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Neuromodulators Link Insect Brain Chemistry With Behavioral States, Motivational Shifts, and Ecological Action Across Biological Scales

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ABSTRACT

Neuromodulators are often discussed as if particular chemicals map predictably onto particular insect behaviors. Evidence from contemporary neurophysiology instead indicates that behavioral consequences depend on where, when, and under which physiological conditions a signal acts. Biogenic amines, neuropeptides, endocrine signals, receptor context, cotransmission, circuit configuration, prior experience, and ongoing motor or motivational state can all modify the relationship between brain chemistry and action. This article develops an original non-empirical neurophysiological framework for interpreting these relationships across biological scales. The framework separates chemical signal identity from receptor and cellular context, circuit transformation, behavioral-state configuration, motivational valuation, and ecological action. Evidence from *Drosophila* demonstrates state-dependent reinforcement, sleep and arousal regulation, serotonergic modulation of stress-associated and social behavior, nutrient-responsive gut-brain signaling, reproductive-state-dependent dietary choice, peptide-mediated sensorimotor bias, and nonlinear cotransmission. Mosquito and honey-bee evidence broadens the ecological domain while emphasizing substantial taxonomic and laboratory-to-field transfer limits. The central argument is that neuromodulators should be interpreted as conditional regulators whose behavioral meaning emerges from interactions among signaling context, circuit state, biological history, and ecological demand rather than from transmitter identity alone. The proposed architecture is therefore not an insect-wide mechanistic law, but a framework for organizing evidence, identifying failed one-to-one interpretations, and generating comparative tests of when neurochemical changes translate into behavioral and ecological action.

Keywords: Biogenic amines, Neuropeptides, Behavioral state, Motivational valuation, Insect neurophysiology, Neuromodulation.

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Introduction

Insect behavior is frequently described using transmitter-centered language: octopamine is associated with arousal or reward, dopamine with reinforcement, serotonin with behavioral state, and neuropeptides with hunger, satiety, or endocrine coordination. Such shorthand is useful descriptively but becomes problematic when chemical identity is treated as a sufficient explanation of action. Recent syntheses instead indicate that energetic condition, social context, and physiological state can alter how neuromodulatory systems influence locomotion, social behavior,

and olfactory priorities [1–3]. Stress-related effects on learning are likewise heterogeneous across processes, taxa, and experimental conditions rather than uniformly impairing or enhancing performance [4].

The inferential problem is therefore not whether neuromodulators influence insect behavior, but where explanatory responsibility should be placed between chemical signal and ecological action. Broad manipulation of dopaminergic, octopaminergic, tyraminerbic, serotonergic, and neuropeptide systems in adult *Drosophila* produced dissociable feeding, locomotor, and metabolic phenotypes rather than a single coordinated syndrome [5]. A transmitter label alone consequently does not specify behavioral direction, magnitude, persistence, or biological consequence.

This article develops a proposed cross-scale neuromodulatory architecture that treats behavioral output as conditionally constructed across several separable levels: chemical and hormonal input; receptor and cellular context; circuit transformation; behavioral-state configuration; motivational valuation; and ecological action. These levels are linked but not equivalent. The framework also permits reciprocal influence, because behavior can alter neuroendocrine activity rather than acting solely as a downstream product of chemistry. Its purpose is not to impose a universal insect mechanism. Instead, it provides a disciplined way to ask when evidence at one level licenses inference at another, while preserving sex, life-stage, taxonomic, temporal, environmental, and laboratory-versus-field boundaries.

Biogenic amines

Biogenic amines illustrate why neuromodulatory meaning cannot be inferred from chemical identity independently of state and circuitry. Under chronic hunger, *Drosophila* maintain aversive reinforcement through compensatory input involving adipokinetic hormone-sensitive octopaminergic signaling to aversive dopaminergic neurons [6]. Hunger therefore did not merely attenuate responsiveness; in this defined paradigm it altered the weighting of inputs supporting reinforcement. The result supports state-dependent reconfiguration of an aminergic circuit, not a general rule that starvation strengthens aversive learning.

Octopamine is similarly unsuitable as a unitary “arousal” label. A small octopaminergic VPM3 circuit projecting toward mushroom-body and central-complex regions affects sleep, arousal, and male courtship, with consequences dependent on circuit target, sex, and sleep history [7]. The relevant explanatory unit is consequently an octopaminergic signal acting within a specified circuit and state, rather than octopamine considered in isolation. Stress-associated and social behaviors reinforce this point. In experimental *Drosophila* paradigms, octopaminergic, dopaminergic, and serotonergic signaling participate in distinct circuit configurations associated with sugar-mediated relief of a chronic-stress-induced depression-like state, serotonergic regulation of another stress-associated behavioral phenotype, and mushroom-body-dependent social attraction [8–10]. These findings should not be collapsed into a generalized “affective” function of insect amines. The depression-like terminology belongs to operational behavioral models and does not establish mechanistic equivalence with human psychiatric states.

The useful generalization is therefore conditional. Amines can alter the gain, persistence, or direction of behavior, but their effects depend on receptor distribution, circuit membership, competing signals, current physiological state, and the behavioral variable measured. A transmitter-centered vocabulary is most informative when it identifies a chemical participant; it becomes overextended when it substitutes that participant for the biological architecture through which behavior is produced.

Neuropeptides and hormonal inputs

Neuropeptides and hormonal signals expand neuromodulation beyond locally released brain chemicals by carrying information about nutritional, reproductive, and temporal state into neural decision systems. In *Drosophila*, a high-protein diet can engage gut-derived CCHamide-1 signaling and sNPF-associated enteric circuitry that constrains further protein intake [11]. This provides a direct example of peripheral physiological information reaching a neural system that modifies consumption. It does not demonstrate a universal nutritional optimum; the documented relationship is conditional on species, dietary context, and pathway integrity.

Reproductive state can similarly transform food valuation. Mating alters yeast preference through sexually differentiated leucokinin circuitry, with male and female responses differing rather than following a single post-mating rule [12]. The important inference is that the apparent value of the same resource can change with reproductive state. Whether such changes are adaptive in a broader evolutionary sense cannot be inferred from the circuit result alone.

At the sensorimotor level, larval *Drosophila* provide unusually explicit evidence that NPF and sNPF signals can bias reciprocally connected inhibitory neurons according to feeding state, thereby changing behavioral selection [13]. This supports a circuit-biasing interpretation of peptide action, while its larval preparation prevents automatic transfer to adult feeding or other insects. Temporal state adds another layer: interactions involving adipokinetic hormone and octopamine tune daily locomotor activity differently across circadian phases [14]. Endocrine action is therefore not necessarily directionally constant through time.

Mosquito pharmacology reveals an additional boundary between molecular engagement and whole-animal action. Small-molecule agonists targeting the *Aedes aegypti* NPY-like receptor NPYLR7 can inhibit blood feeding, yet receptor-level potency does not translate perfectly into behavioral efficacy [15]. Receptor activation is consequently evidence of a molecular event, not sufficient evidence of behavioral magnitude or field-level vector-control effectiveness. Across these examples, peptide and hormonal signals are best interpreted as state-bearing inputs whose meaning is transformed at subsequent cellular and circuit levels.

Receptor and circuit-level effects

A receptor or transmitter becomes behaviorally informative only when its cellular and circuit context is specified. Mapping of the *Drosophila* central complex demonstrates extensive but heterogeneous neuropeptide expression across identified cell types, frequently alongside small-molecule transmitters [16]. Expression establishes potential signaling architecture, but it does not establish that every expressed peptide is released, behaviorally necessary, or functionally equivalent across those cells.

Receptor nomenclature can also invite incorrect mechanistic inference. DopEcR contains “dopamine” in its name, yet toxin-related avoidance and detoxification in *Drosophila* were attributed to ecdysteroid–DopEcR signaling acting in different neuronal and midgut compartments [17]. Receptor identity therefore cannot substitute for determination of the operative ligand, tissue, and downstream process.

Cotransmission creates an even stronger challenge to one-input/one-output models. A single feeding-related neuron can promote or suppress feeding at different activation levels through differential contribution of classical and peptidergic transmitters [18]. The relevant input-output function is nonlinear: neuronal identity alone does not fix behavioral direction.

Circuit position further separates sensation from valuation. A defined interneuron pair can confer positive real-time valence to sweet sensation while leaving aspects of sensory discrimination intact [19]. Conversely, descending and dopaminergic systems controlling walking direction show effects that vary with the animal's current motor state [20]. Together, these studies indicate that sensory representation, value assignment, and motor implementation are analytically separable transformations.

The receptor-and-circuit evidence therefore resolves a central interpretive problem more effectively as a cross-scale grid than as a list of transmitters. The grid below distinguishes when the same chemical or cellular component can support different interpretations because ligand, tissue, activity regime, circuit position, or behavioral mode changes.

Table 1. Cellular and circuit conditions that prevent receptor or transmitter identity from uniquely specifying behavioral output

Circuit distinction	Biological and observable frame	Neuromodulatory meaning	Boundary and status	Decisive test
Peptide coexpression within identified central-complex cell types	Biological context Adult <i>Drosophila</i> central complex Observable evidential basis Cell-type-specific peptide expression and selected sleep phenotypes	Modulatory identity can be combinatorial rather than one-transmitter-per-cell	Boundary or uncertainty Expression does not prove release, necessity, or equal function Status Evidence-supported	Pair expression maps with state-specific functional manipulation
Ligand–receptor–tissue specificity	Biological context Neuronal avoidance and midgut detoxification in <i>Drosophila</i> Observable evidential basis Tissue-specific manipulation of DopEcR-related signaling	Receptor name alone cannot identify the operative transmitter or	Boundary or uncertainty Effects are toxin- and tissue-context dependent Status	Resolve ligand, tissue, and downstream output separately

		organismal consequence	Evidence-supported	
Activation-level-dependent cotransmission	Biological context Feeding-related <i>Drosophila</i> neuron	One neuron can change behavioral direction through transmitter-specific output regimes	Boundary or uncertainty Artificial activation does not define all natural activity ranges Status Evidence-supported	Measure natural firing regimes together with transmitter release
	Observable evidential basis Opposite feeding outcomes under different activation and transmitter conditions			
Sensory identity versus assigned valence	Biological context Sweet-responsive <i>Drosophila</i> circuitry	Valuation can be modified downstream of stimulus identity	Boundary or uncertainty Demonstrated for a specific sensory modality and circuit Status Evidence-supported	Test whether analogous separations occur across modalities and taxa
	Observable evidential basis Positive real-time value changes despite retained sensory discrimination			
Behavioral-mode gating of motor influence	Biological context Walking versus other locomotor states in adult <i>Drosophila</i>	Current action mode can gate the expression of neuromodulatory control	Boundary or uncertainty Evidence does not establish a universal locomotor hierarchy Status Evidence-supported	Compare identical circuit perturbations across defined motor states
	Observable evidential basis State-dependent effects of descending and dopaminergic pathways			
Cross-scale synthesis				
Context-dependent neuromodulatory meaning	Biological context Cross-scale synthesis of the above cases	behavioral meaning should be assigned to signal × receptor/cell × circuit × state combinations rather than chemical identity alone	Boundary or uncertainty Comparative evidence remains strongly <i>Drosophila</i> -weighted Status Proposed synthesis	Test matched signal manipulations across homologous and non-homologous circuits
	Observable evidential basis Convergence of ligand, cellular, circuit, and state dependencies			

Behavioral-state switching

Behavioral-state switching is often represented as a downstream response to neuromodulators, but insect evidence supports a more reciprocal interpretation. Activity of insulin-producing cells changes rapidly with locomotor state in *Drosophila*, including suppression during locomotion and rebound after locomotor episodes [21]. Behavioral state can therefore modify neuroendocrine activity on a timescale relevant to ongoing action. This does not establish the full downstream metabolic consequence of each neural transition, but it rules out an exclusively top-down chemistry-to-behavior description.

State also has history. Social experience in *Drosophila* can produce behavioral changes that persist after the initiating social context has ended, with persistence depending on memory-related processes [22]. That study did not measure a neuromodulatory mechanism, so it cannot establish that amines or peptides caused the retained state. It instead supplies a necessary boundary condition: instantaneous chemical measurements may be insufficient when current behavior carries information from previous experience.

Internal-state integration provides a complementary mechanism. Mushroom-body circuits can combine hunger- and satiety-associated signals to regulate innate food seeking [23]. These signals converge functionally without becoming interchangeable. Consistent with the broader dissociations observed after neuromodulatory-system manipulation [5], a behavioral state should therefore not be treated as a single synchronized variable propagating identically through metabolism, motivation, and action.

The proposed state-field interpretation developed here treats switching as movement through a constrained physiological-behavioral field rather than as passage between chemically labelled boxes. Current energetic state, prior experience, circuit configuration, and active motor regime alter which transitions are available and how a neuromodulatory input is expressed. Some relationships are directly supported within defined *Drosophila*

preparations; the cross-linking of these relationships into a common state architecture is proposed and requires comparative validation.

Because this distinction is difficult to recover from a linear pathway diagram, **Figure 1** separates state trajectories from the conditioning variables that redirect, retain, or feed back onto them.

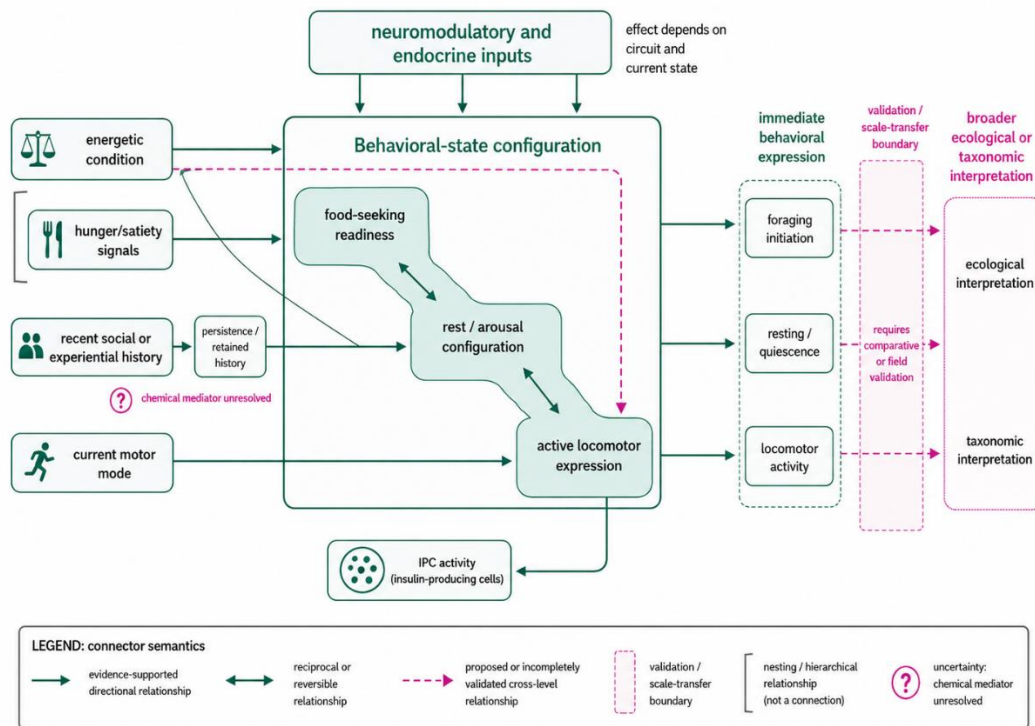


Figure 1. Behavioral states redirect neuromodulatory meaning rather than merely receiving it

Motivation and valuation

Motivation should not be treated as a scalar quantity that rises or falls uniformly with physiological need. Behavioral dissection of hunger in *Drosophila* indicates that experimentally defined hedonic and homeostatic hunger conditions can produce distinguishable behavioral and circuit signatures [24]. “Hunger” is therefore a useful organismal descriptor but an insufficient mechanistic variable unless the underlying state, resource context, and behavioral endpoint are specified.

Valuation adds a further transformation between physiological need and action. Dopaminergic reinforcement systems can sustain reward seeking despite experimentally imposed adverse consequences, demonstrating that competing positive and negative signals need not be integrated into a simple net-value calculation [25]. This result establishes circuit-level competition under a defined laboratory paradigm; it does not justify clinical analogies or imply that similar persistence is universally advantageous under natural conditions.

Valence itself can also be separated from sensory identity. Sweet-responsive information can retain sensory discriminability while defined interneurons assign positive real-time value through downstream circuitry [19]. Conversely, mushroom-body circuits can alter food seeking as hunger- and satiety-associated signals change [23]. Stimulus identity, motivational state, and assigned value are therefore analytically distinguishable even when they converge on the same final action.

The proposed valuation principle developed here is that neuromodulators do not encode fixed values for stimuli. Instead, they alter how sensory information is weighted within a state-dependent decision architecture. This interpretation predicts conditional rather than invariant relationships between transmitter activity and observable preference.

The principal failure modes are easier to distinguish when motivational variables are arranged by the specific inferential error they can generate rather than by chemical class.

Table 2. Conditionality and failure modes in interpreting insect motivation and neural valuation

Hedonic versus homeostatic hunger		Reward versus adverse consequence	
Context and observation	Biological context Adult <i>Drosophila</i>	Context and observation	Biological context Laboratory <i>Drosophila</i> reward-conflict paradigm
	Observable basis Distinguishable behavioral and circuit signatures		Observable basis Persistent reward seeking despite competing negative input
Interpretation and boundary	Interpretation for behavioral choice Similar feeding outcomes can arise from different motivational configurations	Interpretation and boundary	Interpretation for behavioral choice Valuation can reflect competition among partially separable systems
	Failure mode or boundary Treating “hunger” as one scalar state		Failure mode or boundary Equating laboratory persistence with addiction or adaptive benefit
Test and status	Research/test implication Measure motivational context independently of consumption	Test and status	Research/test implication Test naturalistic costs and competing reinforcers
	Status Evidence-supported		Status Evidence-supported
Sensory identity versus valence		Hunger/satiety convergence	
Context and observation	Biological context Sweet-processing circuitry	Context and observation	Biological context Mushroom-body food-seeking circuitry
	Observable basis Preserved discrimination with altered positive value		Observable basis Multiple internal-state signals alter common behavioral output
Interpretation and boundary	Interpretation for behavioral choice Value can be assigned downstream of stimulus identification	Interpretation and boundary	Interpretation for behavioral choice Convergent signals can remain functionally non-equivalent
	Failure mode or boundary Inferring preference directly from sensory coding		Failure mode or boundary Assuming one canonical hunger pathway
Test and status	Research/test implication Separate detection, identity, value, and action experimentally	Test and status	Research/test implication Manipulate state signals individually and jointly
	Status Evidence-supported		Status Evidence-supported
State-dependent stimulus value			
Context and observation	Biological context Cross-study synthesis		
	Observable basis Preference changes with physiological and reproductive context		
Interpretation and boundary	Interpretation for behavioral choice stimulus value is dynamically weighted rather than chemically fixed		
	Failure mode or boundary Overgeneralizing transmitter–value associations across states		
Test and status	Research/test implication Compare identical stimuli across matched physiological states		
	Status Proposed synthesis		

Ecological action

Neuromodulation becomes ecologically meaningful only when laboratory-defined states are connected carefully to naturally expressed actions. Honey-bee foraging provides one such boundary. Appetitive motivation in workers is embedded within colony and social context, with multiple signaling systems implicated rather than a single neurochemical controller [26]. Colony need can therefore shape the conditions under which individual motivation is expressed, but colony-level demand should not be collapsed into a directly measured neural variable.

Foraging specialization provides an additional caution. Pollen and nectar foragers differ in learning and reward responsiveness, yet changing reward composition can alter the apparent magnitude of those task-associated differences [27]. Ecological role and motivational phenotype are therefore mutually informative without being mechanistically equivalent. Because neuromodulators were not directly measured in that study, it cannot establish a neurochemical cause of task specialization.

Mosquitoes illustrate a different translation problem. Their olfactory priorities vary with sex and physiological state, linking sensory modulation to host seeking, nectar seeking, or other ecologically relevant actions [3]. Yet even direct molecular intervention does not guarantee ecological performance. NPYLR7 agonists can suppress blood feeding under laboratory conditions, while receptor-level potency incompletely predicts whole-animal behavioral efficacy [15]. The molecular-to-action relationship is therefore conditional before field complexity is even introduced.

The proposed ecological-action rule is consequently conservative: evidence should cross biological scales only when intermediate transformations remain explicit. Molecular engagement, circuit modulation, motivational change, behavioral execution, and ecological consequence are related levels, not interchangeable endpoints. A trait–process–consequence map clarifies where ecological interpretation is supported and where inference requires additional validation.

Table 3. Where neuromodulatory evidence can and cannot be translated into ecological action

Scenario and setting	Measured state	State-to-action process	Ecological consequence	Transfer boundary	Validation and status
Ecological-action scenario Socially embedded appetitive motivation Taxonomic/behavioral context Worker honey bees	Foraging motivation within colony context	Individual neural state interacts with social demand	Context-dependent expression of foraging effort	Colony-level need is not itself a measured neural signal	Research/test implication Couple individual neurophysiology to independently quantified colony conditions Status Evidence-supported
Ecological-action scenario Reward-conditioned task specialization Taxonomic/behavioral context Pollen versus nectar foragers	Learning and reward responsiveness	Reward context modifies task-associated performance	Behavioral specialization is partly context sensitive	Neuromodulators were not measured directly	Research/test implication Add neurochemical measures without assuming causality Status Evidence-supported
Ecological-action scenario State-dependent olfactory action Taxonomic/behavioral context Mosquitoes	Physiological and sex-dependent sensory priorities	Neuromodulation reweights sensory-action pathways	Host-, nectar-, or reproduction-related action can change with state	Mechanisms and life histories vary among mosquito taxa	Research/test implication Compare state transitions across species and ecological settings Status Evidence-supported
Ecological-action scenario Receptor engagement to host feeding Taxonomic/behavioral context Female <i>Aedes aegypti</i>	NPY-like receptor pharmacology and blood feeding	Receptor activation alters whole-animal feeding probability	Laboratory biting behavior can be modified	Molecular potency does not guarantee behavioral ranking or field effectiveness	Research/test implication Validate receptor, circuit, organismal, and field levels separately Status Evidence-supported
Ecological-action scenario	Signal, circuit, motivation,	Sequential conditional transformations	ecological consequence is credible	Any unmeasured intermediate level can break	Research/test implication

Molecular-to-ecological continuity Taxonomic/behavioral context Cross-scale synthesis	action, environment	only when intermediate levels are demonstrated or explicitly bounded	the inference chain	Design multilevel studies rather than extrapolating directly from molecule to ecology Status Proposed synthesis
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Because ecological translation involves reconciliation across unlike evidence classes rather than simple pathway extension, **Figure 2** displays molecular, circuit, organismal, and ecological levels as related but separated domains.

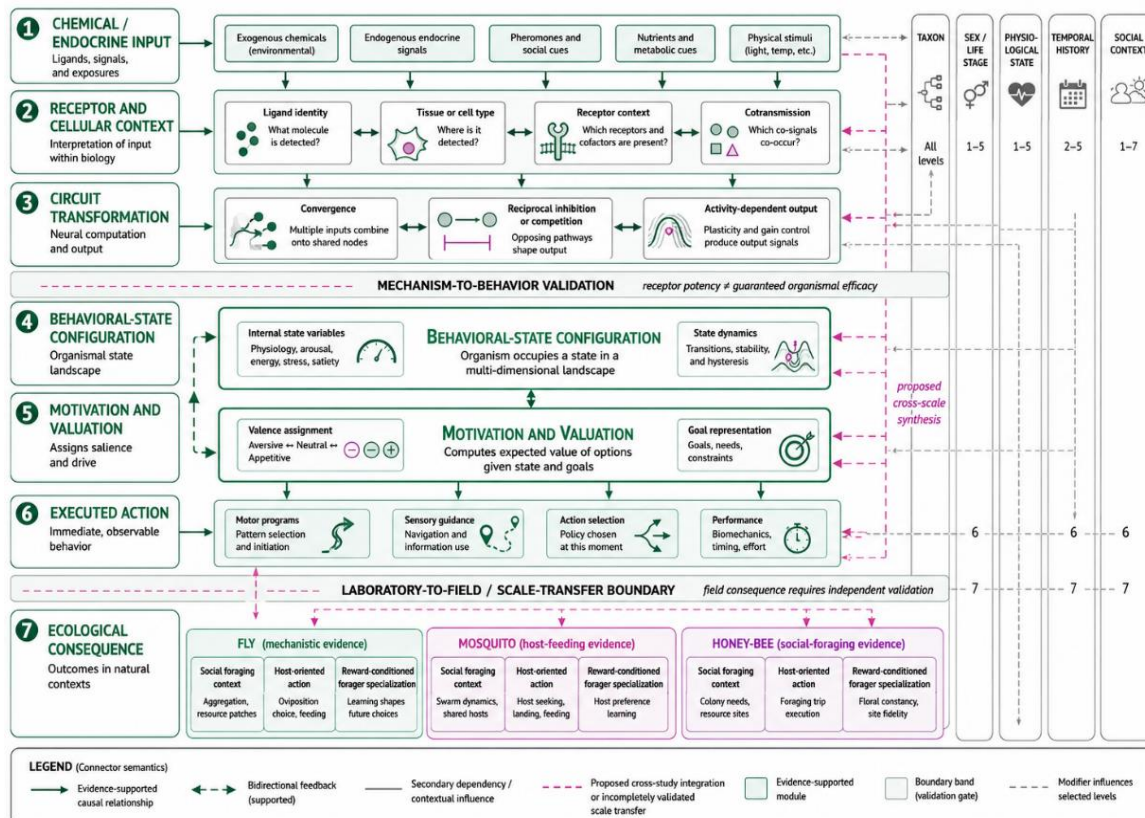


Figure 2. Scale-transfer boundaries determine when insect neuromodulation can support ecological inference

Cross-scale neuromodulatory architecture

The preceding evidence supports integration, but not a universal transmitter-centered hierarchy. Energetic and endocrine state can interact with aminergic control [1], while hunger can specifically reweight reinforcement circuitry [6]. Peripheral nutrient signaling can reach peptide-linked neural systems [11], and the functional meaning of a receptor can vary by operative ligand and tissue [17]. These are distinct entry routes into neural control rather than demonstrations of one conserved master pathway.

At the circuit level, heterogeneity increases further. Peptides can coexist with small-molecule transmitters in identified central-complex neurons [16], activity level can alter which transmitter contribution dominates behavioral output [18], and multiple hunger- and satiety-related signals can converge on mushroom-body control without becoming interchangeable [23]. Circuit transformation therefore constitutes an explanatory level in its own right.

Behavioral output also changes the system it emerges from. Motor-state-dependent neural effects [20] and locomotion-linked changes in insulin-producing-cell activity [21] indicate that ongoing action can gate or feed back onto neuroendocrine processing. The architecture is consequently recursive rather than strictly feed-forward.

The central contribution of this article is the proposed cross-scale neuromodulatory architecture: chemical identity defines a potential signal; receptor and cellular context constrain its immediate meaning; circuit configuration transforms that signal; physiological and historical state determine which transformations are available; motivation and valuation weight competing actions; and ecological context conditions whether an executed behavior has broader significance. Honey-bee social foraging demonstrates why ecological context cannot simply be appended as a final neural output [26], while mosquito receptor pharmacology shows why molecular efficacy must be validated again at the organismal level [15].

This architecture should therefore be read as an evidence-organizing model, not an empirically validated insect-wide pathway. Comparative generalization remains limited by the concentration of mechanistic studies in *Drosophila*, uneven representation of developmental stages and sexes, and the predominance of laboratory preparations. Stress and learning research further demonstrates that even apparently shared state variables can produce process-specific effects [4]. The framework's utility lies precisely in making such breaks in inference explicit.

Comparative predictions

The framework generates several testable propositions, all of which remain proposed predictions rather than established cross-insect laws.

First, receptor, cellular, and circuit context should often predict behavioral direction more accurately than transmitter identity alone. Tissue-specific receptor effects [17] and activity-dependent cotransmission [18] make this prediction plausible, but matched comparative manipulations are required before it can be generalized.

Second, sex, life stage, and physiological state should alter neuromodulatory input-output relationships. Sex-dependent dietary responses [12], larval feeding-state circuitry [13], and female mosquito receptor pharmacology [15] establish the relevant dependencies in particular systems, not a universal rule.

Third, molecular potency should be a weak standalone predictor of ecological action whenever intermediate circuit or state variables are unmeasured. The imperfect receptor-to-behavior translation demonstrated for mosquito NPYLR7 pharmacology [15] supplies a direct reason to test this proposition across additional receptor systems.

Fourth, prior experience may change later neuromodulatory responsiveness even when the initiating context has disappeared. Persistent social-experience effects demonstrate behavioral history [22], but the chemical mediator remains unresolved; direct neural measurements before and after defined experience are therefore essential.

Fifth, social organization and foraging role may alter motivational neuromodulation through context-specific weighting rather than fixed transmitter functions. Honey-bee evidence supports social and reward-context dependence [26], whereas task-specialization experiments show that changing reward conditions can modify apparent performance differences [27]. Cross-caste and cross-task neurophysiological experiments could distinguish stable circuitry from context-dependent valuation.

The most defensible expectation is consequently that comparative regularity will emerge first at the level of conditional architectural principles—state dependence, circuit specificity, nonlinear transformation, reciprocal feedback, and validation boundaries—rather than at the level of exact transmitter-to-behavior mappings.

Conclusion

Neuromodulators connect insect brain chemistry with behavior, but the connection is neither chemically self-explanatory nor biologically uniform. Biogenic amines, neuropeptides, hormones, receptors, cotransmitters, circuits, prior experience, internal state, and ecological context operate at distinguishable levels that can modify one another without becoming interchangeable.

The proposed framework reorganizes these relationships around conditional transformations rather than transmitter labels. It distinguishes molecular participation from receptor function, circuit transformation from behavioral state, motivation from sensory identity, immediate action from ecological consequence, and demonstrated mechanism from cross-scale inference. Reciprocal state–neuroendocrine relationships further prevent behavior from being treated solely as the endpoint of a chemical cascade.

Its principal limitation is also its principal methodological message: mechanistic knowledge remains taxonomically uneven and strongly concentrated in experimentally tractable systems. Comparative progress will

require matched tests across sexes, life stages, taxa, physiological states, social settings, and environmental conditions, together with explicit validation between molecular, circuit, organismal, and field levels. Neuromodulatory chemistry is therefore best understood not as a dictionary assigning molecules to behaviors, but as one layer in a state-dependent architecture through which insects transform internal and external information into action.

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