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Local Behavioral Rules and Distributed Information Flow Generate Collective Insect Decisions Without Centralized Control

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ABSTRACT

Collective insect decisions are often described as products of simple rules executed by many individuals, yet this formulation obscures how local state, interaction topology, signal transfer, inhibition, and thresholding jointly determine group outcomes. This conceptual synthesis develops a proposed distributed-decision architecture in which colony-level or aggregation-level decisions arise from locally accessible information rather than centralized assessment, while allowing individual influence and information access to remain unequal. Evidence from ants, honeybees, wasps, termites, and other insects indicates that local physiological state can regulate colony flows, interaction networks can concentrate influence, trophallaxis and behavior can transmit information, and inhibitory feedback can counter recruitment. Quorum-like thresholds are treated not as fixed colony constants but as context-sensitive system properties that may depend on group size and private-information certainty. The synthesis further distinguishes redundancy by number from robustness produced by spatial reorganization, composition, or cross-level regulation. These mechanisms do not guarantee accurate or adaptive outcomes, and their explanatory reach remains bounded by taxon, task, environment, life stage, and experimental setting. The resulting framework is therefore presented as a testable conceptual organization of distributed insect decision-making rather than a validated universal mechanism.

Keywords: Collective decision-making, Social insects, Distributed information, Feedback regulation, Quorum thresholds, Self-organization

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Introduction

Insect groups can select nests, allocate foragers, regulate food intake, navigate obstacles, excavate substrates, and coordinate social roles without a centralized agent that observes the full system state. Collective-decision theory provides a formal basis for understanding how such outcomes can arise through distributed information accumulation, interaction, and response rather than executive control [1]. In social insects, this distributed organization can generate colony-level performance that differs from the behavior of isolated individuals, but the same feedback processes that amplify useful information can also amplify error [2]. Ant research further shows that the ecological value of a particular interaction rule depends on environmental dynamics, resource distribution, and the timescale over which information remains useful [3].

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A recurring weakness in broad accounts of "simple rules" is that simplicity at the level of an individual behavioral contingency is often mistaken for homogeneity of agents, uniform information access, or fixed decision thresholds. Those assumptions are not required for decentralized control. The present synthesis therefore separates four analytical questions: what information is locally available; how that information moves among insects; how positive and negative feedback alter its influence; and how local responses are reconciled into a group-level commitment. It further distinguishes robustness from optimality and consensus from decision quality. On that basis, this article proposes a distributed-decision architecture in which local rules are conditional on internal and social state, information flow is topologically structured, thresholds are emergent rather than necessarily fixed, and failure can arise from information conflict, inappropriate amplification, or loss of compensatory structure. The proposal is evidence-bounded: most direct demonstrations concern adult workers in a limited set of ant, bee, wasp, and termite systems, and laboratory or model results are not treated as proof of universal field mechanisms.

Local interaction rules

Decentralization does not imply that every individual contributes equally. During repeated house-hunting emigrations, a stable minority of *Temnothorax* workers disproportionately participated in tandem-running networks, creating persistent inequality in information flow despite the absence of a central controller [4]. The relevant local rule is therefore not adequately represented as "each ant does the same thing." A better description is that individuals act on local information while occupying different positions in the interaction structure.

Local physiological state can also encode colony-relevant information. In *Camponotus sanctus*, crop load influenced food-transfer rate, while forager crop state affected the timing of subsequent foraging trips; these local measurements provided a route by which colony satiation could regulate intake without requiring any forager to estimate total colony demand directly [5]. This is strong evidence for distributed state sensing in a feeding context, but it does not establish crop-based control as a general mechanism for other collective decisions.

Interaction history provides a third source of heterogeneity. Longitudinal network analysis in *Camponotus fellah* associated interaction structure with task switching and task allocation, indicating that workers operate within socially structured information environments rather than as independent threshold devices [6]. Because network position and task are correlated, however, causal direction cannot be inferred from association alone. The proposed architecture therefore treats the local rule as a conditional mapping among current private state, recently encountered social information, and accessible environmental cues, while leaving the causal source of individual heterogeneity open to experimental discrimination.

Information generation and transfer

Distributed decisions require more than local sensing: information must either propagate among individuals or be repeatedly sampled from a shared environment. Trophallaxis provides one physical route. In *Tetramorium tsushimae*, experimentally preventing trophallaxis reduced the transmission of information associated with an aphid mutualist, demonstrating that mouth-to-mouth exchange can convey behaviorally relevant ecological information [7]. The inference is specific to that system; other sensory routes may still contribute, and trophallaxis should not be treated as the universal carrier of colony information.

The informational potential of social fluid is nevertheless broader than food delivery alone. Across ants, trophallactic fluid can contain nutrients together with endogenous molecules whose social functions vary in evidential strength [8]. This distinction matters because a material can be transferred without being a signal, and a signal can alter recipient state without immediately producing an observable colony decision. The proposed synthesis therefore separates information carrier, recipient-state change, and behavioral response as distinct inferential steps.

Behavioral interactions likewise require topological analysis. Information-theoretic comparisons showed that superficially similar social behaviors can differ in the direction and structure of information flow; tandem-running ants exhibited bidirectional information flow, whereas the termite interactions examined displayed different directional organization [9]. Thus, contact frequency alone cannot specify how information propagates. Statistical information flow also should not be confused with semantic communication or demonstrated causal influence.

Formal models add a complementary level. Psychophysical models of collective choice predict systematic relationships among option quality, number of alternatives, decision time, and error [10]. Such models are valuable because they turn verbal claims about distributed information integration into testable quantitative expectations, but the predictions remain theoretical until tested in particular taxa and tasks. In the architecture

developed here, information generation, transfer topology, and response function are therefore separable components whose combinations—not any single channel—determine how local evidence becomes collectively consequential.

Positive and negative feedback

Positive feedback is central to many insect recruitment systems because successful choices can recruit further individuals, increasing the representation of the same option. Yet amplification alone is insufficient for stable distributed control. Honeybee foraging provides direct evidence that inhibitory stop signals can suppress recruitment-related activity, creating negative feedback within an otherwise amplifying communication system [11]. The biological point is not that a colony literally implements a neural circuit, but that distributed decisions can combine excitation and inhibition without centralized arbitration.

Theory clarifies why this balance matters. In finite collective-foraging models, negative feedback can reduce deviations around a target allocation and suppress variability that would persist under amplification alone [12]. This result establishes a possible stabilizing function under the modeled assumptions, not an empirical claim that natural colonies implement the exact rule. The proposed synthesis therefore treats feedback as a signed, context-dependent relation: positive feedback increases the future influence of locally reinforced information, whereas negative feedback limits, redirects, or terminates that influence. Stability depends on their timing, target, and coupling to state, rather than on the presence of either sign in isolation.

These distinctions are easier to compare as feedback states than as a list of "benefits" and "costs," because the same mechanism can be beneficial in one informational context and destabilizing in another.

Table 1. Feedback balance changes what local information can become collectively dominant

Feedback route	Collective task	Local signal	Group-level effect	Balance test
		Amplification		
Recruitment amplification	Social-insect recruitment systems	Repeated recruitment toward an already represented option	Speeds accumulation of support and can magnify early differences. Evidence-supported general principle.	Can also magnify outdated, noisy, or initially biased information. Perturb early information quality while holding recruitment opportunity constant
		Inhibition and damping		
Inhibitory stop signaling	Honeybee foraging	Behaviorally expressed inhibitory signals that reduce recruitment activity	Opposes continued amplification and can redirect colony effort. Evidence-supported mechanism.	Demonstrated in a specific foraging communication system. Manipulate inhibitory-signal access independently of resource quality
Local-state damping	Ant food regulation	Transfer rate and foraging recurrence depend on recipient and forager crop state	Couples colony intake to locally measured satiation. Evidence-supported mechanism.	Demonstrated for food flow, not for unrelated decisions. Decouple local physiological state from colony-level demand
		Corrective balance and failure		
Corrective negative feedback	Collective-foraging model	Modeled inhibition reduces departures from target allocation	Can stabilize allocation in finite populations. Theory-supported possibility.	Depends on model assumptions and parameter regime. Test predicted variance reduction under controlled feedback manipulations
Unbalanced amplification	Proposed synthesis across preceding evidence	Reinforcement persists while inhibition, updating, or state correction is weak	Locally common information may dominate without being currently best. Proposed interpretive category.	No universal threshold for when amplification becomes maladaptive. Identify task-specific transitions between rapid consensus and error persistence

Quorum-like thresholds

Quorum language is often used as though colonies possess a fixed numerical trigger. Experimental evidence instead supports a more conditional interpretation. In clonal raider ant colonies, the collective response to increasing temperature depended on group size: the colony-level evacuation threshold shifted as the number of workers changed, and an interaction model with short-range excitation and longer-range inhibition reproduced

the qualitative pattern [13]. A threshold can therefore be an emergent system property even when individuals operate with local interactions.

Information state can also alter threshold use. In house-hunting ants, certainty of private information changed reliance on social information during quorum-based decision processes [14]. Individuals with less certain private information were more responsive to social evidence, showing that the mapping between social accumulation and commitment need not be fixed. These findings do not imply one shared mechanism across ant species; one concerns sensory response under thermal stimulation, the other nest-choice information certainty. Together, however, they undermine the assumption that a quorum-like threshold is simply a constant colony parameter.

This article therefore proposes a three-level reconciliation. At the individual level, insects evaluate locally accessible environmental, physiological, and social information. At the interaction level, information is transmitted through unequal networks and distinct carriers, while positive and negative feedback alter its persistence. At the collective level, commitment occurs when these local processes generate sufficient coordinated response, but the effective threshold may shift with group size, information certainty, topology, and inhibitory structure. **Figure 1** compresses this logic while keeping empirical relationships separate from the proposed cross-study integration.

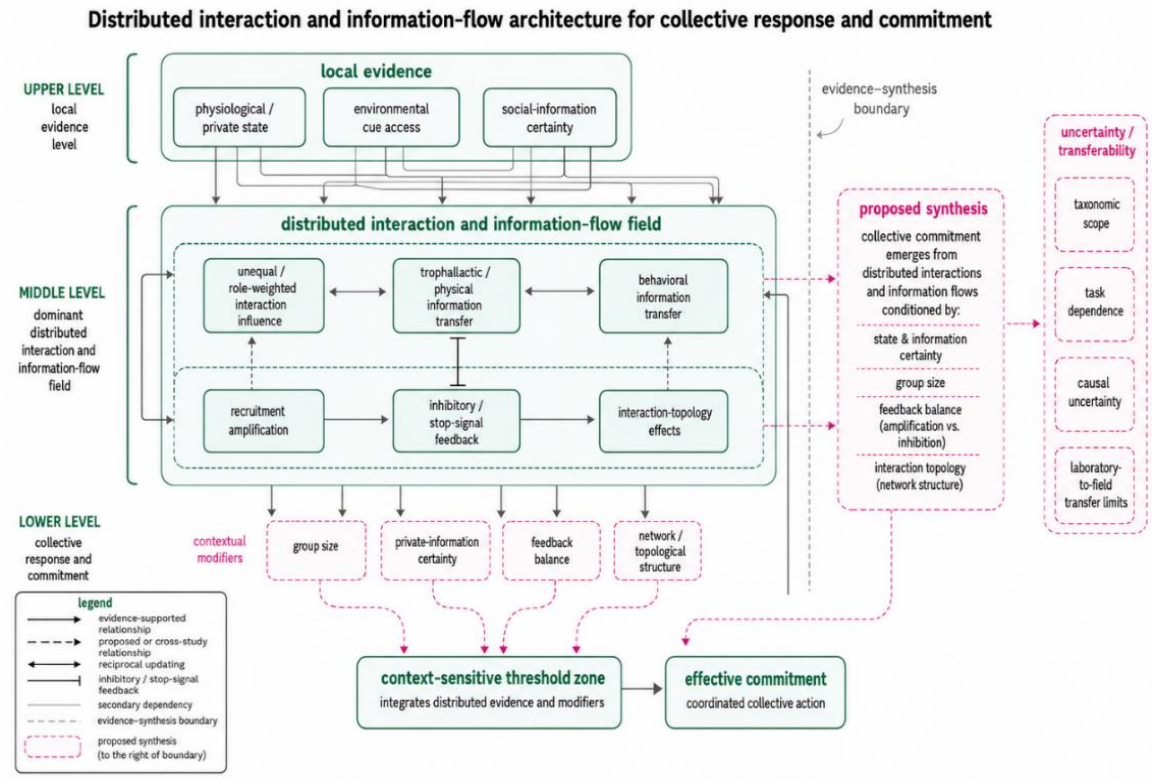


Figure 1. Colony commitment emerges at the boundary between local evidence, information topology, and context-sensitive thresholds

Error correction and redundancy

Distributed systems are often assumed to be robust because many individuals can perform similar actions, but simple numerical redundancy is not sufficient to explain observed resilience. In *Camponotus pennsylvanicus*, experimentally reducing worker density through nest-space expansion did not produce a uniform decline in interaction rate. Colonies altered spatial organization and movement, indicating that compensation can occur by reorganizing where and how workers encounter one another [15]. The result supports interaction homeostasis under the measured perturbation, not a claim that every colony function remained unchanged.

A second limit is exposed by colony composition. Experiments across 120 *Ooceraea biroi* colonies showed that simple response-threshold models could not reproduce all empirical patterns of division of labor under variation in genetic, morphological, and demographic composition [16]. This does not invalidate threshold effects; it shows

that treating workers as interchangeable agents with differently placed thresholds can omit biologically important determinants of task organization.

Robustness can also span biological levels. In *Polistes canadensis*, queen removal combined with behavioral and multi-omic measurements supported a system in which colony-scale inhibition stabilizes worker specialization while external perturbation can permit coordinated reprogramming [17]. That evidence is species- and context-specific, yet it expands the concept of redundancy beyond repeated workers to include compensatory regulation among molecular, individual, and colony levels.

The proposed synthesis therefore distinguishes three routes to error correction: spatial reorganization that preserves opportunities for interaction, compositional diversity that changes available response repertoires, and cross-level regulation that stabilizes roles while retaining plasticity. None should be assumed to operate universally, and none guarantees an optimal outcome. Their value is analytical: they identify different reasons why a distributed system may continue functioning after local information or participant structure changes.

The evidential asymmetry among these routes is best shown as a coverage-and-gap map, because the strongest evidence concerns different taxa, perturbations, and levels of organization.

Table 2. Robustness in distributed insect decisions depends on what is redundant and what can reorganize

	Compensatory architecture		Stress test
Robustness route and colony context	**Direct evidence versus missing test**	**Colony consequence and exposed failure**	**Factorial test and standing**
Spatial interaction compensation. Carpenter-ant colonies under density reduction	Workers can reorganize space and movement so interaction rates do not simply track density. Whether the same compensation preserves decision accuracy, speed, or field performance	Robustness can reside in encounter structure, not worker number alone. Density loss may disconnect information flow if movement cannot compensate	Manipulate density and movement opportunity independently. Evidence-supported route.
Composition-dependent response capacity. Clonal raider-ant colonies varying in composition	Threshold-only models fail to explain all task-allocation patterns. Which compositional features causally generate the missing structure	Redundancy cannot be equated with interchangeable threshold agents. A numerically large colony can still lack the response repertoire required by context	Orthogonally vary composition and inferred threshold distributions. Evidence-supported limitation.
Cross-level inhibitory stabilization. Paper-wasp colonies undergoing queen removal	Colony-scale regulation can stabilize social roles and permit coordinated reprogramming after perturbation. Generality across social insects and tasks unrelated to reproduction	Error correction may couple molecular, individual, and colony levels. Single-level control may misclassify latent plasticity as fixed specialization	Perturb colony context and individual state separately. Evidence-supported exemplar.
Multi-route robustness. Proposed synthesis across preceding mechanisms	No single study tests spatial, compositional, and cross-level compensation together. Relative contribution and interaction among routes are unknown	Robustness should be treated as architecture-specific rather than assumed from group size. Failure may occur when several compensatory routes are simultaneously constrained	Factorially disrupt more than one compensatory route within the same task. Proposed integrative category.

Emergence of group-level decisions

Emergence is most informative when it identifies a group capability that cannot be inferred simply by adding individual responses. During cooperative transport by *Paratrechina longicornis*, collective action increased effective sensing and enabled navigation through disordered environments beyond what individual-scale information alone would predict [18]. The result demonstrates a performance consequence of distributed interaction in that task, but it does not establish a general fitness advantage or imply that larger groups are invariably superior.

Group-level decisions also emerge relative to an ecological objective. In the slave-making ant *Temnothorax americanus*, raiding decisions showed that quantity, spatial opportunity, and timing can become more relevant than a generic preference for the highest-quality option [19]. Collective success therefore cannot be evaluated

against an abstract assumption that colonies should always select the qualitatively "best" alternative. The criterion itself depends on what resources, delays, and opportunities matter in the focal ecology.

Local rules may additionally generate more than one macroscopic regime. Cooperative excavation by *Camponotus pennsylvanicus*, examined through ant experiments, agent-based and continuum descriptions, and robotic analogues, produced qualitatively distinct patterns including productive and unsuccessful excavation states [20]. The value of this result for the present synthesis is not that excavation supplies a universal model of insect decision-making. Rather, it demonstrates that similar classes of local agent–environment interactions can occupy different collective regimes depending on contextual and dynamical conditions.

The proposed synthesis therefore defines emergence operationally: a collective decision is emergent when interactions transform locally accessible information into a group-level state whose functional properties depend on the organization of those interactions. Emergence does not imply optimality. A group may expand sensing, settle on an ecologically appropriate compromise, or enter a poorly performing regime through the same broad principle of decentralized interaction. The distinction between emergence and success is essential for identifying when distributed control fails.

When distributed control fails

Failure cannot be defined solely as failure to reach consensus. A colony may reach consensus quickly but on an outcome that is poor under one criterion, while disagreement can sometimes preserve alternatives until information improves. Experiments manipulating information asymmetry during ant emigration showed that a persistent minority can induce the majority to concede a superior nest choice in order to maintain colony cohesion [21]. Under such conditions, collective quality and collective integrity become competing objectives. Calling the resulting decision simply "irrational" would ignore the possible value of avoiding colony fragmentation.

Social amplification can also move a group away from the preference expressed by isolated individuals. In *Periplaneta americana*, humidity and group size interacted so that shelter preferences at the group level could differ from, and under some conditions invert, isolated preferences [22]. This is a particularly important boundary case because the same observation can be interpreted as error, context-sensitive valuation, or emergent social preference depending on which biological outcome is treated as the relevant benchmark.

At the sensory level, social context can alter what an individual insect responds to before a collective decision is complete. In cockroaches, manipulation of social odor changed behavioral preference and was associated with altered antennal-lobe representations measured by calcium imaging [23]. These results support a link between social sensory context and individual preference, but the neural measurements do not establish a complete causal pathway from antennal processing to group outcome.

These cases suggest that distributed control can fail through several distinct routes: informational conflict among subgroups, amplification of locally common but contextually poor information, sensory or environmental conditions that alter individual valuation, and loss of compensatory organization. The proposed framework therefore treats "failure" as criterion-dependent rather than as a single pathological state.

A comparative adjudication is needed because the same group outcome can represent information loss, cohesion preservation, or context-sensitive revaluation depending on the biological criterion applied.

Table 3. Distinguishing genuine distributed-control failure from alternative collective objectives

Observed collective state	Task context	Primary versus competing objective	Overclaim boundary	Decisive test and standing
Majority concession under information conflict. Majority accepts an option that would be inferior under nest-quality ranking alone	Ant emigration with persistent minority information	Information asymmetry changes the balance between option quality and colony cohesion. Cohesion preservation may itself be a functional objective	Inferior-ranked option is not automatically maladaptive	Manipulate fragmentation cost independently of option quality. Evidence-supported state.
Social preference inversion. Group choice diverges from isolated-individual preference	Cockroach shelter selection across humidity and group size	Social amplification modifies the effective decision landscape. Group preference may reflect a different ecological criterion rather than error	Laboratory shelter preference is not equivalent to fitness	Compare isolated and group choice under ecologically validated consequences. Evidence-supported state.

Sensory-context distortion or reweighting. Social odor changes preference and sensory representation	Cockroach social-odor processing	Social information can modify what individuals perceive as salient. Neural representation may correlate with rather than cause final choice	Calcium-imaging association does not prove behavioral causality	Perturb sensory processing while preserving social exposure. Evidence-supported mechanism with causal gap.
Loss of corrective structure. Amplification persists while inhibition, updating, or compensatory interaction is weakened	Proposed synthesis drawing on feedback and robustness evidence	Distributed control becomes vulnerable when corrective routes are jointly constrained. Apparent failure may instead reflect a changed objective or environment	No universal failure threshold is established	Factorially manipulate amplification, inhibition, and interaction structure. Proposed integrative category.

The boundary between failure and context-sensitive revaluation is the central interpretive problem summarized in **Figure 2**.

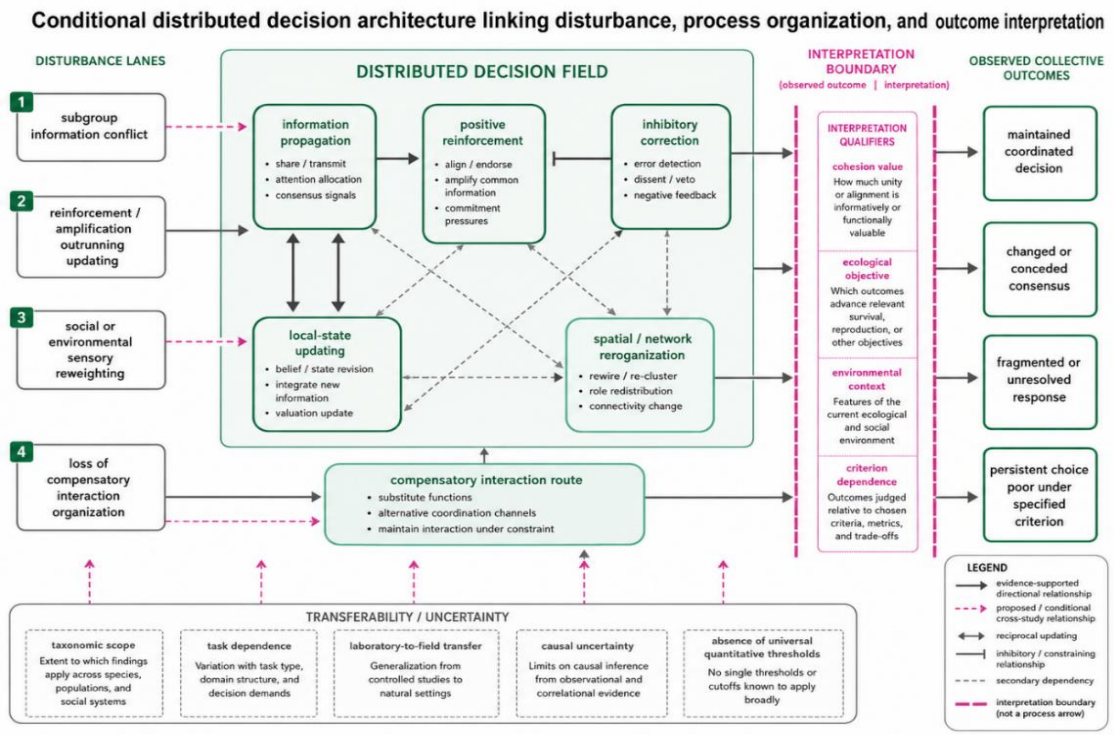


Figure 2. Collective outcomes become unreliable when information conflict, amplification, and corrective capacity cross different biological boundaries

Cross-taxon predictions

The architecture should not be restricted a priori to eusocial species. Reviews of non-eusocial insects show that flies, cockroaches, locusts, and other taxa use social information at sensory and behavioral levels despite lacking the colony organization characteristic of ants, bees, or termites [24]. This widens the comparative domain but does not justify assuming identical mechanisms.

A second prediction concerns individual cognition. Insects can show social learning, recognition, and flexible use of socially acquired information, indicating that distributed organization need not depend on cognitively trivial agents [25]. The proposed framework therefore predicts that similar group-level architectures may be produced by different individual computational capacities.

Three cross-taxon predictions follow. First, systems with repeated local interactions should show stronger dependence on information topology than systems dominated by independent environmental sampling. Second, inhibitory or corrective mechanisms should become especially important when positive recruitment persists after environmental information has changed. Third, taxa with stronger individual learning or memory should display

greater history dependence in local rules, even when the eventual group decision remains decentralized. These propositions are intentionally comparative and require testing rather than acceptance as established generalities.

Future experimental tests

The principal empirical challenge is to separate components that normally covary. Interaction topology should be manipulated while local cue quality is held constant, allowing tests of whether network organization itself alters task switching or information propagation [6]. Directional information flow should likewise be perturbed independently of contact frequency so that statistical dependence can be distinguished from causal transmission [9].

Threshold experiments should vary group size independently of encounter rate. Such designs could test whether collective thresholds arise from number, interaction frequency, or the excitation–inhibition structure implicated in group-size-dependent responses [13]. Colony-composition experiments should independently manipulate composition and inferred response-threshold distributions, directly testing why threshold-only models fail in some division-of-labor settings [16].

A further priority is to map transitions among productive and failing collective regimes without presupposing universal boundaries. Excavation systems offer one route because experimentally observed macrostates can be compared under controlled changes in local interaction rules and environmental structure [20]. Comparable perturbations should then be attempted in navigation, emigration, and foraging systems.

Finally, sensory intervention is required where neural association currently exceeds causal evidence. In cockroaches, manipulating social-odor processing while maintaining social exposure could test whether altered sensory representation is necessary for the observed preference change [23]. Across all such experiments, the strongest designs will manipulate one architectural component while measuring consequences at individual, interaction-network, and collective levels. Field replication should follow laboratory discrimination rather than being assumed from it.

Conclusion

Collective insect decisions can arise without a centralized controller because information need not be globally represented in any individual. Local physiological state, social interaction, material transfer, information-flow topology, feedback, and threshold-like commitment can each contribute to distributed coordination. Yet decentralization is neither synonymous with identical agents nor a guarantee of optimal outcomes.

The synthesis developed here proposes that distributed insect decisions are best analyzed through separable layers of local evidence, information movement, feedback regulation, collective commitment, and corrective capacity. Thresholds may emerge from group organization rather than exist as fixed constants, while robustness can depend on spatial reorganization, composition, and cross-level regulation rather than worker number alone. Failures must be interpreted relative to ecological objectives, cohesion, information asymmetry, and context.

This architecture remains a conceptual synthesis rather than an empirically validated universal mechanism. Its value lies in making competing explanations experimentally separable and in identifying where apparent commonalities across insect taxa may arise through different biological processes.

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