisms should reverse obsolete collective responses faster than colonies in which positive feedback persists, but faster reversal should not be assumed to improve fitness in every ecological context.

Fifth, the framework predicts taxonomic non-equivalence. Ant olfactory architecture has deep phylogenetic structure [7], honey-bee recruitment includes learned dance components [11], and several key tests of environmental plasticity concern desert harvester ants [23]. Termites, social wasps and other social lineages should therefore be treated as comparative tests of transfer rather than as unmeasured confirmations.

Comparative tests should also stratify workers by caste, task and physiological state when these categories alter information acquisition or response. A colony average can conceal whether robustness arises from many moderately responsive workers, a small highly responsive subset, or dynamic switching among states.

Testing these propositions requires temporal measurement at the scale at which collective states change. ALTAA provides one recent example of long-duration automated analysis capable of resolving spatial and temporal activity patterns in ant colonies [32]. Comparable tools could be adapted to quantify detection latency, signal persistence, commitment time and reversal time, but method transfer across species and nesting architectures requires validation. The strongest test of the proposed framework would manipulate environmental turnover while simultaneously measuring individual state, social information flow, colony commitment, and recovery, thereby determining whether timescale matching predicts performance better than any single component alone.

Conclusion

Distributed decision making can support collective intelligence because social-insect colonies distribute sensing, processing, amplification, commitment and correction across many interacting individuals rather than assigning these operations to a central controller. The evidence, however, does not justify treating coordination, consensus

or high recruitment as intrinsically intelligent. Performance depends on context, on the metric being evaluated, and on whether information remains valid long enough to guide action.

The central contribution of this perspective is the proposed view that environmental volatility turns collective intelligence into a problem of temporal matching. Heterogeneous workers can broaden detection, recruitment can expand useful information, quorums can convert distributed responses into action, and corrective processes can reverse outdated states, but each component can also generate failure when its timescale becomes mismatched to environmental change. This synthesis remains strongest for ants and honey bees and must be tested across additional lineages, tasks and field conditions. Its value lies not in asserting a universal colony mechanism, but in providing a falsifiable systems-level basis for asking when distributed decisions remain informative as environments change.

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References

1. McMillen P, Levin M. Collective intelligence: A unifying concept for integrating biology across scales and substrates. Commun Biol. 2024;7(1):378. doi:10.1038/s42003-024-06037-4
2. Marshall JAR, Reina A. On aims and methods of collective animal behaviour. Anim Behav. 2024;210:189-97. doi:10.1016/j.anbehav.2024.01.024
3. Staps M, Tarnita CE, Kawakatsu M. Ecological principles for the evolution of communication in collective systems. Proc Biol Sci. 2024;291(2032):20241562. doi:10.1098/rspb.2024.1562
4. Kao AB, Banerjee SC, Francisco FA, Berdahl AM. Timing decisions as the next frontier for collective intelligence. Trends Ecol Evol. 2024;39(10):904-12. doi:10.1016/j.tree.2024.06.003
5. Gelblum A, Fonio E, Rodeh Y, Korman A, Feinerman O. Ant collective cognition allows for efficient navigation through disordered environments. Elife. 2020;9:e55195. doi:10.7554/eLife.55195
6. Rüegg M, Motes-Rodrigo A, Tuleu A, Stroeymeyt N, Richardson TO, Sakar MS, et al. Precise tactile stimulation of worker ants by a robotic manipulator reveals that individual responses are density- and context-dependent. Methods Ecol Evol. 2024;15(1):117-29. doi:10.1111/2041-210X.14244
7. Marty S, Couto A, Dawson EH, Brard N, d'Ettorre P, Montgomery SH, et al. Ancestral complexity and constrained diversification of the ant olfactory system. Proc Biol Sci. 2025;292(2045):20250662. doi:10.1098/rspb.2025.0662
8. Pagliara R, Gordon DM, Leonard NE. Regulation of harvester ant foraging as a closed-loop excitable system. PLoS Comput Biol. 2018;14(12):e1006200. doi:10.1371/journal.pcbi.1006200
9. Menzel F, Fiocca K, Steiner EB, Gordon DM. Cuticular hydrocarbons and collective response to water stress in a desert ant. Funct Ecol. 2026;40(1):26-35. doi:10.1111/1365-2435.70224
10. Friedman DA, Greene MJ, Gordon DM. The physiology of forager hydration and variation among harvester ant (Pogonomyrmex barbatus) colonies in collective foraging behavior. Sci Rep. 2019;9(1):5126. doi:10.1038/s41598-019-41586-3
11. Dong S, Lin T, Nieh JC, Tan K. Social signal learning of the waggle dance in honey bees. Science. 2023;379(6636):1015-8. doi:10.1126/science.ade1702
12. Kamhi JF, Ye D, Chen J, Do HL, Marble CW, Starcke J, et al. Dopaminergic expression and the regulation of foraging in response to water stress. J Insect Physiol. 2026;172:105014. doi:10.1016/j.jinsphys.2026.105014
13. Herman JJ, Walton A, Rueppell O. The Weak Worker Hypothesis: A new framework for understanding division of labour in social insects. Biol Rev Camb Philos Soc. 2026;101(1):5-13. doi:10.1111/brv.70068

14. Borofsky TM, Barranca VJ, Zhou RZ, von Trentini D, Broadrup RL, Mayack C. Hive minded: Like neurons, honey bees collectively integrate negative feedback to regulate decisions. Anim Behav. 2020;168:33-44. doi:10.1016/j.anbehav.2020.07.023
15. Di Pietro V, Govoni P, Chan KH, Oliveira RC, Wenseleers T, van den Berg P. Evolution of self-organised division of labour driven by stigmergy in leaf-cutter ants. Sci Rep. 2022;12(1):21971. doi:10.1038/s41598-022-26324-6
16. Fernández-López P, Oro D, Lloret-Cabot R, Genovart M, Garriga J, Bartumeus F. Foraging ants as liquid brains: Movement heterogeneity shapes collective efficiency. Proc Natl Acad Sci U S A. 2025;122(31):e2506930122. doi:10.1073/pnas.2506930122
17. Vaes O, de Selliers de Moranville LA, Detrain C. Group level trait and individual performance: The impact of in-nest activity on food recruitment in ants. Anim Behav. 2025;219:122995. doi:10.1016/j.anbehav.2024.10.009
18. Tarpy DR. Collective decision-making during reproduction in social insects: A conceptual model for queen supersedure in honey bees (Apis mellifera). Curr Opin Insect Sci. 2024;66:101260. doi:10.1016/j.cois.2024.101260
19. Rajendran H, Haluts A, Gov NS, Feinerman O. Ants resort to majority concession to reach democratic consensus in the presence of a persistent minority. Curr Biol. 2022;32(3):645-53.e8. doi:10.1016/j.cub.2021.12.013
20. March-Pons D, Pastor-Satorras R, Miguel MC. Non-linear inhibitory responses enhance performance in collective decision-making. Commun Phys. 2025;8(1):119. doi:10.1038/s42005-025-02046-9
21. Hasegawa E, Mizumoto N, Kobayashi K, Dobata S, Yoshimura J, Watanabe S, et al. Nature of collective decision-making by simple yes/no decision units. Sci Rep. 2017;7(1):14436. doi:10.1038/s41598-017-14626-z
22. Doering GN, Prebus MM, Suresh S, Greer JN, Bowden R, Linksvayer TA. Emergent collective behavior evolves more rapidly than individual behavior among acorn ant species. Proc Natl Acad Sci U S A. 2024;121(48):e2420078121. doi:10.1073/pnas.2420078121
23. Gordon DM, Steiner E, Das B, Walker NS. Harvester ant colonies differ in collective behavioural plasticity to regulate water loss. R Soc Open Sci. 2023;10(9):230726. doi:10.1098/rsos.230726
24. Schmickl T, Karsai I. Integral feedback control is at the core of task allocation and resilience of insect societies. Proc Natl Acad Sci U S A. 2018;115(52):13180-5. doi:10.1073/pnas.1807684115
25. Stroeymeyt N, Grasse AV, Crespi A, Mersch DP, Cremer S, Keller L. Social network plasticity decreases disease transmission in a eusocial insect. Science. 2018;362(6417):941-5. doi:10.1126/science.aat4793
26. Nguyen JB, Cook CN. Disruption of collective behaviour correlates with reduced interaction efficiency. Proc Biol Sci. 2025;292(2043):20250039. doi:10.1098/rspb.2025.0039
27. Dawson EH, Hoenigsberger M, Kampleitner N, Grasse AV, Lindorfer L, Robb J, et al. Altruistic disease signalling in ant colonies. Nat Commun. 2025;16(1):10511. doi:10.1038/s41467-025-66175-z
28. Zanola D, Czaczkes TJ, Josens R. Ants evade harmful food by active abandonment. Commun Biol. 2024;7(1):84. doi:10.1038/s42003-023-05729-7
29. Cristín J, Fernández-López P, Lloret-Cabot R, Genovart M, Méndez V, Bartumeus F, et al. Spatiotemporal organization of ant foraging from a complex systems perspective. Sci Rep. 2024;14(1):12801. doi:10.1038/s41598-024-63307-1
30. Liu C, Feng T. Unraveling the forces shaping foraging dynamics in harvester ant colonies: Recruitment efficiency and environmental variability. Math Biosci. 2024;371:109182. doi:10.1016/j.mbs.2024.109182
31. LeBrun EG, Fernandez AS, Sekula LA, Macones CR, Gilbert LE. Social immunity in a supercolonial invasive ant: Nest structure confers immune function. J Anim Ecol. 2026;95(1):84-96. doi:10.1111/1365-2656.70171
32. Oh J, Cremer S. ALTAA: Analysis of long-term activity patterns in ant colonies. Methods Ecol Evol. 2026;17(4):1218-34. doi:10.1111/2041-210X.70277