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The Importance of Neurophysiology in the Study of Predators and Herbivores: A Neuroecological Perspective

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Abstract. Predator–herbivore interactions are central to ecological dynamics, shaping species evolution, population stability, and ecosystem function. Recent advances in neurophysiology have revealed mechanistic layers underlying these interactions, encompassing sensory processing, stress and fear responses, decision-making, learning, and memory. This review synthesizes findings from the past five years to highlight how neural circuits mediate predator detection, prey evasion, and adaptive behaviors, emphasizing individual variation, sex differences, and developmental plasticity. We discuss sensory neurophysiology in both predators and herbivores, showing how multimodal integration, context-dependent processing, and plasticity influence behavior in natural environments. Stress neurobiology and fear responses are explored, illustrating the role of the hypothalamic–pituitary–adrenal axis, limbic circuits, and neurotransmitter dynamics in shaping acute and long-term responses to predation risk. Decision-making, learning, and memory are examined as mechanisms by which experience modifies predator and prey strategies, with implications for co-evolution and ecological fitness. Evolutionary and ecological implications are considered, including the role of neurophysiology in driving selective pressures, shaping trophic interactions, and mediating non-consumptive effects that influence community structure. Finally, we highlight emerging technological advances—such as portable neural imaging, electrophysiology, genomic analyses, and machine learning approaches—that enable integration of neurophysiological data with behavioral and ecological research. Understanding these neurobiological mechanisms not only uncovers hidden layers of predator–herbivore dynamics but also provides actionable insights for wildlife management, conservation planning, and ecosystem restoration. By bridging mechanistic neuroscience with ecological and evolutionary theory, this review emphasizes the value of neurophysiology as a critical tool for predicting behavioral responses and resilience in changing environments.

Highlights

1. Neurophysiology reveals how sensory processing, stress circuits, and learning mechanisms shape predator detection, prey avoidance, and behavioral adaptation.
2. Predator cues drive significant neural and hormonal responses—often sex-specific and long-lasting—that influence decision-making and ecological fitness.
3. Integrating neural mechanisms with ecological models enhances predictions of predator–herbivore dynamics, especially under environmental and anthropogenic change.

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Introduction

Interactions between predators and herbivores are central to ecological communities, shaping behavior, population dynamics, and evolutionary trajectories. Traditional research has emphasized observable behaviors—such as escape, vigilance, or shifts in foraging patterns—and morphological adaptations like speed, camouflage, or horns. However, over the past five years, work in neuroecology and neurophysiology has begun unveiling how internal neural mechanisms mediate and sometimes constrain these predator–herbivore interactions. By exploring multiple levels—from sensory detection, neural processing, hormonal modulation, learning and memory—this emerging perspective helps connect environmental risk to behavioral outcomes with mechanistic clarity [1].

A key avenue has been sensory neuroecology, examining how herbivores detect predator cues (olfactory, auditory, and visual) and how environmental change (noise, pollution, sensory interference) modifies detection thresholds. For example, "Neurobiology and Changing Ecosystems" (2023) discusses how sensory pollution can disrupt neural systems in both predators and prey, altering risk perception and resulting behavior [2]. Comparative studies, such as those assessing sensory system evolutions in *Drosophila*, show how genetic and neural variation in sensory periphery and central processing underlie differences in behavior, which may be analogous in vertebrate herbivores facing predator pressure [3].

Neural pathways involved in decision-making under threat are similarly revealing. Hormonal and neuroendocrine studies show that predator odors or presence trigger stress responses in herbivores, modulating not just behavior (e.g. freezing, flight) but metabolic investment and even reproduction. For instance, mammalian herbivores exposed to predator scents show measurable neuroendocrine changes, indicating activation of stress axes that have downstream costs. Learning and memory also play critical roles: experiences of predation risk—especially early in

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life—can shape future responses through neural plasticity. These changes can manifest in altered vigilance, better spatial memory of risky zones, or refined sensory discrimination [4].

Case studies further illustrate these connections. For example, research on mammals (roe deer, European hare) reveals species-specific behavioral assays where natural predator olfactory cues elicit strong anti-predator responses, thereby indicating that neural detection of odorants and associated stress responses are evolutionarily tuned and ecologically relevant [4]. Moreover, methods for assessing anti-predator behavior (giving-up density, flight initiation distance, etc.) are improving, and designs that incorporate natural cues tend to detect stronger and more consistent behavioral/neurophysiological responses [5].

From a conservation perspective, incorporating neurophysiological insights can improve predictions and management. Climate change, habitat fragmentation, and anthropogenic sensory pollution may degrade detection abilities or interfere with neural stress regulation, reducing a prey's capacity to respond to predators effectively. Understanding specific neural circuits or sensory modalities that are most vulnerable can guide interventions—e.g., preserving auditory or olfactory corridor connectivity, reducing noise, or restoring plant species that produce critical chemical cues.

Sensory Neurophysiology in Predators and Herbivores

Sensory systems act as the very interface through which both predators and herbivores perceive the world — detecting cues about food, danger, mates, or habitat. Recent work has begun to elucidate how differences in sensory neurophysiology underlie ecological strategies, threat detection, and behavioral trade-offs in predator–herbivore systems.

A prime example comes from olfactory detection: the study in [6] demonstrated that wild sockeye salmon (*Oncorhynchus nerka*), traditionally considered visual feeders, show increased neural activity (c-fos expression in the olfactory bulb) when exposed to zooplankton odors. The fish increased swimming, turning, and ascent behaviors, indicating meaningful behavioral modulation via olfaction [6]. This suggests that even species with dominant visual foraging modalities retain

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and use olfactory channels in conditions like low light or murky water, which has implications for how prey (and predators) may evolve flexible multimodal sensory systems.

In herbivores (or lower trophic level prey), phenotypic and neural plasticity in response to chemical predator cues has been documented. In *Daphnia longicephala*, exposure to chemical cues of predators induced structural changes in brain volume (specifically in central brain regions) and increased inhibitory post-synaptic sites during the defense induction phase. Such structural rewiring indicates that predator detection is about not only immediate behavioral escape but also long-term neural remodeling, possibly enhancing subsequent detection, speed of response, or risk assessment [7].

On the predator side, sensory specialization and neural circuits that translate sensory inputs into hunting behavior have been increasingly described. The review article about Neurocircuitry of Predatory Hunting, synthesizes data from zebrafish, rodents, and amphibians, showing how sensory detection, sensorimotor transformation, and motivational systems combine. For instance, certain visual and somatosensory cues feed into subcortical circuits (e.g. superior colliculus → zona incerta in mice) that trigger orientation, pursuit, and attack [8]. Also, cross-sensory modulation (how one sensory modality modulates the detection or processing in another) has been shown in young Nile crocodiles: chemical (olfactory) cues and acoustic cues interact, with feeding state (fasted vs sated) further modulating responses [9].

Many species do not rely on a single sensory modality; the interaction among vision, olfaction, hearing, or mechanoreception is often critical, especially under environmental constraints such as low light, turbidity, or chemical noise. Exposure to predator cues early in life can lead to neural changes, both structural and functional, shifting detection thresholds, responsiveness, or behavioral strategies. Internal state, including factors such as hunger and stress, as well as environmental context like noise and pollution, modulate not just behavior but upstream sensory detection and processing. Finally, although much research focuses on model organisms, less is known about sensory neurophysiology in many herbivores, particularly mammals and birds, in natural settings [10].

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Stress Neurobiology and Fear Responses

Predator cues such as odors, sounds, or visual stimuli can trigger in prey species a coordinated set of neural, hormonal, and behavioral changes commonly described as stress or fear responses. Recent findings show that exposure to predator odors in rodents activates the hypothalamic–pituitary–adrenal (HPA) axis and specific limbic–hypothalamic pathways that go well beyond the classical "fight or flight" reaction. For example, Jovanovic et al. [11] demonstrated that female mice exposed to trimethylthiazoline (TMT), a predator odor, showed not only elevated glucocorticoid secretion but also the recruitment of a sex-specific thermogenic neurocircuit projecting from the olfactory bulb through the medial amygdala to dorsomedial hypothalamus neurons expressing cholecystokinin (CCK), which mediates both brown adipose tissue activation and feeding suppression [11]. This work highlights the metabolic and behavioral breadth of predator-evoked stress responses and their sex-dependent nature.

Predator scent stress (PSS) also produces long-lasting neurochemical changes that resemble mood and anxiety disorders. Wilkinson et al. [12] exposed female rats to predator scent and found persistent alterations in monoamine neurotransmitter turnover—particularly dopamine and serotonin—in the prefrontal cortex, nucleus accumbens, and hippocampus. These brain areas are central to emotion regulation, cognitive control, and stress reactivity, suggesting that predation risk leaves enduring "neural fingerprints" that can shape subsequent behavior [12]. This chronic effect extends the concept of fear from an acute survival mechanism to a factor influencing long-term neural plasticity.

Evidence from non-mammalian models supports the idea that predator exposure can produce generalized anxiety-like behaviors. Thapa and his coworkers reported that zebrafish chronically exposed to background predation risk displayed heightened vigilance, reduced exploration, and predator neophobia, illustrating how sustained risk alters baseline behavior and potentially fitness in aquatic prey species [13]. Together, these findings emphasize that stress neurobiology and fear responses are conserved across vertebrates and not limited to laboratory rodents.

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An emerging theme is the integration of neural circuits with metabolic and behavioral outputs, revealing the amygdala, hypothalamus, prefrontal cortex, and hippocampus as hubs for coordinating predator-induced stress. Sex differences and individual variability are consistently observed: some individuals show resilience to predator cues, while others exhibit heightened susceptibility [14]. Furthermore, behavioral phenotypes extend beyond mere fleeing to include feeding suppression, thermogenesis, altered exploration, and long-term mood or cognitive shifts, indicating a broader ecological cost of fear [11, 12].

Despite these advances, most detailed neurophysiological studies occur under controlled laboratory conditions, leaving a knowledge gap about how stress and fear circuits operate in wild or semi-natural environments. There is still limited understanding of how acute versus chronic exposure to predator's shapes neural plasticity across developmental stages, or how the energetic costs of thermogenesis, vigilance, and suppressed foraging translate to fitness outcomes in nature [13]. Another challenge is clarifying the neurobiological mechanisms of resilience: which neural or hormonal signatures predict recovery or adaptive flexibility [14].

Looking ahead, new opportunities include applying in vivo imaging and molecular markers (e.g., immediate early genes, receptor expression profiling) in wild populations to map natural variation in stress and fear circuits [12]. Longitudinal field studies can track individuals before, during, and after predator exposure to assess resilience, recovery, and long-term costs. Combining stress neurobiology with ecological models of trophic cascades can also predict how population-level patterns emerge from individual fear responses. Finally, anthropogenic factors such as habitat fragmentation, sensory pollution (light, noise, odor), and human disturbance may amplify or dampen predator-induced stress responses, and integrating these factors into neurobiological studies can provide more realistic predictions of prey behavior under global change scenarios [13].

Decision-Making, Learning, and Memory

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Decision-making, learning, and memory are central to how both predators and herbivores cope with risk, optimize foraging, and adapt to environmental variation. Recent research has begun to unravel how past experience shapes anti-predator behavior, how memory retention varies among populations or sexes, and how animals integrate uncertain information to make decisions that balance risk and reward. For instance, a recent study on the marine snail *Nucella canaliculata* found that exposure to predator cues produced long-term anti-predator learning and memory that differed significantly among populations and sexes: male snails maintained risk aversion over more than seven months, while females, after the cues ceased, resumed more normal feeding and growth rates, illustrating sex- and population-dependent memory carryover effects [15]. Similarly, tadpoles learned to recognize novel predatory odors when paired with fresh alarm cues and retained that memory for days, but recognition and response strength waned as the cue aged, revealing how temporal uncertainty about information reduces memory retention and thus decision-making under risk [16].

Wild mammals also illustrate how predation risk can shape learning and memory with fitness consequences. A field study on free-living white-footed mice exposed to chronic predation risk via playback experiments showed that such exposure impaired both learning rates and memory performance in spatial tasks when compared to control mice; these impairments were particularly pronounced in long-term memory tests [17]. On the predator side and in predation-driven behavior, zebrafish larvae offer powerful models: larval zebrafish hunting behavior improves with experience, showing better capture success, faster responses, and more efficient movement trajectories, accompanied by identifiable changes in neural circuits, e.g. strengthened connectivity between visual centers and motor control regions, and experience-dependent modulation of sensory-motor transformations [18].

These studies suggest several key patterns: memory duration and strength are not fixed but vary with cue freshness, sex, population, and prior experience; decision-making under predation risk involves trade-offs, such as risk aversion versus foraging or growth; and neural plasticity underlies behavioral improvements in hunting or escape, indicating that learning is a potent modifier of both prey and predator strategies.

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However, important gaps remain. Much of what we know comes from laboratory or semi-controlled settings; comparatively fewer studies test how learning and memory function in fully natural settings where environmental variability, multiple predator types, resource limitation, and other stressors (e.g. human disturbance, habitat change) are at play. The mechanisms governing trade-offs — for example, how memory of risk imposes energetic, growth, or reproductive costs — are not well quantified. Also, little is understood about how ontogenetic stage (juvenile vs adult), individual variation (personality, prior risk exposure), or sex differences interact with learning and memory under ecological complexity to influence survival outcomes.

Novel opportunities include conducting longitudinal field experiments in natural populations that manipulate predation risk and measure decision-making, learning, and memory over time, enabling assessment of both adaptive benefits and costs. Neuroscientific tools such as neural imaging, molecular markers of neural plasticity, or gene expression profiling could be integrated with behavioral assays in wild or semi-wild settings to link observed changes in memory or decision dynamics to underlying neural changes. Also, comparative work across species and populations that differ in predation regimes, sensory environments, and life histories could reveal how learning strategies evolve under varying selective pressures. Finally, exploring how anthropogenic change (e.g. habitat fragmentation, sensory pollution, climate change) disrupts or reshapes learning, memory retention, and decision thresholds under risk is crucial for predicting how predator–herbivore interactions may shift in future ecosystems.

Evolutionary and Ecological Implications

Neurophysiological mechanisms in predators and herbivores do not operate in isolation; their influence ripples through evolutionary trajectories and ecological dynamics, affecting trait evolution, species interactions, and community stability. For instance, studies on multiple defense strategies in prey show that possessing more than one form of defense (e.g., visual, chemical, behavioral) imposes cognitive load on predators, delaying or altering their attack decisions. This may favor evolution of prey unpredictability and priming effects, in which one sensory cue amplifies predator sensitivity to another [19]. Such dynamics suggest that sensory

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neurophysiology contributes directly to selective pressures shaping not only prey defenses but also predator perceptual systems.

Beyond defense, evolving sensory systems in predators (such as refinements in vision, olfaction, or mechanoreception) can drive diversification and innovation in predatory behavior. For example, the review *Neurocircuitry of Predatory Hunting* describes how neural circuits in rodents and zebrafish have adapted to optimize prey search, pursuit, and capture in ecologically relevant contexts, a process likely shaped by evolutionary pressures where sensory detection speed and accuracy confer fitness advantages [20]. Over evolutionary time, such sensory and neural modifications can influence predator–prey coevolution, where prey evolve detection sensitivity or evasion strategies in response, and predators counter-adapt.

On the ecological side, neurophysiological traits influence non-consumptive effects (fear effects) which in turn can cause trophic cascades. For example, Batabyal [21] emphasizes how predator presence—even without consumption—can modify prey behavior and physiology, altering habitat use, foraging, and thus nutrient flows or energy budgets in ecosystems. These changes mediated by neural and hormonal stress responses can shift ecosystem structure and function, particularly under changing environmental conditions [21].

Further, ecological dynamics such as predator extinction, community composition, or stability are affected by evolutionary dynamics in sensory and neural systems. A recent modeling study on predator–prey interactions showed that role reversals (where prey can attack or deter predators) introduce strong evolutionary and ecological feedbacks, possibly causing bistability zones or catastrophic extinction events for predators if prey counter-attacks are frequent [22]. Similarly, traits that confer early or strong predator detection may entail costs (energetic, cognitive, risk of false alarms) which can influence trade-offs in life histories.

Looking ahead, understanding evolutionary implications requires integrating neurophysiology with phylogenetics, population genetics, and eco-evolutionary modeling. Studies that map sensory receptor gene evolution, variation in neural circuit architectures, or stress hormone regulatory

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networks across populations subjected to different predation pressures will clarify how plastic vs heritable variation mediate adaptive responses. Also, human-induced changes—such as sensory pollution, habitat fragmentation, climate warming—are creating novel selective landscapes, likely altering how neurophysiological traits evolve, how fast, and in which directions. These evolutionary shifts, in turn, may reshape ecological relationships and the resilience of ecosystems under stress.

Future Directions and Technological Advances

Emerging technological tools and methodological frameworks are opening new horizons for studying neurophysiology in predator–herbivore systems. One promising advance involves the integration of genomic and functional studies of sensory receptor repertoires. For example, the study by Niimura, Matsui, & Touhara [23] showed variation in bitter taste receptor (T2R) gene repertoires aligning with diet among vertebrates, which suggests that future work could leverage comparative genomics to predict sensory capabilities in lesser-studied species and link these to behavioral and ecological outcomes [23]. More recently, "Functional Evolution of Vertebrate Sensory Receptors" by Fetcho, Yang, & others [24] examines functionally important residues in receptor proteins across multiple species, suggesting that combining such molecular data with in vivo electrophysiology and behavioral assays will illuminate how sensory shifts evolve [24].

Remote sensing and environmental structure quantification are other areas of advance. Fu, Xu, Gao, Feng, Guo, & Yang [25] used LiDAR (Light Detection and Ranging) to map 3D forest structure and assessed its effect on vision-mediated predator–prey interactions, demonstrating how fine-scale habitat complexity affects detectability and can be tied back to sensory neurophysiology [25]. The "Dynamic energy landscapes of predators and the implications for modifying prey risk" framework [26] suggests integrating predator energy constraints (energetics, movement, hunting cost) with fear landscape models—a combination likely to benefit from technology such as biologging, GPS tracking, accelerometers, and perhaps remote telemetry to capture not just where animals are, but what energetic state and risk environment they are experiencing [26].

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Another frontier is deploying neural markers, imaging, and electrophysiology in more naturalistic settings. The review "Neurocircuitry of Predatory Hunting" in [20] emphasized how genetically tractable models like zebrafish and rodents have enabled detailed circuit mapping, but also noted limitations in ecological realism. Expanding this work into semi-wild or wild populations using portable imaging (e.g., fiber optics, mini-aturized calcium imaging), or novel tags that can report neural activity or hormone levels non-invasively, will help bridge the gap between laboratory and field. Additionally, machine learning and AI frameworks are increasingly used to analyze complex behavioral datasets—automated classification of escape behavior, stress or vigilance moments from video or accelerometer data—and can be combined with physiological recording to understand individual variation in decision thresholds (for example in the Cognitive Ecology of Surprise framework by Smith, Taylor, & others [27].

Conclusion

Neurophysiology provides a novel lens for understanding predator–herbivore interactions, revealing mechanistic layers that traditional ecological or behavioral approaches may overlook. By linking sensory processing, stress responses, learning, memory, and decision-making to ecological outcomes, researchers can uncover how individual variation in neural circuits drives population- and species-level patterns. For example, sex-dependent differences in predator odor processing in rodents [11] or experience-dependent improvements in prey hunting efficiency in zebrafish [18] demonstrate that neurophysiological mechanisms shape behavior in ways that cannot be predicted solely by observing overt actions. These insights emphasize that neurophysiological traits are integral to ecological dynamics, not mere adjuncts, highlighting their role in co-evolutionary processes and species interactions ([19, 20].

Understanding these neural mechanisms also provides a framework to anticipate responses under anthropogenic stressors. Changes in sensory environments caused by light, noise, or chemical pollution can disrupt predator detection, prey evasion, and risk assessment, potentially altering trophic cascades and community structure [21, 25]. Integrating neurophysiological data with behavioral ecology allows for more accurate models of animal responses to habitat alteration,

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climate change, or introduction of novel predators, providing predictive power for conservation planning. For instance, identifying which species or individuals are more resilient or susceptible to environmental change can inform targeted interventions in wildlife management and ecosystem restoration programs [26].

Finally, the incorporation of neurophysiology into conservation biology opens new avenues for applied research. Monitoring stress hormone responses, neural activity markers, or sensory capabilities can complement population surveys, allowing managers to evaluate habitat suitability, restoration success, and the impact of reintroduced predators. Moreover, linking neural plasticity and learning capacity to long-term survival or reproductive success provides actionable insights for species reintroduction programs or management of predator–prey balance [23, 28]. Overall, these advances underscore that neurophysiology not only enriches our mechanistic understanding but also serves as a bridge between fundamental research and applied conservation practice.

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