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Learning, Memory, Attention, and Adaptive Decision Making Across the Ecological Contexts of Insect Cognition

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ABSTRACT

Research on insect cognition has established sophisticated learning, memory, selective information use, and flexible choice in several model systems, but these capacities are often studied as separate traits. This separation can obscure the ecological problem insects actually face: past experience must be retained selectively, current signals differ in reliability and value, internal state alters responsiveness, and actions change the information available next. This integrative review examines how learning mechanisms, memory formation and retention, selective attention, and decision making under uncertainty interact across ecological contexts. Evidence from bees, ants, wasps, and Drosophila shows that cognitive performance is conditional on reinforcement history, stimulus timing, reward composition, social setting, season, and acute thermal stress. Mechanistic studies identify circuit, neuromodulatory, and metabolic contributors in tractable models, but their cross-taxon generality remains unresolved. Field-linked evidence further shows that stronger measured memory is not uniformly beneficial, while null and context-dependent effects caution against interpreting laboratory performance as adaptation or fitness advantage. We therefore propose a context-conditional integration principle in which acquired information, retained representations, selective weighting, and choice are coupled but analytically separable. This synthesis emphasizes inference boundaries among behavioral performance, mechanism, ecological function, and evolutionary consequence, and identifies comparative and multiscale tests needed to connect cognitive process with real ecological demands.

Keywords: Insect cognition, Associative learning, Memory retention, Selective attention, Decision making, Sensory ecology.

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Introduction

Insects solve recurrent information problems under constraints of time, energy, sensory access, and environmental variability. Bee research has shown that learning, discrimination, navigation, memory, and problem solving can be experimentally separated, making “cognition” an umbrella for multiple processes rather than a single measurable faculty [1]. Social insects add further demands because information can be acquired from nestmates, competitors, or individually recognizable rivals; however, this evidence is taxonomically concentrated and should not be generalized as a uniform social-cognitive phenotype across insects [2].

A second limitation is that cognitive processes are often isolated from the temporal and physiological conditions under which they operate. Trace-conditioning studies show that insects can bridge a gap between cue and reinforcement, but performance depends on temporal structure and does not imply one conserved trace-memory

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mechanism [3]. In adult Drosophila, internal state can alter olfactory responses and learned behavior through dopaminergic modulation of mushroom-body circuitry [4]. The broader principle—that the value and expression of information depend on state—is therefore supported, whereas the specific circuit should remain species- and paradigm-bounded.

The central inferential problem is consequently not whether insects can learn or remember. It is how acquired information becomes available for later choice, how competing information is prioritized, and when measured cognitive performance matters in the ecological task being solved. This review develops a proposed context-conditional integration principle: learning changes the informational consequences of experience; memory controls what remains available across time; selective attention or related weighting processes alter which signals influence current processing; and decision rules convert those weighted signals into action. The proposal is organizational, not a claim of a single conserved mechanism. It deliberately separates observed behavioral performance from mechanistic explanation, laboratory competence from field function, and ecological effect from evolutionary adaptation.

Learning mechanisms

Learning in insects spans associative, social, sensory-plastic, and circuit-defined phenomena, but these categories should not be collapsed. In bumblebees, observers acquired a rewarded ball-moving task more effectively than controls and could improve on the demonstrated solution [5]. The finding establishes task-specific social learning and behavioral flexibility under controlled conditions; it does not demonstrate cumulative culture, a general imitation faculty, or ecological advantage outside the assay.

Mechanistic experiments resolve a different level of explanation. In adult Drosophila, targeted work on asymmetric neurons showed that a specific neural component is necessary for normal olfactory learning in the tested paradigm [6]. Such necessity evidence is stronger than a correlation between neural activity and behavior, yet it remains insufficient to establish either sufficiency or conservation across insect orders. Mechanistic precision therefore increases explanatory depth while narrowing the taxonomic domain to which the causal statement safely applies.

Learning and memory can also depend on physiological allocation. In Drosophila, CRH-like signaling can redirect glial glycolytic flux toward neurons in a manner relevant to memory performance, linking mnemonic function to regulated cellular energy supply [7]. Honey-bee research synthesized at the neurochemical level likewise implicates biogenic amines in modulation of learning, memory, and state-dependent behavior, while emphasizing that stress can perturb these systems [8]. These findings support state-sensitive cognition but not a single cross-insect biochemical pathway. They also leave open whether a change in cognitive performance reflects altered valuation, sensory processing, motivation, motor capacity, or memory itself.

The useful synthesis is therefore layered. Behavioral learning identifies what information changes later performance; mechanistic intervention identifies components required for that change; physiological studies identify conditions under which those components are modulated. A context-conditional account should preserve these levels rather than translating every performance difference into a neural mechanism or every neural effect into an ecological benefit.

Memory formation and retention

Memory is not one endpoint. Formation, stabilization, retention, retrieval, and state-dependent expression can be dissociated experimentally and can respond differently to ecological timing. In Drosophila, sleep and memory regulation involve interacting circuits, making behavioral state relevant to memory maintenance and expression [9]. In social insects, especially honey bees, time-linked learning demonstrates that recurring associations between resources, places, and temporal schedules can be remembered [10]. These findings justify treating temporal organization as part of memory ecology while avoiding analogies with human episodic memory or assuming a single internal clock.

Reinforcement valence provides another boundary condition. In ants, a single appetitive learning event produced detectable mid-term memory in the tested paradigm, whereas an aversive task did not produce the same memory outcome [11]. The contrast shows that exposure alone does not determine retention. Differences in salience, motivation, punishment structure, or task design remain plausible explanations, so the result should not be interpreted as evidence that ants generally lack aversive memory.

Most importantly, stronger memory is not uniformly more useful. In field-linked work with foraging bees, better measured memory predicted greater foraging efficiency in spring but not summer [12]. The seasonal change directly limits any claim that superior memory has constant ecological value. Floral richness, resource turnover, prior experience, energetic state, and other seasonal variables can alter which information is worth retaining. The evidence therefore supports a distinction between memory capacity and memory value: the former is a measured cognitive property, whereas the latter is conditional on how the environment rewards remembered information.

Selective attention

Selective attention is difficult to infer in insects because a behavioral preference for one cue can arise from sensory gain, learned value, motivation, motor bias, or competition among signals. Here, attention is used operationally when experiments measure selective allocation of sensory inspection or behavioral processing among available alternatives, rather than as a claim that insects possess one vertebrate-like attentional system.

Bumblebee visual-search experiments provide direct behavioral evidence for learned reallocation. As bees gained experience, inspection became more concentrated on rewarding flowers and less on unrewarding or irrelevant regions, with reward quality modifying the pattern [13]. This establishes experience-dependent selective search, but the measure remains behavioral: it does not by itself identify the underlying circuit or fully separate reward salience from attentional control.

Cue conflict adds a second dimension. When bumblebees encountered different visual information on arrival at and departure from a food source, discrimination learning remained broadly robust, although some effects depended on stimulus properties [14]. The result argues against a simple rule in which one temporal cue always dominates. It also leaves multiple mechanisms open, including trace conditioning, backward associations, generalization, and differential cue salience.

Experience can additionally retune sensory processing itself. Olfactory studies show plasticity at multiple processing levels after experience, demonstrating that later responsiveness can change before any higher-order "attentional" interpretation is invoked [15]. In honey bees, responses to competing conspecific cues likewise vary with social context rather than following one fixed priority hierarchy [16]. Together, these findings support a distinction between sensory tuning, learned value, and selective behavioral weighting. They may interact, but they are not interchangeable mechanisms.

Because the same outward choice can arise from different underlying information-processing states, the distinctions are more efficiently adjudicated by explicitly mapping what each evidence pattern establishes and where interpretation must stop.

Table 1. Selective information weighting in insect cognition: coverage, inference limits, and unresolved tests

Boundary or uncertainty and decisive check	Selective-attention patt with evidential standing	Biological with observed basis
Inspection time does not uniquely identify a neural attention mechanism **Pair search behavior with circuit or sensory-state measurements**	Learned visual prioritization Evidence-supported	Bumblebee flower search Increasing inspection of rewarding targets across experience Prior reward history can reallocate visual search
Salience, motivation, and negative reinforcement may contribute **Manipulate reward value and perceptual salience independently**	Reward-sensitive allocation Evidence-supported	Bumblebee search under different reward quality Treatment-dependent changes in inspection Value modifies selective search
Stimulus-specific effects prevent a fixed temporal hierarchy **Vary cue reliability and timing independently**	Temporal cue conflict Evidence-supported	Bumblebee arrival versus departure information Learning persists despite conflicting visual states Different task phases can contribute to cue weighting without universal disruption
Sensory plasticity is not equivalent to selective attention **Measure sensory tuning and subsequent choice in the same individuals**	Experience-dependent olfactory tuning Evidence-supported	Insect olfactory systems Sensory responses change after experience Prior experience can modify later sensory representation
Specific cues and colony conditions limit transfer	Context-dependent social weighting Evidence-supported	Honey-bee competing conspecific cues Behavioral responses change with social setting Cue priority is conditional on social context

Test across roles, colonies, and cue combinations		
This decomposition is not a validated universal taxonomy	Process-separation rule	Cross-domain synthesis
Use dissociative experiments that manipulate candidate processes independently	Proposed synthesis	Similar choices may follow tuning, valuation, memory, or selective weighting Candidate processes should be separated before mechanistic inference

Decision making under uncertainty

Decision making becomes uncertain when current evidence is incomplete, reward is delayed or multidimensional, competing cues disagree, or the value of past experience changes with state. Insects need not explicitly represent mathematical probability for behavior to be uncertainty-sensitive; action can change as a function of learned signal value, delay, reliability, and competing alternatives.

Bumblebees trained with delayed reinforcement later showed stimulus-specific persistence, indicating that learned delay history can modify how long an animal continues to search or remain associated with a cue [17]. The safe inference is that temporal expectation changes persistence. Calling the behavior patience, self-control, or abstract delayed gratification would exceed what the assay establishes.

Reward structure is also multidimensional. Pollinator rewards differ in amount, composition, timing, and reliability, and these dimensions can impose distinct cognitive demands rather than collapsing into one scalar value [18]. This matters because a decision that appears suboptimal under one laboratory metric may be appropriate when another reward dimension or future information is relevant.

Individual heterogeneity further complicates population-level interpretation. Honey bees can display distinct cognitive performance profiles under controlled conditions [19]. Such variation may influence how individuals resolve uncertain choices, but "cognitive phenotype" should remain conditional on task definition, repeatability, and physiological state. Transient motivation or experience can mimic stable individual differences.

We therefore propose that uncertain insect choice be represented as a temporal signal-integration problem rather than a fixed input–output rule. Current sensory evidence, remembered value, reinforcement timing, and internal state contribute in parallel; learned persistence and action alter what information becomes available next. Evidence supports several component relations, while their integration into one cross-process architecture remains proposed.

The figure is placed here because a recurrent visual architecture can distinguish empirically grounded component relations from the proposed links that connect them across time more clearly than a linear prose description.

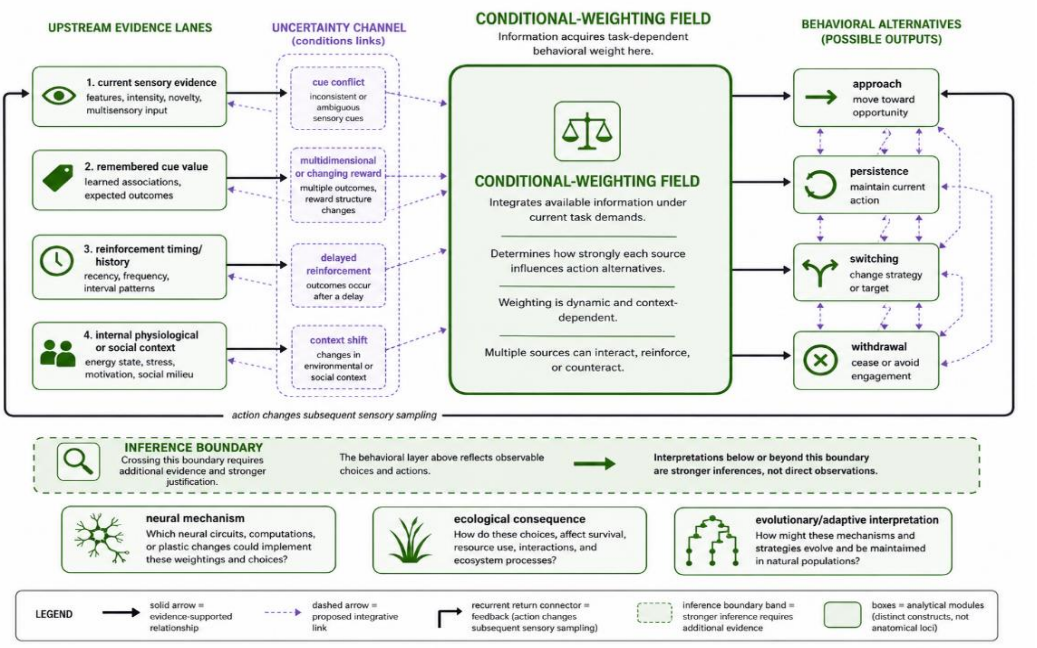


Figure 1. Temporal weighting of remembered value, current evidence, and persistence during uncertain insect choice

Ecological context and task demands

Context should not be treated as a residual explanation for unexplained variance. In insect sensory ecology, behavior reflects interaction between internal state and external conditions, with phylogenetic history and prior experience further constraining how information is used [20]. Ecological context therefore includes not only habitat or season, but also energetic state, recent reinforcement, cue availability, social setting, and the structure of the task itself.

This distinction matters because laboratory competence and ecological function are different evidential claims. Work on adaptive learning in non-social insects has emphasized that laboratory demonstrations require field linkage before adaptive value can be inferred [21]. A task may reveal genuine learning while remaining weakly connected to problems faced by that species in nature. Conversely, failure in a standardized assay may reflect sensory mismatch or motivation rather than absence of a cognitive process.

Environmental stress can alter performance directly. Short-term exposure of Bombus terrestris workers to heatwave-like temperature impaired associative learning and eliminated detectable one-hour retention in the tested conditioning assay [22]. That result demonstrates acute thermal sensitivity of measured cognition, not population decline, long-term fitness loss, or evolved vulnerability. Translational claims require additional links among environmental exposure, behavioral consequence, survival or reproduction, and population dynamics.

Task demands can also change the direction of cognitive effects. Multiple reward components influence bumblebee learning asymmetrically, demonstrating that reward dimensions should not automatically be reduced to one value axis [23]. At the life-history level, a direct test of proposed learning costs found no detectable reduction in reproductive success under the tested bumblebee conditions [24]. This null result prevents the assumption that cognitive processing necessarily carries a measurable reproductive penalty.

Taken together, these studies support three separations. Context can change cognitive performance without proving adaptation; performance can change without demonstrating ecological consequence; and ecological consequences can be positive, negative, or undetectable depending on task, season, life stage, reward structure, and environmental stress. The comparative matrix below therefore separates the contextual driver, endpoint actually observed, and stronger inference requiring additional evidence.

Table 2. When context changes cognition—and when it does not: adjudicating task effects, ecological consequences, and transfer limits

Interpretation justified within its limit	Taxon / biological setti with observed basis	Discriminating check
Seasonal change in memory value		
Evidence-supported		
Ecological value of measured memory is season-dependent **Better memory universally increases fitness** **Multiple seasonal variables covary**	Foraging bees across spring and summer Memory predicts foraging efficiency in one season but not the other	Measure memory, resource structure, and fitness-linked outcomes across seasons
Acute thermal stress		
Evidence-supported		
Cognitive performance is acutely temperature-sensitive **Heat-driven population decline or evolved maladaptation** **Laboratory exposure and short timescale**	Adult bumblebee workers Impaired associative learning and one-hour retention after heat exposure	Link realistic exposure histories to field behavior and demographic endpoints
Multidimensional reward structure		
Evidence-supported		
Task value cannot always be represented by one reward dimension **Universal optimal reward-integration rule** **Reward type and assay structure are specific**	Bumblebee foraging and learning Reward components affect learning asymmetrically	Manipulate reward dimensions independently under ecologically realistic availability
Laboratory-to-field transfer boundary		
Evidence-supported		
Cognitive competence and ecological function are separate evidential levels **Laboratory success establishes adaptive value**	Non-social insect learning literature	Validate assay performance against natural behavior and consequences

Ecological relevance varies by species and task	Laboratory learning may be demonstrated without direct field consequence	
Reproductive-cost null		
Evidence-supported		
Proposed cognitive costs require direct life-history testing **Learning is generally cost-free** **Stage, nutrition, power, and endpoint constrain the null**	Bumblebee reproductive context No detectable reproductive-success penalty under tested learning-cost conditions	Replicate across life stages, environments, and cost manipulations
Context-conditional consequence rule		
Proposed synthesis		
Cognitive value should be conditioned on environment and measured endpoint **A universal direction of cognitive effect** **Cross-study differences prevent pooled causal interpretation**	Cross-section synthesis Impairment, benefit, asymmetry, and null effects coexist across tasks	Predefine context, cognitive process, endpoint, and inference level

Individual variation

Population means can obscure biologically meaningful heterogeneity in how insects acquire, retain, and use information. Individual cognitive variation is therefore a level of analysis in its own right, but its causes and consequences should not be assumed. A multilevel perspective on honey-bee cognition links variation in behavior to candidate genetic, neural, experiential, and social-network processes while emphasizing that the causal chain among these levels remains incomplete [25]. Differences among individuals can thus be real without being fixed, heritable, or fitness-determining.

Social performance provides one context in which such heterogeneity matters. Individuality affected communication success in honey bees, showing that information transfer is not equivalent across workers [26]. Yet variation in signaling success could reflect sender behavior, receiver response, motor performance, experience, or role as well as cognition. Earlier evidence for cognitive phenotypes in honey bees is useful only with the same qualification: task-defined performance profiles should not be reified as immutable "types" without repeatability across contexts [19]. The proposed integration principle therefore treats individual state and history as potential modifiers of information weighting, while reserving trait-level interpretation for designs that distinguish persistent individual differences from transient condition.

Comparative cognition across insect taxa

Cross-taxon comparison becomes misleading when different tasks are arranged on an implicit ladder of intelligence. A better comparison asks what information was available, what had to be learned or retained, what response was measured, and how closely the assay matches the species' ecology. Bumblebees, for example, can socially acquire a multi-step rewarded behavior that naive controls did not solve under the same experimental conditions [27]. Paper wasps can instead acquire information about identifiable rivals by observing social interactions and use that information later [28]. Both findings demonstrate social information use, but they involve different problems and do not justify a single cognitive rank.

The same interpretive discipline applies to numerical tasks. Controlled honey-bee experiments demonstrate learned numerical-rule performance, including ordering an empty set within a trained relation and transferring color-cued addition- or subtraction-like rules over small numerosities [29, 30]. These results show flexible rule learning under carefully designed conditions; they do not establish human-equivalent mathematical semantics.

Ecologically embedded tasks broaden the comparison. Associative experience with non-nestmate cues can improve enemy recognition in ants [31], demonstrating learning in a colony-defense context rather than a floral-foraging task. Conversely, work with wild non-eusocial bees warns that standardized cognitive tests may favor generalists because task engagement and performance depend partly on sensory ecology, motivation, and ecological fit [32]. Poor performance or non-participation is therefore not equivalent to low cognitive capacity.

The state-and-response ledger below separates what is observed from the inference permitted, while the subsequent validation architecture shows why comparative claims require explicit boundaries between task performance, process interpretation, ecological transfer, and broader taxonomic inference.

Table 3. Comparing insect cognition without ranking intelligence: task states, responses, and inference ceilings

Comparative state with evidential standing	Taxon / ecological task and warranted reading	Observed response and decisive check
Social acquisition of a multi-step task **Evidence-supported**	Bumblebee; rewarded puzzle Social information can enable complex task acquisition	Observers acquire a solution unavailable to naive controls under tested conditions Does not establish cumulative culture or general intelligence Test transfer, persistence, and ecological relevance
Social eavesdropping **Evidence-supported**	Paper wasp; rival assessment Observed social events can inform individual-specific decisions	Later behavior changes after observing interactions Does not establish mental-state attribution Separate recognition, memory, and inferred opponent quality
Numerical-rule transfer **Evidence-supported**	Honey bee; visual discrimination Flexible learned rule application	Choices generalize according to trained numerical relations Does not establish human-like mathematics Test alternative perceptual strategies and broader transfer
Enemy-recognition learning **Evidence-supported**	Ant; colony defense Associative learning can refine socially relevant discrimination	Non-nestmate experience improves later recognition Does not show all recognition is learned Partition innate/template and acquired contributions
Assay–ecology mismatch **Evidence-supported**	Wild non-eusocial bees; standardized tasks Comparative scores can contain task-validity bias	Engagement/performance varies with ecological fit Poor performance cannot directly rank cognitive capacity Validate sensory, motivational, and ecological suitability by taxon
Task-to-inference separation **Proposed synthesis**	Cross-taxon synthesis Compare process and task demand before comparing performance	Similar scores may arise from different processes; different tasks may solve different ecological problems No universal intelligence scale follows from heterogeneous assays Use matched constructs with taxon-specific validity checks

Because comparative error often arises after a behavioral result has been obtained, the next figure makes the evidence-to-inference boundaries explicit rather than presenting cross-taxon cognition as a single continuum.

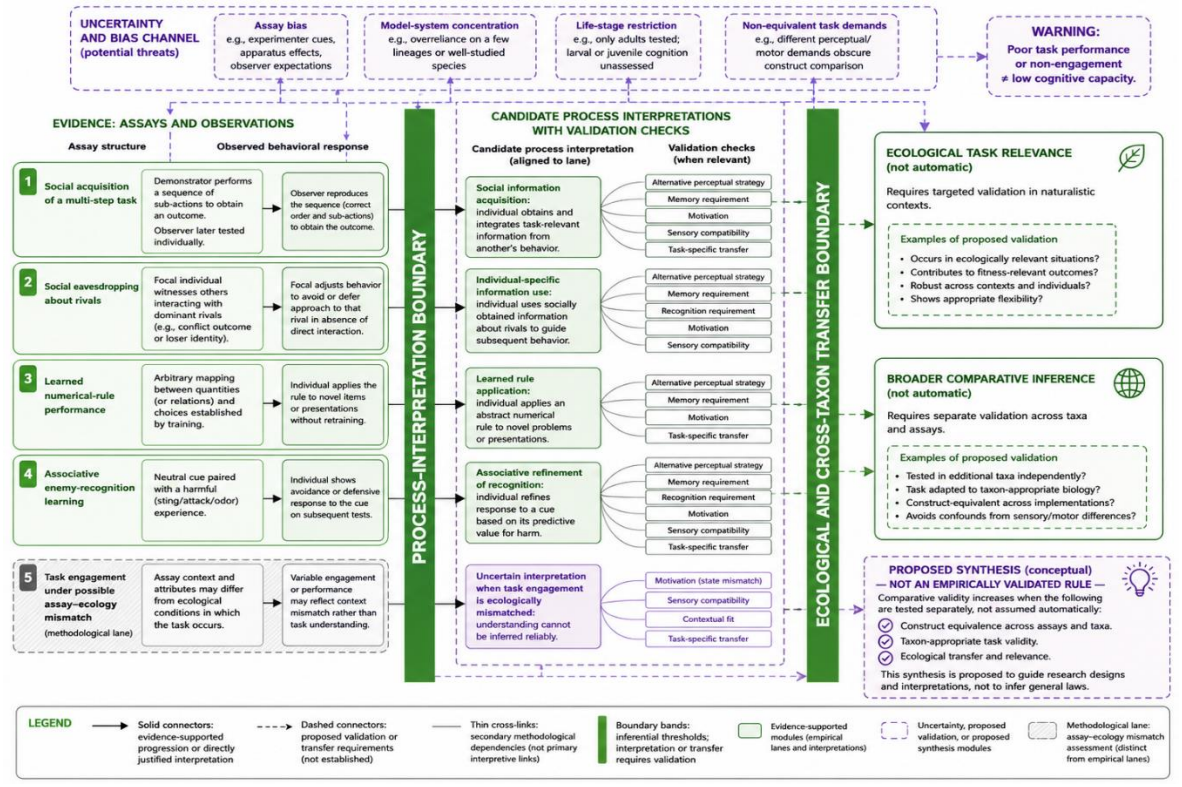


Figure 2. Where comparative insect-cognition claims gain—and lose—validity across task, process, and ecological transfer

Emerging experimental tools

New tools can reduce, but not erase, the gap between behavioral description and mechanism. Computer vision can quantify insect movement and interaction continuously and at higher throughput, allowing fine-scale behavior to be aligned with molecular or neural measurements [33]. Its outputs remain measurements, however: tracking accuracy, behavioral classification, annotation choices, and arena design must be validated before automated states are interpreted as cognitive states.

Single-cell transcriptomics adds a complementary level by resolving nervous-system cell types and molecular states across insect development and evolution [34]. Such resolution can generate hypotheses about cells associated with learning or state-dependent behavior, but transcriptomic identity is not itself a cognitive mechanism. Stronger inference requires temporal linkage to behavior, functional perturbation, and careful evaluation of cell-type homology across taxa.

Future questions

The main priority is not simply to make cognition assays more elaborate, but to make inference chains testable. Laboratory measures should be challenged across seasons and natural task structures because memory value can change with ecology [12]. Assay validity should also be tested explicitly in species whose sensory and motivational ecology differs from familiar models [32]. Field linkage remains necessary before adaptive value is inferred [21].

Mechanistic work should connect continuous behavior to causal neural or cellular perturbations without skipping intermediate levels. Computer-vision measurements [33] and cell-resolved molecular maps [34] make such designs increasingly feasible, but validation should include failures: conditions in which a neural correlate does not predict behavior, a laboratory score does not transfer to the field, or an individual difference disappears after state is controlled. The proposed context-conditional integration principle will be useful only if these boundary failures are treated as tests of the model rather than exceptions to be explained away.

Conclusion

Insect cognition is neither a single capacity nor a collection of processes that can be interpreted independently of ecology. Learning changes the consequences of experience, memory governs what persists, selective weighting determines which available information influences current behavior, and decisions alter subsequent information acquisition. Evidence across bees, ants, wasps, and *Drosophila* supports each of these components but remains uneven across taxa, tasks, life stages, and levels of mechanism. The proposed context-conditional integration principle organizes these relationships without assuming one conserved architecture. Its central requirement is evidential discipline: cognitive performance must be separated from mechanism, ecological function, and evolutionary consequence. Progress will depend on comparative assays with taxon-appropriate validity, multiscale mechanistic tests, and field designs capable of showing when cognitive differences matter—and when they do not.

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References

1. Chittka L. Bee cognition. Curr Biol. 2017;27(19):R1049-R53. doi:10.1016/j.cub.2017.08.008
2. Chittka L, Rossi N. Social cognition in insects. Trends Cogn Sci. 2022;26(7):578-92. doi:10.1016/j.tics.2022.04.001
3. Paoli M, Macri C, Giurfa M. A cognitive account of trace conditioning in insects. Curr Opin Insect Sci. 2023;57:101034. doi:10.1016/j.cois.2023.101034

4. Lin S. Internal-state-dependent modulation of olfactory responses: A tale of dopamine neurons in the adult Drosophila mushroom body. Curr Opin Insect Sci. 2023;59:101104. doi:10.1016/j.cois.2023.101104
5. Loukola OJ, Solvi C, Coscos L, Chittka L. Bumblebees show cognitive flexibility by improving on an observed complex behavior. Science. 2017;355(6327):833-6. doi:10.1126/science.aag2360
6. Abubaker MB, Hsu FY, Feng KL, Chu LA, de Belle JS, Chiang AS. Asymmetric neurons are necessary for olfactory learning in the Drosophila brain. Curr Biol. 2024;34(5):946-57.e4. doi:10.1016/j.cub.2024.01.037
7. Francés R, Rabah Y, Preat T, Plaçais PY. Diverting glial glycolytic flux towards neurons is a memory-relevant role of Drosophila CRH-like signalling. Nat Commun. 2024;15(1):10467. doi:10.1038/s41467-024-54778-x
8. Raza MF, Li W. Biogenic amines in honey bee cognition: Neurochemical pathways and stress impacts. Curr Opin Insect Sci. 2025;70:101376. doi:10.1016/j.cois.2025.101376
9. Wu L, Liu C. Integrated neural circuits of sleep and memory regulation in Drosophila. Curr Opin Insect Sci. 2023;59:101105. doi:10.1016/j.cois.2023.101105
10. Roy T, Beer K. Time memory in social insects with a special focus on honey bees. Curr Opin Insect Sci. 2025;68:101327. doi:10.1016/j.cois.2024.101327
11. Hosakere Mathada J, Romrig L, Poissonnier LA. Single-trial learning leads to mid-term memory formation in ants during an appetitive, but not an aversive, task. Proc Biol Sci. 2025;292(2045):20243054. doi:10.1098/rspb.2024.3054
12. Pull CD, Petkova I, Watrobska C, Pasquier G, Perez Fernandez M, Leadbeater E. Ecology dictates the value of memory for foraging bees. Curr Biol. 2022;32(19):4279-85.e4. doi:10.1016/j.cub.2022.07.062
13. Robert T, Tarapata K, Nityananda V. Learning modifies attention during bumblebee visual search. Behav Ecol Sociobiol. 2024;78(2):22. doi:10.1007/s00265-024-03432-z
14. Guiraud MG, MaBouDi H, Woodgate J, Bates OK, Ramos Rodriguez O, Gallo V, et al. How bumblebees manage conflicting information seen on arrival and departure from flowers. Anim Cogn. 2025;28(1):11. doi:10.1007/s10071-024-01926-x
15. Pírez N, Klappenbach M, Locatelli FF. Experience-dependent tuning of the olfactory system. Curr Opin Insect Sci. 2023;60:101117. doi:10.1016/j.cois.2023.101117
16. Westwick RR, Brackett GP, Brown CE, Ison BJ, Rittschof CC. Response to competing conspecific cues depends on social context in the honey bee Apis mellifera. Anim Behav. 2023;206:75-90. doi:10.1016/j.anbehav.2023.09.015
17. Zhou Y, MaBouDi H, Peng C, Galpayage Dona HS, Gutierrez Al-Khudhairy S, Chittka L, et al. Bumblebees display stimulus-specific persistence behaviour after being trained on delayed reinforcement. Behav Ecol Sociobiol. 2024;78:3. doi:10.1007/s00265-023-03414-7
18. Hemingway CT, Leonard AS, MacNeill FT, Pimplikar S, Muth F. Pollinator cognition and the function of complex rewards. Trends Ecol Evol. 2024;39(11):1047-58. doi:10.1016/j.tree.2024.06.008
19. Tait C, Naug D. Cognitive phenotypes and their functional differences in the honey bee, Apis mellifera. Anim Behav. 2020;165:117-22. doi:10.1016/j.anbehav.2020.04.023
20. Dahake A, Raguso RA, Goyret J. Context and the functional use of information in insect sensory ecology. Curr Opin Insect Sci. 2023;58:101058. doi:10.1016/j.cois.2023.101058
21. Nieberding CM, Van Dyck H, Chittka L. Adaptive learning in non-social insects: From theory to field work, and back. Curr Opin Insect Sci. 2018;27:75-81. doi:10.1016/j.cois.2018.03.008
22. Gérard M, Amiri A, Cariou B, Baird E. Short-term exposure to heatwave-like temperatures affects learning and memory in bumblebees. Glob Chang Biol. 2022;28(14):4251-9. doi:10.1111/gcb.16196
23. Muth F, Papaj DR, Leonard AS. Multiple rewards have asymmetric effects on learning in bumblebees. Anim Behav. 2017;126:123-33. doi:10.1016/j.anbehav.2017.01.010
24. Watrobska CM, Sima P, Ramos Rodrigues A, Leadbeater E. Potential costs of learning have no detectable impact on reproductive success for bumble bees. Anim Behav. 2024;214:173-85. doi:10.1016/j.anbehav.2024.05.005
25. Smith BH. Cognition from genes to ecology: Individual differences in cognition and its potential role in a social network. Anim Cogn. 2025;28(1):32. doi:10.1007/s10071-025-01951-4
26. McHenry LC, Schürch R, Johnson LE, Ohlinger BD, Couvillon MJ. Individuality impacts communication success in honey bees. Curr Biol. 2025;35(4):R137-8. doi:10.1016/j.cub.2024.12.047

27. Bridges AD, Royka A, Wilson T, Lockwood C, Richter J, Juusola M, et al. Bumblebees socially learn behaviour too complex to innovate alone. Nature. 2024;627(8004):572-8. doi:10.1038/s41586-024-07126-4
28. Tibbetts EA, Wong E, Bonello S. Wasps use social eavesdropping to learn about individual rivals. Curr Biol. 2020;30(15):3007-10.e2. doi:10.1016/j.cub.2020.05.053
29. Howard SR, Avarguès-Weber A, Garcia JE, Greentree AD, Dyer AG. Numerical ordering of zero in honey bees. Science. 2018;360(6393):1124-6. doi:10.1126/science.aar4975
30. Howard SR, Avarguès-Weber A, Garcia JE, Greentree AD, Dyer AG. Numerical cognition in honeybees enables addition and subtraction. Sci Adv. 2019;5(2):eaav0961. doi:10.1126/sciadv.aav0961
31. Bey M, Endermann R, Raudies C, Steinle J, Nehring V. Associative learning of non-nestmate cues improves enemy recognition in ants. Curr Biol. 2025;35(2):407-12.e3. doi:10.1016/j.cub.2024.11.054
32. Kashetsky T, Raine NE, Forrest JRK. Cognitive tasks could be biased towards generalists: A lesson from wild non-eusocial bees. Behav Ecol. 2025;36(4):araf054. doi:10.1093/beheco/araf054
33. Traniello IM, Kocher SD. Integrating computer vision and molecular neurobiology to bridge the gap between behavior and the brain. Curr Opin Insect Sci. 2024;66:101259. doi:10.1016/j.cois.2024.101259
34. Liu W, Li Q. Single-cell transcriptomics dissecting the development and evolution of nervous system in insects. Curr Opin Insect Sci. 2024;63:101201. doi:10.1016/j.cois.2024.101201