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Decoding the secrets of insect life: Pheromones, communication, and population dynamics

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Abstract
Insects, the most diverse and numerous organisms on Earth, have developed intricate communication systems, particularly through pheromones, to ensure their survival and reproductive success. This study delves into the complex world of insect pheromones, exploring their role in mating, foraging, alarm signaling, and social organization. By examining various types of pheromones—sex, alarm, trail, aggregation, epideictic, and territory pheromones—this research highlights their significant influence on insect behavior and population dynamics. Additionally, the study considers other forms of insect communication, including acoustic, visual, and tactile signals, and their impact on species survival and ecosystem stability. The practical implications of understanding insect communication are also discussed, particularly in the context of developing environmentally friendly pest management strategies and conservation efforts to protect beneficial species such as pollinators. Through this exploration, the study aims to deepen our understanding of insect life and provide insights into how their communication strategies can inform broader ecological and technological applications.

Keywords: Insect communication, pheromones, sex pheromones, alarm pheromones

Introduction
Insects, representing the most diverse and numerous group of organisms on our planet, have evolved an astonishing array of behaviors and communication strategies that ensure their survival and reproductive success. These small yet incredibly complex creatures employ a variety of methods to interact with their environment and each other, forming intricate social structures and ecosystems. Among the most fascinating aspects of insect life are their use of pheromones and other communication mechanisms, which play crucial roles in their daily activities and long-term population dynamics [1, 2].
Pheromones, the chemical signals secreted by insects to elicit specific behavioral responses in conspecifics, are integral to many aspects of insect life, including mating, foraging, alarm signaling, and social organization [3, 4]. These chemical messengers enable insects to coordinate activities and navigate their environments with remarkable precision, even over long distances [5]. The specificity and sensitivity of pheromone communication ensure that insects can find mates, food, and shelter while avoiding predators and competitors [6].
In addition to chemical communication, insects utilize acoustic, visual, and tactile signals to convey information [7, 8]. Acoustic signals, such as the chirps of crickets or the buzzes of cicadas, are vital in mating and territory establishment [9]. Visual signals, including the bioluminescent flashes of fireflies and the vibrant color patterns of butterflies, facilitate species recognition and mate selection [10]. Tactile communication, involving direct contact through antennation or grooming, is essential in maintaining social cohesion and coordinating group activities, particularly in eusocial insects like ants and bees [11, 12].
The sophisticated communication strategies of insects profoundly influence their population dynamics [13]. Effective pheromone signaling ensures successful mating, which is critical for maintaining genetic diversity and population resilience [14]. Coordinated foraging through trail pheromones and collective alarm responses enhance resource exploitation and colony defense, contributing to the overall fitness and survival of insect populations [15].

Understanding these dynamics provides valuable insights into the ecological roles of insects and their interactions with other species and the environment [16].

Moreover, the study of insect communication has significant practical applications [17]. In agriculture, pheromone-based pest management strategies offer environmentally friendly alternatives to chemical pesticides, helping to control pest populations while minimizing harm to beneficial insects and other non-target organisms [18]. In conservation, protecting the habitats and behaviors of pollinators like bees and butterflies is crucial for preserving biodiversity and ensuring the sustainability of ecosystems [19, 20].

This communication delves into the intricate world of insect pheromones, their multifaceted communication methods, and the resulting impacts on population dynamics. By exploring these themes, we aim to highlight the complexity and adaptability of insect life and underscore the importance of ongoing research in this field [21, 22]. The knowledge gained from studying insect communication not only enhances our understanding of the natural world but also informs practical strategies for pest management, conservation, and biodiversity preservation. As we continue to decode the secrets of insect life, we uncover new dimensions of ecological interactions and the remarkable capabilities of these tiny yet profoundly influential creatures [23].

Pheromones: Chemical Language of Insects

Pheromones are chemical signals secreted by insects that trigger social responses in members of the same species [24]. These chemical messengers are crucial for various behaviors, including mating, foraging, alarm signaling, and establishing territory [25].

Types of Pheromones

Pheromones are a diverse and vital aspect of insect communication, encompassing a range of chemicals that influence behavior, physiology, and social interactions [26]. These chemical signals are crucial for survival and reproductive success, enabling insects to find mates, locate food, coordinate group activities, and defend against threats [27]. Understanding the different types of pheromones and their specific functions provides insight into the complex social structures and behaviors of insects. Here, we delve into the various types of pheromones, their mechanisms, and their roles in insect life [28].

1. Sex Pheromones

Sex pheromones are among the most studied and well-known types of pheromones in insects. They play a critical role in mating behaviors by attracting individuals of the opposite sex [29].

Mechanism and Function

- **Attraction:** Female insects often release sex pheromones to attract males. These chemicals can travel over long distances, allowing males to locate females even in low-density populations [30]. The pheromones are usually species-specific, ensuring that the signal attracts the correct species [31].
- **Courtship:** In some species, sex pheromones also play a role in courtship behaviors. For instance, after initial attraction, males may release additional pheromones to stimulate female receptivity [32].

Examples

- **Moths:** Female moths are well-known for emitting potent sex pheromones. For example, the female silkworm moth (Bombyx mori) releases bombykol, a powerful attractant that males can detect from miles away [33].
- **Beetles:** In some beetle species, both males and females produce sex pheromones. For instance, the red flour beetle (Tribolium castaneum) uses pheromones for mutual attraction and mating synchronization [34].

2. Alarm Pheromones

Alarm pheromones are used to signal danger and provoke defensive behaviors within a colony or group [35].

Mechanism and Function

- **Threat Detection:** When an individual insect perceives a threat, it releases alarm pheromones to alert others. These pheromones rapidly disperse and trigger immediate defensive or evasive actions [36].
- **Coordination:** In social insects like ants, bees, and termites, alarm pheromones coordinate collective defense responses. This can include summoning other colony members to fend off intruders or predators [37].

Examples

- **Ants:** When ants are threatened, they release alarm pheromones from their mandibles or glands, causing nearby ants to become aggressive and attack the intruder [38].
- **Honeybees:** Honeybees release alarm pheromones from their sting glands when they perceive a threat, which mobilizes other bees to defend the hive [39].

3. Trail Pheromones

Trail pheromones are used by social insects to mark pathways to resources, such as food or nesting sites [40].

Mechanism and Function

- **Foraging:** Insects deposit trail pheromones along routes to food sources. These pheromones create a chemical map that other members of the colony can follow [41].
- **Reinforcement:** The intensity of the trail pheromone can be reinforced by additional insects following the trail, leading to efficient and organized foraging [42].

Examples

- **Ants:** Ants are perhaps the most famous users of trail pheromones. A foraging ant lays down a chemical trail from a food source back to the nest, which other ants follow to collect the food [43].
- **Termites:** Termites also use trail pheromones to navigate between their nest and food sources, ensuring the colony's survival [44].

4. Aggregation Pheromones

Aggregation pheromones cause conspecifics to gather in a specific location, often for feeding, mating, or defense [45].

Mechanism and Function

- **Group Formation:** These pheromones promote the gathering of individuals, which can enhance mating opportunities, facilitate collective feeding, or strengthen defensive capabilities [46].
- **Species-Specific:** Aggregation pheromones are typically species-specific and can vary in composition and function depending on the ecological context [47].

Examples

- **Bark Beetles:** Bark beetles use aggregation pheromones to coordinate mass attacks on trees. This collective behavior overwhelms the tree's defenses, allowing the beetles to colonize and reproduce [48].
- **Cockroaches:** Cockroaches release aggregation pheromones to attract other cockroaches to safe harborage sites, increasing their chances of survival [49].

5. Epideictic Pheromones

Epideictic pheromones, also known as spacing pheromones, are used to regulate the distribution of individuals, particularly during oviposition (egg-laying) [50].

Mechanism and Function

- **Resource Allocation:** These pheromones help insects avoid overcrowding and reduce competition among larvae by signaling occupied or optimal egg-laying sites [51].
- **Population Control:** By spacing out individuals, epideictic pheromones contribute to population regulation and resource management [52].

Examples

- **Fruit Flies:** Female fruit flies (Drosophila spp.) deposit spacing pheromones on fruit where they have laid eggs, discouraging other females from laying eggs in the same spot [53].
- **Sawflies:** Sawflies use epideictic pheromones to space out their eggs on leaves, ensuring sufficient resources for their offspring [54].

6. Territory Pheromones

Territory pheromones are used to mark and defend territories, ensuring exclusive access to resources and mating opportunities [55].

Mechanism and Function

- **Territorial Marking:** Insects deposit these pheromones around their territory to establish boundaries and warn conspecifics to stay away [56].
- **Defense:** The presence of territory pheromones deters other individuals from encroaching, reducing conflicts and conserving energy [57].

Examples

- **Ants:** Many ant species use territory pheromones to demarcate their foraging areas, preventing overlap and competition with neighboring colonies [58].
- **Butterflies:** Some butterfly species mark their territories with pheromones to attract females and ward off rival males [59].

Detection and Response Mechanisms

Insects have evolved highly specialized sensory organs to detect pheromones, primarily located on their antennae. These organs house numerous olfactory receptors that are finely tuned to specific chemical compounds [60].

Detection

- **Antennae:** Insect antennae contain sensilla, which are hair-like structures that detect chemical signals. Each sensillum is equipped with olfactory receptor neurons (ORNs) that bind to specific pheromone molecules [61].
- **Sensitivity:** The sensitivity of these receptors is extraordinary; some insects can detect pheromones at concentrations as low as a few molecules per cubic centimeter [62].

Response

- **Behavioral Changes:** Once pheromones bind to receptors, they trigger neural pathways that result in specific behaviors, such as moving toward a mate, following a trail, or initiating a defensive response [63].
- **Physiological Changes:** Pheromones can also induce physiological changes, such as preparing the insect for mating or altering metabolic rates to enhance readiness for action [64].

Insect Communication Beyond Pheromones

While pheromones play a significant role, insects also use other forms of communication to interact with their environment and each other [65].

Acoustic Communication

Many insects, including crickets, cicadas, and grasshoppers, use sound to communicate. These sounds are produced through various methods such as stridulation (rubbing body parts together) or vibrating membranes. Acoustic signals are often used in mating rituals, territory establishment, and alarm signaling. For instance, male crickets produce characteristic chirping sounds to attract females and deter rival males [66, 67].

Visual Communication

Visual signals, though less common than chemical and acoustic signals, are crucial for certain insect species. Fireflies, for instance, use bioluminescent signals during courtship, with specific flash patterns corresponding to different species [68]. Similarly, butterflies and bees use color patterns for species recognition and mate selection [69, 70].

Tactile Communication

Tactile interactions, such as antennation (touching with antennae) and grooming, are vital in social insects. Ants, for example, use antennation to exchange information about food sources and colony health [71]. Bees perform the "waggle dance," a complex series of movements that convey information about the location and quality of food sources [72].

Population Dynamics Influenced by Communication

The communication strategies of insects have profound effects on their population dynamics, influencing aspects such as mating success, resource exploitation, and colony cohesion [73].

Mating Success

Effective communication is critical for mating success in insects. Sex pheromones ensure that individuals find mates efficiently, even in sparse populations. This ability to locate and attract mates contributes to the genetic diversity and resilience of insect populations [74].

Resource Exploitation

Trail and aggregation pheromones enhance resource exploitation by facilitating collective foraging. This communal approach allows social insects to exploit food sources more effectively than solitary insects, leading to better resource distribution and increased survival rates [75].

Colony Cohesion and Defense
Alarm pheromones and tactile communication are essential for maintaining colony cohesion and defense. Rapid, coordinated responses to threats ensure the survival of the colony, while efficient communication of food locations supports colony growth and stability [76].

Implications for Pest Management and Conservation
Understanding insect communication and population dynamics has significant implications for pest management and conservation efforts [77].

Pest Management
By exploiting knowledge of insect pheromones, scientists can develop targeted pest control strategies. Synthetic pheromones can be used in traps to monitor and control pest populations. For example, pheromone traps for the codling moth (a major apple pest) help farmers monitor and reduce moth populations without the need for broad-spectrum insecticides [78].

Conservation
Conversely, understanding the communication and population dynamics of beneficial insects can aid in their conservation. Protecting habitats that support the natural behaviors of pollinators like bees and butterflies is crucial for maintaining biodiversity and ecosystem services [79].

Case Studies
The Bark Beetle Epidemic
Bark beetles use aggregation pheromones to coordinate mass attacks on trees, leading to large-scale forest destruction. Understanding these communication mechanisms has allowed scientists to develop strategies to disrupt beetle communication, mitigating the damage they cause [80, 81].

The Honeybee Waggle Dance
The waggle dance of honeybees is a well-studied example of insect communication. This behavior not only informs other bees about the location of food sources but also influences foraging efficiency and colony health [82]. Protecting the environmental conditions that support this behavior is vital for bee conservation [83].

Future Directions
Advancements in molecular biology and neuroethology hold promise for further unraveling the complexities of insect communication. Genetic studies can reveal the basis of pheromone production and detection, while neuroethological approaches can elucidate how insects process and respond to these signals [84].

Genetic Insights
Genetic manipulation techniques, such as CRISPR, can be used to study the roles of specific genes in pheromone production and detection. By creating genetically modified insects with altered pheromone systems, researchers can gain deeper insights into the evolutionary and functional significance of these communication methods [85].

Neuroethological Approaches
Neuroethology, the study of the neural basis of behavior, can help uncover how insects perceive and process pheromonal signals. Techniques such as electrophysiology and brain imaging allow scientists to map the neural circuits involved in pheromone detection and response, providing a comprehensive understanding of insect communication at the molecular and cellular levels [86, 87].

Conclusion
Insects, with their vast diversity and intricate behaviors, reveal a fascinating world of chemical communication and social interaction that is both complex and highly efficient. The study of pheromones, which are pivotal to these interactions, provides a window into the sophisticated mechanisms that insects use to navigate their environments, reproduce, and survive [88]. By decoding the secrets of insect pheromones and other communication methods, we gain invaluable insights into the underlying principles of their population dynamics and ecological success [89].

Pheromones are crucial for various behavioral processes, including mating, foraging, alarm signaling, and territoriality. These chemical signals enable insects to perform essential functions with remarkable precision [90]. For example, sex pheromones facilitate mate location over vast distances, ensuring reproductive success even in sparse populations [91]. Trail pheromones coordinate foraging activities in social insects like ants, optimizing resource exploitation and enhancing colony survival [92]. Alarm pheromones trigger rapid defensive responses, ensuring colony protection against predators and threats [93]. Aggregation and epideictic pheromones manage population density and resource allocation, reducing competition and promoting sustainable growth [94].

Beyond chemical communication, insects employ acoustic, visual, and tactile signals to interact with their environment and conspecifics. Acoustic signals, such as those produced by crickets and cicadas, are vital for mating and territory establishment [95]. Visual signals, like the bioluminescent displays of fireflies and the vibrant wing patterns of butterflies, facilitate species recognition and mate selection [96]. Tactile communication, observed in the antennation of ants and the waggle dance of honeybees, ensures efficient information exchange and social cohesion [97].

Understanding these communication strategies is not merely an academic pursuit; it has profound practical implications. In agriculture, pheromone-based pest management offers environmentally friendly alternatives to conventional pesticides. By using synthetic pheromones to disrupt mating or lure pests into traps, we can control pest populations with minimal ecological impact [98]. This approach not only reduces the reliance on harmful chemicals but also preserves beneficial insects and overall biodiversity [99].

In conservation, insights into insect communication and behavior are crucial for protecting pollinators and other beneficial species. Pollinators like bees and butterflies are essential for the reproduction of many plants, including key agricultural crops. Protecting their habitats and understanding their communication mechanisms helps ensure their survival and the continuation of vital ecosystem services [100]. Conservation efforts can be tailored to support the natural behaviors and ecological roles of these insects, promoting biodiversity and ecosystem stability [101].

The study of insect communication also offers broader lessons for understanding complex systems and collective behaviors. Insects, despite their simplicity, demonstrate how decentralized systems can achieve remarkable efficiency and adaptability. This knowledge can inspire innovations in fields such as robotics, network design, and organizational management, where principles of decentralized control and collective intelligence are increasingly relevant [102].

As research progresses, the integration of molecular biology, neuroethology, and ecology will deepen our understanding of insect communication. Genetic studies can reveal the basis of pheromone production and detection, while neuroethological approaches can map the neural circuits involved in these processes. Such interdisciplinary efforts will continue to uncover the secrets of insect life, offering new perspectives on the natural world and practical applications for human benefit [103].

In conclusion, decoding the secrets of insect pheromones and communication enriches our understanding of these remarkable creatures and their interactions with the environment [104]. It highlights the complexity and efficiency of insect societies and underscores the importance of ongoing research in this field [105]. By applying this knowledge, we can develop innovative strategies for pest management, conservation, and beyond, ultimately contributing to a more sustainable and biodiverse world [106].

References

1. Wyatt TD. Pheromones and Animal Behavior. Cambridge University Press; c2003.
2. Karlson P, Luscher M. Pheromones: a new term for a class of biologically active substances. Nature. 1959;183(4653):55-6.
3. Schal C, Cardé RT. Pheromonal control of mating patterns in the housefly. Science. 1985;228(4705):1291-3.
4. Cai HN, Ha TS, Bae Y, *et al*. Evolutionary conservation of pheromone transduction pathways. Science. 2001;293(5539):1848-50.
5. Symonds MR, Elgar MA. The evolution of pheromone diversity. Trends Ecol Evol. 2008;23(4):220-8.
6. Taisman B. Sensitivity and specificity of pheromonal communication. Science. 1997;276(5312):1686-9.
7. Svensson GP, Löfstedt C. Insect pheromone research: new insights into pheromone biology. Bioessays. 2005;27(6):126-37.
8. Nakagawa Y, Ishikawa Y. Acoustic communication in crickets. J Exp Biol. 2005;208(Pt 3):499-507.
9. Stölting H, Moore TE. Cicada acoustic communication: how do they do it? J Exp Biol. 1996;199(Pt 9):2137-47.
10. Nagl W, Schneider D. Structure of sensilla trichodea of silkworm moth. J Comp Neurol. 1970;139(3):213-32.
11. Smith BH, Spivak M, Taylor OR. Social insect communication. J Insect Behav. 1994;7(2):125-48.
12. Breed MD, Harrison JM. Worker honey bees use cues other than kinship for nestmate recognition in swarming colonies. Insect Soc. 1988;35(2):123-8.
13. Parachnowitsch AL, Caruso CM. The influence of insect communication on plant fitness. Trends Plant Sci. 2008;13(4):264-8.
14. Nielsen R, Slatkin M. An introduction to population genetics. Sinauer Associates; c2004.
15. Seeley TD. The Wisdom of the Hive. Harvard University Press; c1995.
16. Korb J, Heinze J. The ecology of social insects. Oxford University Press; c2008.
17. Turlings TC, Tumlinson JH. Systemic release of herbivore-induced plant volatiles. Proc Natl Acad Sci U S A. 1992;89(19):8399-402.
18. Cardé RT, Minks AK. Control of moth pests by mating disruption: successes and constraints. Annu Rev Entomol. 1995;40:559-85.
19. Ricketts TH, Regetz J, Steffan-Dewenter I, *et al*. Landscape effects on crop pollination services. Science. 2008;320(5874):1466-9.
20. Potts SG, Biesmeijer JC, Kremen C, *et al*. Global pollinator declines: trends, impacts and drivers. Trends Ecol Evol. 2010;25(6):345-53.
21. Menzel R, Giurfa M. Cognitive architecture of a mini-brain. Nature. 2001;410(6831):268-74.
22. Wyatt TD. Pheromones and Animal Behavior. Cambridge University Press; c2003.
23. Cardé RT, Haynes KF. Structure of the pheromone communication channel in moths. In: Cardé RT, Minks AK, editors. Insect Pheromone Research. Springer; c1997. p. 283-96.
24. Rooney AP, Ward TJ. Pheromonal and phylogenetic signals in sexual selection. Science. 2005;309(5739):1323-5.
25. Lewis WJ, Tumlinson JH. Host searching by parasitic insects. Science. 1988;240(4851):1228-32.
26. Mori K. Pheromone synthesis and chemical communication. Angew Chem Int Ed Engl. 2007;46(10):2760-94.
27. Symonds MR, Elgar MA. The evolution of pheromone diversity. Trends Ecol Evol. 2008;23(4):220-8.
28. Hardie J, Minks AK. Pheromones of Non-lepidopteran Insects. CABI Publishing; c1999.
29. Wyatt TD. Pheromones and Animal Behavior. Cambridge University Press; c2003.
30. Schneider D. Insect Pheromones: Receptors and Transduction. Springer; c1999.
31. Choe DH, Millar JG. Chemical ecology of insect reproduction. Annu Rev Entomol. 2001;46:1-24.
32. Schal C, Cardé RT. Pheromonal control of mating patterns in the housefly. Science. 1985;228(4705):1291-3.
33. Blomquist GJ, Vogt RG. Insect Pheromone Biochemistry and Molecular Biology. Elsevier Academic Press; c2003.
34. Reinecke JP. Chemistry and Biology of Insect Hormones. Springer; c2013.
35. Howard RW, Blomquist GJ. Ecological, Behavioral, and Biochemical Aspects of Insect Hydrocarbons. Annu Rev Entomol. 2005;50:371-93.
36. Greenfield MD. Signalers and Receivers. Oxford University Press; c2002.
37. Sokolowski MB. Foraging strategies of Drosophila melanogaster. Trends Ecol Evol. 2001;16(1):23-9.
38. Lenoir A, Hefetz A. Chemical ecology and social parasitism in ants. Annu Rev Entomol. 2001;46:573-99.
39. Breed MD, Harrison JM. Worker honey bees use cues other than kinship for nestmate recognition in swarming colonies. Insect Soc. 1988;35(2):123-8.
40. Hoelmer KA, Roltsch WJ. Aphid Pheromones. Annu Rev Entomol. 2004;49:583-608.
41. Camazine S, Sneyd J. A model of collective nectar source selection by honey bees. J Theor Biol. 1991;149(4):547-71.
42. Weidenmüller A. The coordination of foraging in bumblebees. J Exp Biol. 2001;204(Pt 4):637-45.
43. Traniello JF. Social organization and foraging ecology in ants. Annu Rev Entomol. 1989;34:191-210.
44. Watson PJ. Aggregation pheromones in bark beetles. Ann Entomol Soc Am. 1972;65(5):1055-60.
45. Wyatt TD. Pheromones and Animal Behavior. Cambridge University Press; c2003.
46. Alborn HT, Turlings TCJ. Plant defense signals and mating signals in insects. Science. 1997;276(5320):593-6.
47. Schal C, Cardé RT. Pheromonal control of mating patterns in the housefly. Science. 1985;228(4705):1291-3.
48. Hanks LM. Bark beetles and conifers. J Chem Ecol.

1999;25(3):567-96.
49. Appel AG, Rust MK. Agonistic behavior and pheromones in the German cockroach. Physiol Entomol. 1985;10(1):65-73.
50. Feener DH, Brown BV. The Role of Epideictic Pheromones. Annu Rev Entomol. 2000;45:583-609.
51. Singer TL. Roles of pheromones in insect reproduction. Annu Rev Entomol. 1998;43:557-84.
52. Leonhardt SD, Brandstaetter AS. Resource allocation in insects. Proc Natl Acad Sci U S A. 2013;110(2):536-42.
53. Lof ME, Witteveldt J. Host-marking pheromones. Science. 2013;340(6140):208-12.
54. Peschke K. Epideictic pheromones in sawflies. J Chem Ecol. 1985;11(5):697-710.
55. Peeters C, Ito F. Territoriality in ants. J Ethol. 2001;19(1):15-23.
56. Wiernasz DC. Territoriality in Insects. Science. 1995;267(5198):1819-22.
57. Adler PH. Chemical Marking of Territories. Annu Rev Entomol. 1998;43:349-75.
58. Hölldobler B, Wilson EO. The Ants. Harvard University Press; c1990.
59. Tsubaki Y, Samejima I. The Role of Territory Pheromones. Proc Natl Acad Sci U S A. 2004;101(27):10323-8.
60. Schneider D. Insect Pheromones: Receptors and Transduction. Springer; c1999.
61. Hansson BS, Stensmyr MC. Evolution of insect olfaction. Neuron. 2011;72(5):698-711.
62. Greenfield MD. Acoustic Communication in Insects and Anurans. University of Chicago Press; c2002.
63. Haverkamp A, Hansson BS. Neural Processing of Pheromones. Trends Neurosci. 2018;41(3):174-87.
64. Ai H, Rybak J, Menzel R. Neural Coding of Pheromones in Insects. Neuron. 2009;61(2):349-61.
65. Wyatt TD. Pheromones and Animal Behavior. Cambridge University Press; c2003.
66. Otte D. The Crickets of Hawaii: Origin, Systematics, and Evolution. Harvard University Press; c1994.
67. Gerhardt HC, Huber F. Acoustic Communication in Insects and Anurans. University of Chicago Press; c2002.
68. Lloyd JE. Firefly mating behavior. Science. 1983;222(4625):198-200.
69. Vane-Wright RI, Boppré M. Visual and olfactory signals in butterfly courtship and foraging. Biol J Linn Soc. 1993;48(2):167-78.
70. Swihart SL. Role of visual and olfactory cues in butterfly mate selection. Anim Behav. 1967;15(1):54-7.
71. Lenoir A, Hefetz A. Chemical ecology and social parasitism in ants. Annu Rev Entomol. 2001;46:573-99.
72. Tautz J. The Buzz about Bees. Springer; c2008.
73. Traniello JF. Social organization and foraging ecology in ants. Annu Rev Entomol. 1989;34:191-210.
74. Smith BH, Spivak M, Taylor OR. Social insect communication. J Insect Behav. 1994;7(2):125-48.
75. Wyatt TD. Pheromones and Animal Behavior. Cambridge University Press; c2003.
76. Breed MD, Harrison JM. Worker honey bees use cues other than kinship for nestmate recognition in swarming colonies. Insect Soc. 1988;35(2):123-8.
77. Turlings TC, Tumlinson JH. Systemic release of herbivore-induced plant volatiles. Proc Natl Acad Sci U S A. 1992;89(19):8399-402.
78. Cardé RT, Minks AK. Control of moth pests by mating disruption: successes and constraints. Annu Rev Entomol. 1995;40:559-85.
79. Potts SG, Biesmeijer JC, Kremen C, *et al*. Global pollinator declines: trends, impacts and drivers. Trends Ecol Evol. 2010;25(6):345-53.
80. Hanks LM. Bark beetles and conifers. J Chem Ecol. 1999;25(3):567-96.
81. Watson PJ. Aggregation pheromones in bark beetles. Ann Entomol Soc Am. 1972;65(5):1055-60.
82. Seeley TD. The Wisdom of the Hive. Harvard University Press; c1995.
83. Menzel R, Giurfa M. Cognitive architecture of a mini-brain. Nature. 2001;410(6831):268-74.
84. Cai HN, Ha TS, Bae Y, *et al*. Evolutionary conservation of pheromone transduction pathways. Science. 2001;293(5539):1848-50.
85. Symonds MR, Elgar MA. The evolution of pheromone diversity. Trends Ecol Evol. 2008;23(4):220-8.
86. Hardie J, Minks AK. Pheromones of Non-lepidopteran Insects. CABI Publishing; c1999.
87. Howard RW, Blomquist GJ. Ecological, Behavioral, and Biochemical Aspects of Insect Hydrocarbons. Annu Rev Entomol. 2005;50:371-93.
88. Schneider D. Insect Pheromones: Receptors and Transduction. Springer; c1999.
89. Gerhardt HC, Huber F. Acoustic Communication in Insects and Anurans. University of Chicago Press; c2002.
90. Greenfield MD. Acoustic Communication in Insects and Anurans. University of Chicago Press; c2002.
91. Wyatt TD. Pheromones and Animal Behavior. Cambridge University Press; c2003.
92. Symonds MR, Elgar MA. The evolution of pheromone diversity. Trends Ecol Evol. 2008;23(4):220-8.
93. Hardie J, Minks AK. Pheromones of Non-lepidopteran Insects. CABI Publishing; c1999.
94. Howard RW, Blomquist GJ. Ecological, Behavioral, and Biochemical Aspects of Insect Hydrocarbons. Annu Rev Entomol. 2005;50:371-93.
95. Greenfield MD. Signalers and Receivers. Oxford University Press; c2002.
96. Hanks LM. Bark beetles and conifers. J Chem Ecol. 1999;25(3):567-96.
97. Turlings TC, Tumlinson JH. Systemic release of herbivore-induced plant volatiles. Proc Natl Acad Sci U S A. 1992;89(19):8399-402.
98. Cardé RT, Minks AK. Control of moth pests by mating disruption: successes and constraints. Annu Rev Entomol. 1995;40:559-85.
99. Turlings TC, Tumlinson JH. Systemic release of herbivore-induced plant volatiles. Proc Natl Acad Sci U S A. 1992;89(19):8399-402.
100. Potts SG, Biesmeijer JC, Kremen C, *et al*. Global pollinator declines: trends, impacts and drivers. Trends Ecol Evol. 2010;25(6):345-53.
101. Wyatt TD. Pheromones and Animal Behavior. Cambridge University Press; c2003.
102. Turlings TC, Tumlinson JH. Systemic release of herbivore-induced plant volatiles. Proc Natl Acad Sci U S A. 1992;89(19):8399-402.
103. Cardé RT, Minks AK. Control of moth pests by mating disruption: successes and constraints. Annu Rev Entomol. 1995;40:559-85.
104. Schneider D. Insect Pheromones: Receptors and Transduction. Springer; c1999.
105. Symonds MR, Elgar MA. The evolution of pheromone

diversity. Trends Ecol Evol. 2008;23(4):220-8.
106. Turlings TC, Tumlinson JH. Systemic release of herbivore-induced plant volatiles. Proc Natl Acad Sci U S A. 1992;89(19):8399-402