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Microclimate, Host Cues, and Behavioral Filtering Turn Ecological Niches into Dynamic Sensory Worlds for Insects

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ABSTRACT

Ecological niches are commonly described from environmental conditions and resources measured at scales convenient to observers, yet insects encounter physical and biological information at much finer spatial and temporal resolutions. Environmental availability alone therefore cannot specify the sensory world experienced by an individual. This ecological perspective separates five analytically distinct components of that problem: local physical exposure, biologically associated information, peripheral detectability, behavioral filtering, and the spatial and temporal consequences of information use. The separation is analytical rather than a claim that these components form a universal linear mechanism. Evidence from thermal ecology, host seeking, plant–insect interactions, predator responses, sensory physiology, neural processing, and insect cognition shows why these components cannot safely be collapsed. Microhabitat can alter apparent thermal responses; multimodal signals may depend on conditional gating; competitor-associated information can acquire unexpected behavioral value; and sensory capacities differ among taxa, developmental states, sexes, and receptor systems. We consequently develop a proposed realized sensory niche: the dynamically restricted portion of locally available physical and biotic information that is accessible to an insect's sensory system and behaviorally weighted under its current state, previous experience, and ecological context. The construct is offered as an ecological synthesis requiring direct validation rather than as an established niche metric or universal mechanism.

Keywords: Insect sensory ecology, Microclimate, Multimodal cues, Sensory detection, Behavioral filtering, Realized sensory niche

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Introduction

An insect does not encounter the environment at the resolution at which climate surfaces, habitat categories, or vegetation classes are usually mapped. Temperatures at organism-relevant scales can depart substantially from coarse climatic summaries, and fine-scale conditions may either buffer or intensify exposure rather than consistently moderating it [1]. This scale problem has consequences beyond thermal biology. If environmental measurements are treated as direct descriptions of what an insect experiences, the distinction between environmental availability and organismal exposure disappears. A habitat can therefore contain nominally suitable

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conditions while presenting a markedly different physical interface to insects occupying particular substrates, boundary layers, heights, or microhabitats.

The same problem applies to biological information. Bumblebee floral recognition illustrates that ecologically relevant objects can be represented through combinations of sensory modalities and that the usefulness of those modalities depends on context and learning [2]. Multimodality, however, does not imply that all available signals are detectable, equally informative, or equally weighted. A volatile, wavelength, humidity gradient, thermal contrast, predator signal, or competitor-associated odor may physically exist while remaining outside the effective sensory world of a particular individual.

This perspective therefore asks a narrower question than a general review of insect sensory ecology: how do microclimate, biologically associated cues, detection limits, and behavioral filtering transform a nominal ecological niche into the sensory environment actually available for action? The central distinction is among information that is locally present, information that can enter the sensory system, and information that influences behavior. These layers can interact recursively, and none is assumed to determine the next automatically. The resulting synthesis culminates in a proposed realized sensory niche that treats sensory experience as conditional on organism, place, time, and state rather than as a fixed property of habitat or species.

Conceptual methods

This article is an ecological perspective based on structured conceptual synthesis rather than a systematic review, meta-analysis, or new empirical dataset. Evidence was organized across linked levels: fine-scale physical exposure; host-, plant-, predator-, and competitor-associated information; peripheral and neural detectability; behavioral weighting; and spatial or temporal consequences. The distinction between coarse environmental description and organism-relevant exposure provides the scale rationale for this organization [1]. These levels are separated analytically to prevent observations made at one level—for example, receptor structure or neural representation—from being treated automatically as evidence of ecological preference, performance, or fitness.

Transfer among study systems is likewise conditional. Multimodal floral recognition in bumblebees demonstrates the ecological importance of combining information channels, but it does not establish an invariant sensory architecture for other insects [2]. Throughout the perspective, taxon, life stage, sex, environmental setting, temporal scale, and experimental context are therefore retained when they affect interpretation. Mechanistic laboratory evidence is used to establish what can occur within demonstrated systems; comparative and field evidence establishes different classes of ecological constraint. Original connections among these evidence classes are identified as synthesis rather than empirical validation.

Physical microclimate

The first restriction on an insect's sensory world occurs before sensory transduction: the organism must physically encounter a condition or signal. This point is particularly clear for temperature. In a controlled multi-species experiment, the configuration of microhabitats altered the relationship between heat and insect activity, demonstrating that the same broad thermal treatment need not produce the same behavioral exposure when refuges and habitat structure differ [3]. Microhabitat should therefore not be treated as uniformly protective; its arrangement can modify, including reverse, an apparent heat response.

Even within the same vegetation, body geometry changes physical coupling to thermal heterogeneity. Measurements and biophysical analysis of plant-associated arthropods showed that body size influences how closely organismal temperature tracks heterogeneous plant-surface temperatures [4]. Thus, a thermal mosaic is not a single exposure field shared identically by all occupants. Surface properties, weather, morphology, and position can alter the thermal conditions effectively encountered by different insects.

These short-term exposure differences can propagate into longer biological timescales. Fine-scale microclimatic variation altered modeled developmental timing, synchrony, and voltinism in *Pieris napi*, showing that coarse climatic averages can miss biologically consequential thermal structure [5]. Yet response to thermal environments cannot be reduced to exposure alone. Across tropical Odonata, upper thermal physiology covaried with environmental, morphological, taxonomic, and sex-related factors, whereas lower thermal responses did not reproduce the same environmental pattern [6]. The contrast argues against treating a single thermal axis or one tolerance measure as a complete representation of insect–environment coupling, and the associations do not by themselves establish evolutionary adaptation.

The physical interface may also be reciprocal. In particular plant–herbivore systems, feeding modified leaf physiological conditions and consequently the thermal environment at the leaf surface [7]. This provides direct evidence that an insect can sometimes alter the microenvironment with which it subsequently exchanges heat. Such feedback should not be generalized into universal niche construction or presumed beneficial. It instead establishes a narrower principle important for sensory ecology: organismal activity can occasionally change the physical field from which later sensory exposure arises.

Taken together, these cases define physical microclimate as an exposure filter, not merely background habitat. Temperature, humidity, light, and transported chemicals can only contribute to an insect's momentary sensory world in the forms that reach its occupied microspace. The proposed synthesis therefore places organism-scale exposure upstream of sensory accessibility while allowing behavior and organism–environment feedback to modify subsequent encounters.

Host-associated information

Host-associated information demonstrates why physical presence is not equivalent to behavioral relevance. Female *Aedes aegypti* provide a particularly clear example: carbon dioxide altered attraction to particular visual spectra during host-oriented flight [8]. A visual stimulus could therefore be available in the arena without carrying the same behavioral value outside the appropriate olfactory context. This result supports conditional access to multimodal information, not a claim that vision is generally subordinate to olfaction.

Host odor itself is not represented as an undifferentiated signal. Neural measurements in *Ae. aegypti* distinguished features of human and animal odor mixtures, showing that biologically relevant odor blends can engage structured neural representations [9]. Such neural differentiation is important because environmental odor availability must pass through species-specific sensory coding before it can become a candidate for behavioral use. It does not, however, establish a universal neural template for host identity.

The peripheral architecture underlying that coding is also less uniform than simplified receptor-to-neuron schemes suggest. Single-cell and functional analyses in *Ae. aegypti* found extensive receptor co-expression in olfactory neurons, challenging a strict application of canonical one-receptor/one-neuron organization to this mosquito [10]. The ecological implication is bounded but important: the accessible chemical information of an insect cannot safely be inferred from an overly simple receptor map. Receptor organization constrains sensory access, but representation remains distinct from host recognition or realized preference.

Integration across modalities can also be directionally unequal. In female *Ae. aegypti*, carbon dioxide modified visually guided steering and visual neural responses, while the relationship between the modalities was not simply reciprocal in equivalent form [11]. A sensory world should therefore not be pictured as a collection of parallel channels whose outputs are automatically summed. Interactions among channels can alter which otherwise detectable information gains behavioral influence.

Thermal host information adds another route into this conditional architecture. Genetic experiments in *Anopheles gambiae* identified a causal contribution of the cooling receptor IR21a to heat-seeking behavior [12]. This receptor-level mechanism establishes one route by which thermal contrast can participate in mosquito host orientation, but it does not warrant extending the same receptor dependence to insect thermotaxis generally. Host-associated sensory worlds are consequently both multimodal and taxonomically constrained.

Plants add further complexity because a signal associated with a host need not simply advertise immediate resource quality. In larvae of *Spodoptera litura*, exposure to herbivore-induced plant volatiles elicited physiological and transcriptional responses associated with subsequent plant defensive conditions [13]. The evidence supports context-dependent use of plant-derived volatile information; it does not show that such information universally improves herbivore performance.

More strikingly, biological labels such as "competitor cue" do not determine cue value. Ovipositing *Manduca sexta* were attracted to information associated with competing beetles in a multitrophic system where larval competition was counterbalanced by altered parasitoid exposure [14]. Competition remained a cost, but the broader ecological consequence changed the apparent value of the cue. A signal associated with a competitor can therefore contribute positively to a decision under one food-web configuration without becoming intrinsically attractive.

Information quality also depends on the structure producing the signal. In the parasitoid *Cotesia glomerata*, plant intraspecific variation and the presence of nonhost herbivores changed host-location behavior, indicating that additional plant-associated information does not invariably improve search performance [15]. The relevant

distinction is between cue presence and cue reliability. Host-associated information is consequently best treated as relational: its behavioral consequence depends on the receiver, the signal-producing context, competing sources of information, and the ecological outcome linked to following it.

Predator and competitor cues

Predator-associated information further demonstrates that cue identity does not specify a fixed response. In field experiments with *Bombus terrestris* workers, predator avoidance differed among worker body-size classes, with the observed pattern running against a simple expectation that smaller individuals should always exhibit stronger avoidance because of vulnerability [16]. Individual phenotype can therefore alter risk-related behavioral filtering, while reward conditions and other unmeasured state variables may also contribute. The result is specific to the studied workers and field context rather than evidence for a universal size rule.

Predator information can also operate across more than one temporal depth. Exposure of the planthopper *Laodelphax striatellus* to predator-associated cues produced behavioral and morphological plastic responses whose expression differed with cue modality and sex [17]. Immediate avoidance and developmental change should therefore not be merged into a single category of "predator response." They occur at different biological timescales, can depend on different properties of the receiver, and need not share a common direction. The observed plasticity likewise does not by itself establish that the induced phenotype is an evolutionary adaptation.

Together with competitor-associated oviposition and parasitoid-search examples, these findings show why predator and competitor cues are better classified by information consequence and receiver context than by the ecological identity of the signal source alone. The critical analytical problem is determining when a nominal risk or competition signal changes current movement, alters future phenotype, is discounted, or acquires an unexpected value because other ecological costs are simultaneously changing.

Because those alternatives are difficult to compare in prose without collapsing cue identity into cue valence, **Table 1** separates four distinct predator–competitor information states by receiver context, evidential basis, consequence, and inferential boundary.

Table 1. Predator–competitor information states in which cue identity fails to determine behavioral consequence

Biological setting · Evidence	Interpretive consequence	Limits and uncertainty · Research or test	Synthesis standing
Multitrophic competitor-value reversal			
Ovipositing hawkmoth within a plant–beetle–parasitoid system **Attraction to beetle-associated host information despite larval competition**	Competitor association can acquire positive decision value when another ecological cost changes	Competition remains costly; demonstrated in a specific food-web configuration Manipulate competitor burden and enemy exposure independently to separate their contributions	Evidence-derived pattern; cross-system classification is proposed
Context-degraded host-location information			
Female parasitoid searching among variable plants and nonhost herbivores **Host-location performance changes with plant identity and nonhost context**	More biological information does not necessarily mean more reliable information	Signal apparency and patch profitability are system dependent Measure cue reliability rather than cue number when comparing search environments	Evidence-derived pattern; reliability framing is proposed
Phenotype-filtered predator avoidance			
Bumblebee workers differing in body size **Predator-associated avoidance differs among worker size classes**	Receiver phenotype can alter the behavioral weight assigned to risk information	Direction should not be transferred to other taxa, castes, or environments Test phenotype × reward × predator-cue interactions within populations	Evidence-derived pattern; filtering-axis interpretation is proposed
Temporal-depth predator response			
Planthopper exposed to predator-associated cues across development **Behavioral and morphological responses differ by sex and cue modality**	Risk information can influence immediate behavior and later phenotype through distinguishable response windows	Laboratory system; plasticity is not equivalent to demonstrated adaptation Separate acute movement, developmental plasticity, sex, and cue modality in future designs	Evidence-derived pattern; temporal-depth classification is proposed

Sensory detection limits

Physical exposure defines what reaches the organism, but receptor and neural architecture further restrict what can enter its sensory system. Chemosensory ionotropic receptors in host-seeking mosquitoes mediate multiple behaviorally relevant sensory functions, demonstrating that peripheral receptor complement constrains access to environmental information [18]. This boundary is permissive rather than deterministic: possessing a detection route can make a signal accessible without specifying how strongly the insect will respond to it.

Humidity illustrates why ecological importance and sensory mechanism must remain separate levels of inference. In *Drosophila melanogaster*, genetic and neural evidence identified TMEM63 as a required component of a moisture-sensing pathway, with disruption altering normal humidity responses [19]. Earlier synthesis had already established humidity as an ecologically important sensory dimension while emphasizing unresolved questions about how insect hygrosensation was transduced and organized [20]. The newer mechanistic result therefore resolves part of an earlier gap without demonstrating that TMEM63 constitutes a universal insect hygrosensor. Other taxa, sensory structures, and transduction routes remain relevant boundaries.

At a still finer level, molecular architecture imposes genuine constraints without directly describing an ecological sensory world. Cryo-electron microscopy resolved the ion-channel architecture of the insect olfactory co-receptor Orco [21]. Structural information of this kind identifies physical properties of a receptor system, but several inferential steps separate protein architecture from environmental detection, neural representation, behavioral weighting, and ecological consequence. A molecular result should therefore not be converted directly into a claim about niche realization.

Comparative evidence further resists such reduction. Odorant-receptor repertoires, developmental expression, and functional organization vary across insect lineages and life stages [22]. Consequently, even where broad receptor principles are conserved, the chemical information accessible to one species or developmental stage cannot be assumed to represent another. Receptor number alone is likewise not a validated measure of sensory-niche breadth because expression, ligand sensitivity, neural organization, and ecological encounter conditions intervene between genomic repertoire and realized behavior.

Vision provides the same lesson through a different sensory system. Insect color discrimination depends on photoreceptor sensitivities, retinal organization, neural processing, ecology, sex, and sometimes regional specialization within the eye [23]. Environmental wavelengths are therefore observer-relative information: the same spectral field need not constitute the same discriminable visual world for different insects, sexes, or retinal regions. Human-defined color categories are particularly poor substitutes for demonstrated insect discrimination.

Sensory detection limits thus create a second major restriction after microclimatic exposure. The proposed synthesis treats locally available signals as accessible information only when the relevant organism possesses sensory machinery capable of registering them under the conditions encountered. Yet accessibility remains distinct from use. A detectable odor may be behaviorally ignored, a visible target may require olfactory context before becoming attractive, and receptor architecture may constrain input without determining choice. That final transformation—from detectable information to behaviorally weighted information—is the problem addressed next under behavioral filtering.

Behavioral filtering

Detectable information still need not control action. In *Drosophila*, experimentally defined sensory conflict was resolved through a neuronal ensemble whose contribution depended on current hunger and previous outcome history [24]. The finding is task-bounded, but it establishes an important distinction: simultaneous sensory inputs can be available to the nervous system without receiving invariant behavioral weights. Behavioral filtering is therefore not synonymous with peripheral detection.

Internal physiological state provides another source of reweighting. Whole-brain imaging in *Drosophila* showed that metabolic and reproductive states altered food-choice processing through distinguishable neural patterns rather than through one generic state signal [25]. This evidence does not show that every insect state modifies every sensory modality, but it rejects the assumption that an accessible cue has a fixed behavioral consequence independent of the receiver.

Experience adds an explicitly temporal component. In *Bombus terrestris audax*, the relationship between short-term memory performance and field foraging efficiency changed across seasonal environments: an association observed in spring reversed during summer resource dearth [26]. “Better” memory therefore cannot be assigned

a context-free ecological value. In *Cotesia glomerata*, persistent learned information reduced foraging efficiency and increased errors when previously reliable information became unreliable [27]. Conversely, honey bees exposed to unpredictable reward histories later broadened their search, while search persistence did not change in the same experiment [28]. These results show that history can alter subsequent filtering without implying that learning is inherently beneficial, harmful, or optimal.

We therefore use behavioral filtering as a proposed analytical term for the context-dependent transformation between detectable information and expressed action. It includes state-dependent weighting, conflict resolution, memory, and experience-dependent search, but does not assume that these processes share one neural mechanism. **Figure 1** compresses this distinction by showing trajectories through a field of physically available cues, sensory-access boundaries, and behavioral states; alternative paths remain possible when state, history, cue reliability, or cross-modal context changes.

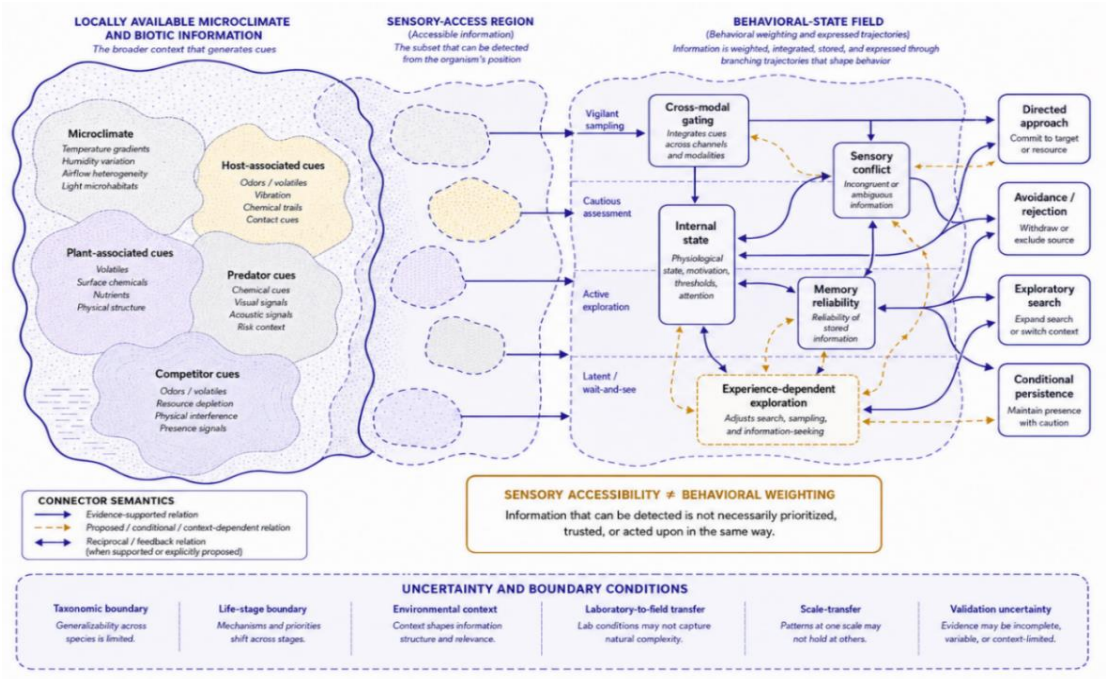


Figure 1. Behavioral trajectories diverge within the same sensory field when detectability and behavioral weighting are conditional

Realized sensory niche

Navigation provides a useful boundary case because cue priority can change without the sensory environment becoming meaningless. Dung beetles combine celestial, wind, and other orientation information flexibly, with cue weighting changing according to availability and context rather than following one fixed universal hierarchy [29]. This principle is demonstrative rather than a claim that dung-beetle navigation represents all insect decisions.

We define the realized sensory niche as a proposed synthesis: the portion of locally available physical and biotic information that is both accessible to a focal insect's sensory system and behaviorally weighted under its current state, history, and ecological context. The construct separates three questions that are often merged. Microhabitat organization determines which conditions are encountered [3]. Olfactory context can determine whether an otherwise visible host cue becomes attractive [8]. Sensory conflict can then alter how simultaneously available inputs influence choice [24]. These examples support the component distinctions, not empirical validation of the combined construct.

The proposed niche is consequently conditional rather than a static species attribute. Cue reliability varies with plant and nonhost context [15]. Internal states can modify sensory-to-choice processing [25]. Navigation cues can be reprioritized as conditions change [29]. Species averages may remain useful, but they should not be mistaken for a measured individual sensory niche. **Table 2** reconciles evidence patterns that could otherwise appear contradictory by locating them at different layers of availability, access, or behavioral weighting.

Table 2. Reconciling apparently conflicting evidence by locating change within the proposed realized sensory niche

Focal distinction	Same heat, different activity	Visible cue, conditional attraction	Competitor cue, positive oviposition response	Learning, reduced performance	Memory value, seasonal reversal	Flexible cue hierarchy
Limits and uncertainty	Semi-controlled systems; not universal buffering	Mosquito laboratory context	System-specific food web	Semi-field parasitoid system	One species and seasonal context	Navigation-specific evidence
Evidence · Interpretation within the realized sensory	Habitat configuration changes the heat–activity relationship Physical availability and refuge structure alter encounter conditions before sensory choice	Visual preference depends on olfactory context Detectable visual information may receive different behavioral weight across multimodal states	Competitor-associated information attracts oviposition under altered enemy risk Ecological consequence can reverse simple cue-valence expectations	Outdated learned information increases search errors Previously useful information can remain behaviorally weighted after reliability declines	Memory–efficiency relationship changes direction across seasons Behavioral weighting or performance value is temporally conditional	Orientation cues are reweighted with availability and context Realized sensory priority can be dynamically reordered
Biological setting · Research or test	Multi-species microhabitat experiment Pair organism-scale exposure with expressed behavior	Female Aedes host seeking Manipulate modalities separately and jointly	Hawkmoth multitrophic system Separate direct competition from indirect enemy effects	Parasitoid foraging Measure information persistence and changing reliability together	Bumblebee foraging Repeat cognition–performance relationships across resource regimes	Dung-beetle navigation Test whether hierarchy shifts extend beyond navigation
Evidential standing	Evidence-derived; niche placement proposed	Evidence-derived; niche placement proposed	Evidence-derived; interpretation proposed	Evidence-derived; niche placement proposed	Evidence-derived; temporal interpretation proposed	Evidence-derived; broader extension proposed

Spatial and temporal dynamics

A realized sensory niche also changes because the individual sampling the environment changes through time. Longitudinal tracking of honey-bee workers showed age-related behavioral shifts alongside persistent among-individual variation [30]. Age therefore explains part, but not all, of temporal heterogeneity in activity and task expression.

Different processes operate on different clocks. Fine-scale temperature can alter developmental timing [5]. The performance value associated with memory can change between seasonal foraging environments [26]. Recent reward predictability can alter later exploration [28]. Their joint interaction has not been measured in one system; the synthesis is that developmental history, season, and recent experience can each shift the sensory conditions an insect encounters or weights.

Movement may further modify later exposure. Habitat-dependent activity changes which microclimates are visited [3], while flexible navigation changes the route through available cue fields [29]. We therefore propose a reciprocal possibility: behavioral filtering can influence subsequent sensory availability by changing where and when an insect moves. This feedback remains a testable inference rather than a demonstrated universal loop.

Results and Discussion

The central implication is methodological as much as conceptual. Environmental measurement should not be discarded, but its biological resolution must match the organismal question. Fine-scale coupling differs with body size [4], and visual accessibility differs among insect sensory systems [23]. Environmental availability and sensory accessibility are complementary measurements, not interchangeable proxies.

Behavior likewise cannot be treated as a direct readout of cue intensity. Competitor-associated information can acquire unexpected value under multitrophic trade-offs [14]. Sensory conflict can reweight simultaneous information [24]. The association between memory and foraging performance can even reverse across ecological contexts [26]. These examples converge on conditionality while remaining taxonomically and mechanistically distinct.

The proposed realized sensory niche is therefore a research framework, not a validated index. A direct test should combine matched organism-scale environmental measurements, manipulations or measurements of sensory accessibility, freely expressed behavioral tracking, repeated temporal sampling, and replication across relevant taxa, stages, and sexes. Microhabitat experiments demonstrate feasible exposure measurements [3]. Semi-field tracking demonstrates how information-dependent search can be observed outside minimal laboratory assays [27]. Longitudinal worker tracking demonstrates how within-individual and among-individual variation can be separated through time [30]. None validates the complete framework.

A further boundary concerns scale transfer. A cue can be mechanistically detectable under laboratory presentation yet rarely encountered at behaviorally meaningful intensity in a natural microhabitat, while a coarse field association can arise without identifying the operative modality. Taxonomic breadth in the present evidence base likewise reflects multiple demonstrations of conditionality rather than replication of one mechanism across insects. The framework should therefore be challenged with deliberately discordant cases: organisms with similar habitats but different sensory repertoires, life stages sharing receptors but occupying different microclimates, and individuals exposed to the same cue field under contrasting physiological or informational states. Failure of the proposed layers to improve explanation in such comparisons would be informative rather than something to be absorbed by adding post hoc categories.

Important boundaries remain. Molecular mechanisms should not be read upward automatically into ecological performance, laboratory host-seeking results should not be universalized across insects, and plasticity should not be labelled adaptive without evolutionary evidence. Conversely, field correlations do not identify the sensory mechanism by themselves. The framework is most useful when those boundaries remain explicit: it asks investigators to identify where along availability, detectability, weighting, movement, and time an apparent ecological response is actually changing.

Conclusion

Insect ecological niches contain more conditions and signals than any individual necessarily experiences as behaviorally relevant information. Fine-scale physical exposure restricts what reaches the organism; sensory architecture restricts what can be detected; and behavioral filtering further changes which accessible information influences action. These restrictions are conditional on taxon, life stage, sex, phenotype, internal state, history, ecological interactions, and time.

The proposed realized sensory niche formalizes this distinction without assuming a universal mechanism or quantitative metric. Its value lies in making explicit where inference can fail when habitat measurements, receptor capacity, neural representation, and observed behavior are treated as equivalent. Testing the construct will require simultaneous measurement of local environments, sensory accessibility, behavior, and temporal change across deliberately contrasted biological contexts.

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