Vibrations in hemipteran and coleopteran insects: behaviors and application in pest management

メタデータ	言語: English 出版者: 公開日: 2020-06-02 キーワード (Ja): キーワード (En): vibrational signals, communication, pest control, behavioral disruption, sense organ 作成者: 上地, 奈美 メールアドレス: 所属:
URL	https://repository.naro.go.jp/records/3384

Vibrations in hemipteran and coleopteran insects: behaviors and application in pest management

Takuma Takanashi[1]*, Nami Uechi[2], Haruki Tatsuta[3,4]

[1] Department of Forest Entomology, Forestry and Forest Products Research Institute, Tsukuba, Ibaraki 305-8687, Japan

[2] NARO Institute of Fruit Tree and Tea Science, National Agriculture and Food Research Organization, Tsukuba, Ibaraki 305-8605, Japan

[3] Department of Agro-Environmental Sciences, Faculty of Agriculture, University of the Ryukyus, Okinawa 903-0213, Japan

[4] The United Graduate School of Agricultural Sciences, Kagoshima University, Korimoto 1-21-24, Kagoshima 890-8580, Japan

*Correspondence: takanasi@affrc.go.jp

Abstract

Many groups of insects utilize substrate-borne vibrations for communication. They display various behaviors in response to vibrations in sexual and social communication and in predator–prey interactions. Although the number of reports on communication and behaviors using vibrations has continued to increase across various insect orders, there are several studies of the exploitation of vibrations for pest management in Hemiptera and Coleoptera. Here, we review studies of behaviors and communication using vibrations in hemipteran and coleopteran insects. For instance, pentatomid bugs display species- and sex-specific vibrational signals during courtship, whereas cerambycid beetles show startle responses to vibrations in the context of predator–prey interactions. Concepts and case studies in pest management using vibrations—especially regarding the disruption of communication and behavior—are also presented.

Key words vibrational signals, communication, pest control, behavioral disruption, sense organ

Introduction

Many insect species utilize mechanical information from substrate-borne vibrations or airborne sounds, or both, for various behaviors (Cocroft and Rodríguez 2005; Greenfield 2002; Hill 2008). Vibrations account for the majority of mechanical communications, and the number of species that use vibrations is estimated as 195,000 or more (Cocroft and Rodríguez 2005). Vibrations travel well through plants or other substrates, allowing conspecifics and/or predators to detect the vibrations (Michelsen et al. 1982).

Insects display various behaviors in response to vibrations. The functional significance of vibration-mediated interactions can be classified into i) sexual communication; ii) social communication; and iii) predator-prey interactions (e.g. Hill 2008; Takanashi et al. 2016). Sexual communication is mediated by vibrational sexual signals or aggressive signals (Hill 2008). For instance, males of the brown planthopper *Nilaparvata lugens* Stål (Delphacidae) locate females that produce vibrations by drumming their abdomens on the rice plant (Ichikawa and Ishii 1974). In prairie mole cricket *Gryllotalpa major* Saussure (Gryllotalpidae), males use the vibrations of rivals' calls transmitted via the ground, instead of the sounds of their calls through the air, to maintain space each other in a lek (Hill 2008; Hill and Shadley 2001). With regard to social communication, synchronous hatching of the brown marmorated stink bug *Halyomorpha halys* (Stål) (Pentatomidae) is induced by single eggshell-cracking vibration over a short period in a clutch of eggs in contact with each other (Endo et al. 2018). Mutualism between *Iridomyrmex* ants (Formicidae) and lycaenid butterflies is engaged by vibrational signals emitted by larvae and pupae of the butterfly (Travassos and Pierce 2000). Predator–prey interactions include prey localization and antipredatory behavior using vibrational cues (Hill 2008). The parasitoid wasp *Sympiesis sericeicornis* Nees (Eulophidae) perceives the exact locations of its lepidopteran host in leaf mines by eavesdropping on vibrations (Djemai et al. 2004). The red flour beetle *Tribolium castaneum* (Herbst) (Tenebrionidae) shows tonic immovability (death-feigning) in response to vibrations as a defense against predators (Kiyotake et al. 2014).

Although the number of reports of communication and behaviors using vibrations has continued to increase across various insect orders (Greenfield 2002; Hill 2008; Virant-Doberlet and Čokl 2004), studies of pest species damaging plants remain limited in Hemiptera, Coleoptera and a few other orders (e.g., Endo et al. 2018; Ichikawa and Ishii 1974; Polajnar et al. 2015). In particular, pest control by exploiting such signals has been studied in Hemiptera and Coleoptera alone (Eriksson et al. 2012; Hosomi 1996; Lujo et al. 2016; Polajnar et al. 2015). Indeed, hemipteran and coleopteran insects exhibit a variety of vibrational communications and behaviors. In this review, we focus on Hemiptera and Coleoptera in studies of both behavior and pest management using vibrations. We also review vibrational senses, behaviors, and communication in Hemiptera and Coleoptera, and we discuss the effectiveness of vibrations in pest management.

Vibrational senses

In insects, the sense organs involved with vibrations are internal mechanoreceptors, called chordotonal organs, which are located in the legs and other body parts (Field and Matheson 1998; Hill 2008). Two chordotonal organs in the legs—the femoral chordotonal organs and subgenual organs—play an important role in vibrational reception (Field and Matheson 1998). The chordotonal organs, within which the neurons are clustered into scoloparia, consist of multiple sensory neurons and attachment cells; for example, there are 24 sensory neurons in the brown-winged green bug *Plautia stali* Scott (Pentatomidae) and 70 sensory neurons in the Japanese pine sawyer beetle *Monochamus alternatus* Hope (Cerambycidae) (Fig. 1) (Nishino et al. 2016; Takanashi et al. 2016). The sensory neurons respond with high sensitivity to vibrations via the attachment cells (Field and Matheson 1998). The femoral chordotonal organ of *M.*

alternatus is attached to the tibia via a cuticular apodeme, whereas that of *P. stali* is attached to the tibia via attachment cells, without the apodeme (Fig. 1b, e). In both species, vibrations are transmitted from substrates via the tibia to the femoral chordotonal organs. The subgenual organs in the tibia possess air sacs for transmission of vibrations in orthopteran insects, but not in *P. stali* (Field and Matheson 1998; Nishino et al. 2016). Coleopteran insects including *M. alternatus* do not have subgenual organs (Takanashi et al. 2016). There are other mechanoreceptors, such as external ones for detecting strain on cuticular surfaces (Čokl and Virant-Doberlet 2003; Keil 1997).

Vibrational communications and behaviors

Hemiptera

Heteroptera, the so-called stink bugs or true bugs, are large group in the order Hemiptera. Pheromones are well-known communication signals in this order. Male adults attract adults and nymphs of both sexes by using pheromones (e.g., Mizutani 2006). Vibrations are also widely used among stink bugs. Chemical signals such as pheromones are used for long-distance communication, whereas physical signals such as vibrations and visual signals are used mainly for close-range communication on plants (Sakakibara 2016). Among the Heteroptera, 16 families of land bugs are listed as using vibrations as communication signals and to have mechanisms for producing vibrations (Virant-Doberlet and Čokl 2004; for examples of these families, see Table 1).

In many cases, vibrations are used for male courtship and for communication between sexes [e.g., Čokl et al. 1978 for the southern stink bug, *Nezara viridula* (Linnaeus) (Pentatomidae); Kon et al. 1988 for the eastern green stink bug, *Nezara antennata* Scott and *N. viridula* (Pentatomidae); Numata et al. 1989 for the bean bug, *Riptortus pedestris* (Fabricius) (Alydidae); Polajnar et al. 2016b for *H. halys* (Pentatomidae)]. Adults of *N. viridula* produce several stereotyped species- and sex-specific vibrational signals in the course of their courtship. The signals, called songs, are often exchanged in a duet (Čokl et al. 2000). Most of the Pentatominae species studied so far show similar behavioral sequences and vibrational repertoires and syntax (Virant-Doberlet and Čokl 2004). However, some songs might be missing from some repertoires, and different repertoires might be added (Virant-Doberlet and Čokl 2004).

Vibrations are also used as signals for parent–embryo communication. In the subsocial burrower bugs *Adomerus rotundus* (Hsiao) (Cydnidae) and *Parastrachia japonensis* Scott (Parastrachiidae), mothers produce vibrations by shaking their bodies rhythmically while maintaining an egg-guarding posture. The vibrations promote synchronous hatching (Mukai 2016; Mukai et al. 2012, 2014), which decreases the frequency of sibling cannibalism (Mukai et al. 2018). Unlike the subsocial burrower bugs, *H. halys* does not guard its eggs, but it does synchronize hatching (Endo and Numata 2017). Synchronous hatching of *H. halys* is induced by single eggshell-cracking vibration in a clutch of eggs (Endo et al. 2018). Hemipteran embryos generally may have an ability of responses to vibrations. A mother of *P. japonensis* vibrates her abdomen and produces a low-pitched fluttering sound when she serves food (drupes) to her nymphs in their nest. This provisioning call is considered to be a type of parent-offspring communication (Nomakuchi et al. 2012). By using the provisioning call as a cue, nymphs are likely to be able to distinguish between mother and predators when the female enters the nest (Nomakuchi et al. 2012).

Vibrations are also used as information for defense or predation against different species. In Cydnidae and Reduviidae, in which the nymphs constitute a colony, individuals in the same colony vibrate together as a collective defense against predators (Čokl and Virant-Doberlet 2003). Adults of some species of Triatominae, a subfamily of Reduviidae, produce defensive vibrations using a stridulatory organ when disturbed or handled. In addition, female adults stridulate to reject copulatory attempts made by males (Lazzari et al. 2006; Schilman et al. 2001). Some predacious reduviid species detect the vibrations of caterpillar prey (Čokl and Virant-Doberlet 2003).

Among the suborder Auchenorrhyncha, vibrational communications are spread across several families (Table 1). Ichikawa and Ishii (1974) discovered that males of the brown planthopper *N. lugens* (Delphacidae: Fulgoromorpha) use females vibrations for mate location on the rice plant. In response to the female vibrations, the males also produce vibrations with abdominal tymbals, which exist in Auchenorrhyncha and Heteroptera (Hoch et al. 2006; Ichikawa 1976; Mitomi et al. 1984). Similarly, both sexes use vibrations for mate location in Cicadomorpha [e.g., the American grapevine leafhopper, *Scaphoideus titanus* Ball (Cicadellidae) and some species of treehoppers (Membracidae); Cocroft and Rodríguez 2005; Mazzoni et al. 2009]. Furthermore, males of *S. titanus* produce disturbance vibrations against rival males (Mazzoni et al. 2009). Mothers of the thorn bug treehopper *Umbonia crassicornis* (Amyot and Serville) defend their offspring against attacking predators after they produce vibrations for the purposes of aggregation (Cocroft 1996).

Among Sternorrhyncha, both sexes of whiteflies (Aleyrodidae) produce vibrations by drumming the abdomen for communication on the leaf of a host plant [e.g., the greenhouse whitefly *Trialeurodes vaporariorum* (Westwood), the sweet potato whitefly *Bemisia tabaci* (Gennadius) and the woolly whitefly *Aleurothrixus floccosus* Maskell; Kanmiya 1996, 2006; Kanmiya and Sonobe 2002]. Male vibrations are species-specific in terms of temporal and spectral characteristics, suggesting that vibrational signals are used for species recognition (Kanmiya 2006). Males of the Asian citrus psyllid, *Diaphorina citri* Kuwayama (Liviidae), locate females that are producing vibrations; the males intermittently produce vibrational replies as a duet (Lujo et al. 2016; Wenninger et al. 2009). In the sweet pepper aphid, *Aphis nerii* Boyer de Fonscolombe (Aphididae), and the large cat’s ear aphid *Uroleucon hypochoeridis* (Fabricius) (Aphididae), visual signals in combination with twitching-related vibrations on the plant constitute a synchronizing defense against insect predators (Hartbauer 2010). Nymphs of the pea aphid, *Acyrthosiphon pisum* Harris (Aphididae), drop off the host plant in response to vibrations and other stimuli, such as the humid breath of mammalian herbivores (Gish et al. 2012).

Coleoptera

Coleoptera is the largest insect order and includes many pest species. Although there are numerous reports of sound production by stridulatory organs across various coleopteran families (Wessel 2006), most of these reports concern vibrational communication or interactions (Table 2). In the mountain pine beetle *Dendroctonus ponderosae* (Hopkins) (Curculionidae), stridulation generates vibrations on the host tree as well as airborne sounds, presumably for sexual communication at close range (Flemming et al. 2013). Males of the deathwatch beetle *Xestobium rufovillosum* (De Geer) (Anobiidae) tap their heads on the substrate; this enables them to locate females emitting vibrational replies at long range (Goulson et al. 1994). Among tenebrionid species, males of *Psammodes striatus* (Fabricius) tap their abdomens on the substrate for sexual communication, with a range of >50 cm (Lighton 1987). *Onymacris plana plana* Péringuey (Tenebrionidae) is sensitive to vibrations between 100 and 5000 Hz, presumably for detecting food through vibrations generated by the wind on the surface of the sand (Hanrahan and Kirchner 1994). As a defense against predators, the red flour beetle *T. castaneum* (Tenebrionidae) shows tonic immovability (death-feigning) in response to vibrations (Kiyotake et al. 2014). Vibration-induced tonic immovability is also found in the Colorado potato beetle, *Leptinotarsa decemlineata* Say (Chrysomelidae) (Acheampong and Mitchell 1997), and the sap beetle, *Phenolia* (*Lasiodites*) *picta* (MacLeay) (Nitidulidae) (Kishi and Takanashi 2019). In cerambycids, startle and freezing responses are induced by vibrations in *M. alternatus*, *Paraglenea fortunei* (Saunders), and the house longhorn beetle, *Hylotrupes bajulus* (Linnaeus) (Breidbach 1986; Takanashi et al. 2016; Tsubaki et al. 2014). The responses seem to serve as recognition of approaching conspecifics or predators.

Vibrations mediate communication or interactions among adults, larvae, and pupae. Group-living larvae of *Trypoxylus dichotomus* (Linnaeus) (Scarabaeidae) freeze in response to vibrations produced by drumming pupae, thereby protecting the pupal cells in the soil (Kojima et al. 2012c). The freezing response to pupae of *T. dichotomus* is likely to have evolved from the response to predators because larvae also show freezing to vibrations produced by moles (Kojima et al. 2012a, b). Females of the cowpea beetle *Callosobruchus maculatus* (Fabricius) (Chrysomelidae) use vibrations from feeding larvae within a host bean for the purpose of oviposition (Guedes and Yack 2016).

Pest control using vibrations

The importance of physical pest control by using lights or other non-chemical methods has been increasing in response to societal needs for environmentally friendly alternatives to synthetic pesticides (Polajnar et al. 2015; Shimoda and Honda 2013). Knowledge of sensitivities and behaviors in response to vibrations is applicable to pest management for behavioral manipulation and disruption. To apply artificial vibrations to insect pests, vibration exciters (as hardware) and the temporal and spectral characters of the vibrations (as software) are of great importance. In addition, the possible side-effects of vibrations on plants and non-target insects need to be assessed carefully (for a review, see Polajnar et al. 2015). Below, we present in detail some examples of disruption of vibrational communication or behavior.

Disruption of vibrational communication

In pest species that use vibrational communication between sexes, it is a rational strategy to disrupt this communication with artificial vibrations. Here, we review two successful cases. Males of *S. titanus*, a vector of the lethal grapevine disease Flavescence dorée, produce male-disturbance vibrations as well as sexual signals (Mazzoni et al. 2009). Eriksson et al. (2012) demonstrated vibrational disruption of this species by using mimic disturbance vibrations from an electromagnetic shaker. When the disturbance vibrations were transmitted to grapevines through a supporting wire, the mating frequency in field cages of the species decreased significantly. The amplitude threshold for efficacy in mating disruption was determined in the laboratory and validated in the field (Polajnar et al. 2016a). The other example is communication disruption in *D. citri*, which is a vector of citrus greening disease, one of the most destructive citrus disease worldwide (Hall et al. 2013). The two sexes of this species exchange vibrational communication to locate each other (Wenninger et al. 2009). Application of female vibrational mimics generated by a piezoelectric buzzer led to a significant decrease in the mating percentage on a citrus tree (Lujo et al. 2016).

Disruption of behavior with vibrations

Cerambycids—the so-called longicorn beetles—include many pests, and their larvae damage fruit and ornamental trees. These beetles include serious pests known to be invasive species and vectors of tree diseases (Kobayashi et al. 1984; Wang 2017). In cerambycids, although vibrational communication for mate localization over long ranges has not yet been found, a series of behaviors is displayed in response to vibrations (Breidbach 1986; Takanashi et al. 2016; Tsubaki et al. 2014). This means that various cerambycid behaviors can be disrupted by artificial vibrations for pest control. Indeed, Hosomi (1996) investigated vibrational disruption by using mechanical knocker on fig trees against adults of *Apriona japonica* Thomson. Intermittent vibrations at 5 to 40 Hz disrupt feeding to some extent, but not oviposition. No fatal negative effects of the vibrations on fruit and shoot growth have been detected (Hosomi 1996).

Monochamus alternatus, the vector of the pine wilt nematodes that kill pine trees (Kobayashi et al. 1984), demonstrates freezing and startle responses when exposed to vibrations below 1 kHz (Fig. 2) (Takanashi et al. 2016). The freezing is mediated by femoral chordotonal organs (Fig. 1b, c) that detect low-frequency vibrations (Takanashi et al. 2016). Also, *P. fortunei* dwelling on herbaceous plants shows freezing and startle responses when exposed to low-frequency vibrations (Fig. 2) (Takanashi et al. 2016; Tsubaki et al. 2014). Thus, these two cerambycid beetles show high sensitivity to frequencies of 100 to 500 Hz (Fig. 2). Because freezing means cessation of walk and other behavior, low-frequency vibrations are assumed to disrupt the feeding, oviposition, and residence of cerambycids on host trees. Also, it is possible that vibrations enhance repellency, that is, escape from the host tree. Preliminary experiments have shown that feeding and other behaviors in *M. alternatus* are disrupted by low-frequency vibrations (T. Takanashi et al. unpublished data). Low-frequency vibrations might therefore be also useful for pest control in cerambycids.

On the basis of our findings of vibrational sensitivity in cerambycid beetles, we are currently developing a new procedure for pest management by using vibrations as an environmentally friendly alternative to synthetic pesticides. To generate vibrations at large amplitudes on trees, a prototype of a vibration exciter was made by using a giant magnetostrictive material (GMM) as a new technology (Fig. 3). GMM, an alloy comprised of iron and rare metals, exhibits a large magnetostrain, namely a strain caused by a magnetic field (Söderberg et al. 2005). This exciter generates low-frequency vibrations at high acceleration, and these vibrations are expected to manifest enough power to disrupt the behaviors of target pests (Takanashi et al. 2016). In addition, intermittent application of vibrations can help avoid the problem of habituations to vibrations. Our pilot experiments demonstrated disruption of behavior in *M. alternatus* by a GMM vibration exciter attached to a tree (H. Sakamoto, T. Koike, N. Fukaya, T. Takanashi in preparation); this was also shown in the brown-winged green bug, *P. stali* (N. Uechi and T. Takanashi in preparation). Future studies are essential to explore and resolve several issues, including installation of the exciter and jigs for vibrational transmission, reduction of the cost of the exciter, and the possibility of side-effects on plants and other organisms.

Conclusion

Because many insects in a variety of taxa exhibit sensitivity to vibrations (Cocroft and Rodríguez 2005; Greenfield 2002; Hill 2008), artificial vibrations are applicable to the disruption of behaviors or communication. Furthermore, a vibration exciter that uses GMM technology is able to generate vibration on various substrates (e.g., crops in greenhouses). Such new pest control technologies will help to reduce the need to apply synthetic pesticides and will become part of integrated pest management (IPM) in the future (Polajnar et al. 2015). Potential negative side effects of the vibrations on plants and non-target beneficial insects will need to be minimized (Polajnar et al. 2015). We should be able to find the most appropriate procedures to use against various pests, and we will be able to promote IPM by combining several existing procedures with newly developed technologies, including vibration.

Acknowledgements

We thank H. Nishino for the drawing of chordotonal organs in *P. stali*, K. Honda and members of Shindou unit for kind cooperation during studies of SIP project. Thanks are also due to two anonymous reviewers for helpful comments of this manuscript and editors for kind handling of this special issue, ‘Behavioral control and pest management using vibrations’. This work was partly supported by Cabinet Office, Government of Japan, Cross-ministerial Strategic Innovation Promotion Program (SIP), “Technologies for creating next-generation agriculture, forestry and fisheries” (funding agency: Bio-oriented Technology Research Advancement Institution, NARO) and by Narishige Zoological Science Award.

References

Acheampong S, Mitchell BK (1997) Quiescence in the Colorado potato beetle, *Leptinotarsa decemlineata*. Entomol Exp Appl 82:83–89

Breidbach O (1986) Studies on the stridulation of *Hylotrupes bajulus* (L.) (Cerambycidae, Coleoptera): communication through support vibration-morphology and mechanics of the signal. Behav Proc 12:169–186

Claridge MF, Morgan JC, Moulds MS (1999) Substrate-transmitted acoustic signals of the primitive cicada, *Tettigarcta crinita* Distant (Hemiptera: Cicadoidea: Tettigarctidae). J Natur Hist 33:1831–1834

Cocroft RB (1996) Insect vibrational defence signals. Nature 382:679–680

Cocroft RB, Rodríguez R (2005) The behavioral ecology of insect vibrational communication. BioScience 55:323–334

Čokl A, Gogala A, Blaževič A (1978) Principles of sound recognition in three Pentatomide bug species (Heteroptera). Biol Vestn 26:81–94

Čokl A,Virant-Doberlet M (2003) Communication with substrate-borne signals in small plant-dwelling insects. Ann Rev Entomol 48:29–50

Čokl A, Virant-Doberlet M, Mcdowell A (1999) Vibrational directionality in the southern green stink bug, *Nezara viridula* (L.), is mediated by female song. Anim Behav 58:1277–1283

Čokl A, Virant-Doberlet M, Stritih N (2000) The structure and function of songs emitted by southern green stink bugs from Brazil, Florida, Italy and Slovenia. Physiol Entomol 25:196–205

Djemai I, Casas J, Magal C (2004) Parasitoid foraging decisions mediated by artificial vibrations. Anim Behav 67:567–571

Eben A, Mühlethaler R, Gross J, Hoch H (2014) First evidence of acoustic communication in the pear psyllid *Cacopsylla pyri* L. (Hemiptera: Psyllidae). J Pest Sci 88:87–95

Endo J, Numata H (2017) Effects of embryonic responses to clutch mates on egg hatching patterns of Pentatomidae (Heteroptera). Physiol Entomol 42:412–417

Endo J, Takanashi T, Mukai H, Numata H (2018) Egg-cracking vibration as a cue for stink bug siblings to synchronize hatching. Curr Biol. https://doi.org/10.1016/j.cub.2018.11.024

Eriksson A, Anfora G, Lucchi A, Lanzo F, Virant-Doberlet M, Mazzoni V (2012) Exploitation of insect vibrational signals reveals a new method of pest management. Plos One 7:e32954

Field LH, Matheson T (1998) Chordotonal organs in insects. Adv Insect Physiol 27:1–228

Fleming AJ, Lindeman AA, Carroll AL, Yack JE (2013) Acoustics of the mountain pine beetle (*Dendroctonus ponderosae*) (Curculionidae, Scolytinae): sonic, ultrasonic, and vibration characteristics. Can J Zool 91:235–244

Gish M, Dafni A, Inbar M (2012) Young aphids avoid erroneous dropping when evading mammalian herbivores by combining input from two sensory modalities. Plos One 7:e32706

Gogala M (1984) Vibration producing structures and songs of terrestrial Heteroptera as systematic character. Biol Vestn 32:19–36

Gogala M (1990) Distribution of low frequency vibrational songs in local Heteroptera. Scopolia Suppl 1:125–132

Goulson D, Birch MC, Wyatt TD (1994) Mate location in the deathwatch beetle, *Xestobium rufovillosum* De Geer (Anobiidae): orientation to substrate vibrations. Anim Behav 47:899–907

Greenfield MD (2002) Signalers and receivers. Oxford University Press, New York

Guedes RNC, Yack JE (2016) Shaking youngsters and shaken adults: female beetles eavesdrop on larval seed vibrations to make egg-laying decisions. Plos One 11:e0150034

Hall DG, Richardson ML, Ammar ED, Halbert SE (2013) Asian citrus psyllid, *Diaphorina citri*, vector of citrus huanglongbing disease. Entomol Exp Appl 146:207–223

Hanrahan SA, Kirchner WH (1994) Acoustic orientation and communication in desert tenebrionid beetles in sand dunes. Ethology 97:26–32

Hartbauer M (2010) Collective defense of *Aphis nerii* and *Uroleucon hypochoeridis* (Homoptera, Aphididae) against natural enemies. Plos One 5:e10417

Hill PSM (2008) Vibrational communication in animals. Harvard university press, Cambridge

Hill PSM, Shadley JR (2001) Talking back: sending soil vibration signals to lekking prairie mole cricket males. Am Zool 41:1200–1214

Hoch H, Deckert J, Wessel A (2006) Vibrational signalling in a Gondwanan relict insect (Hemiptera: Coleorrhyncha: Peloridiidae). Biol Lett 2:222–224

Hoch H, Mühlethaler R, Wachmann E, Stelbrink B, Wessel A (2011) *Celebenna thomarosa* gen. n., sp. n. (Hemiptera, Fulgoromorpha, Cixiidae, Bennini) from Indonesia: Sulawesi with notes on its ecology and behaviour. Dtsch Entomol Z 58:241–250

Hosomi A (1996) Effect of vibration to the infestation of *Apriona japonica* (Thomson) (Coleoptera: Cerambycidae) adults on the fig. Proceedings of Japan informal group meeting on human response to vibration held at the Hokkaido safety and health service, 25–34

Ichikawa T (1976) Mutual communication by substrate vibrations in the mating behavior of planthoppers (Homoptera: Delphacidae). Appl Entomol Zool 11:8–21

Ichikawa T, Ishii S (1974) Mating signal of the brown planthopper, *Nilaparvata lugens* Stål (Homoptera: Delphacidae): vibration of the substrate. Appl Entomol Zool 9:196–198

Kanmiya K (1996) Discovery of male acoustic signals in the greenhouse whitefly, *Trialeurodes vaporariorum* (Westwood) (Homoptera: Aleyrodidae). Appl Entomol Zool 31:255–262

Kanmiya K (2006) Mating behaviour and vibratory signals in whiteflies (Hemiptera: Aleyrodidae). In: Drosopoulos S, Claridge MF (eds) Insect sounds and communication: physiology, behaviour, ecology and evolution, Taylor and Francis, London, pp 365–379

Kanmiya K, Sonobe R (2002) Records of two citrus pest whiteflies in Japan with special reference to their mating sounds (Homoptera: Aleyrodidae). Appl Entomol Zool 37:487–495

Keil TA (1997) Functional morphology of insect mechanoreceptors. Microsc Res Tech 39:506–531

Kishi M, Takanashi T (2019) Tonic immobility and startle responses induced by substrate-borne vibrations in the sap beetle, *Phenolia (Lasiodites) picta* (Coleoptera: Nitidulidae). Jpn J Appl Entomol Zool (in press) (In Japanese with English abstract)

Kiyotake H, Matsumoto H, Nakayama S, Sakai M, Miyatake T, Ryuda M, Hayakawa Y (2014) Gain of long tonic immobility behavioral trait causes the red flour beetle to reduce anti-stress capacity. J Insect Physiol 60:92–97

Kobayashi F, Yamane A, Ikeda T (1984) The Japanese pine sawyer beetle as the vector of pine wilt disease. Ann Rev Entomol 29:115‑135

Kojima W, Ishikawa Y, Takanashi T (2012a) Deceptive vibratory communication: pupae of a beetle exploit the freeze response of larvae to protect themselves. Biol Lett 8:717–720

Kojima W, Ishikawa Y, Takanashi T (2012b) Pupal vibratory signals of a group-living beetle that deter larvae: are they mimics of predator cue? Commun Integr Biol 5:262–264

Kojima W, Takanashi T, Ishikawa Y (2012c) Vibratory communication in the soil: pupal signals deter larval intrusion in a group-living beetle *Trypoxylus dichotoma*. Behav

Ecol Sociobiol 66:171–179

Kon M, Oe A, Numata H, Hidaka T (1988) Comparison of the mating behavior between two sympatric species *Nezara antennata* and *N. viridula* (Heteroptera: Pentatomidae) with special reference to sound emission. J Ethol 6:91–98.

Koczor S, Čokl A (2015) Percussion signals of *Lygus rugulipennis* Poppius (Heteroptera: Miridae). Cent Eur J Biol 9:543–549

Lazzari C, Manrique G, Schilman P (2006) Vibratory communication in Triatominae (Heteroptera: Reduviidae). In: Drosopoulos S, Claridge MF (eds) Insect sounds and communication: physiology, behaviour, ecology and evolution, Taylor and Francis, London, pp 297–304

Liao YC, Yang MM (2017) First evidence of vibrational communication in Homotomidae (Psylloidea) and comparison of substrate-borne signals of two allied species of the genus *Macrohomotoma* Kuwayama. J Insect Behav 30:567–581

Lighton JRB (1987) Cost of tokking: the energetics of substrate communication in the tok-tok beetle, *Psammodes striatus*. J Comp Physiol B 157:11–20

Lubanga UK, Guédot C, Percy DM, Steinbauer MJ (2014) Semiochemical and vibrational cues and signals mediating mate finding and courtship in Psylloidea (Hemiptera): a synthesis. Insects 5:577–595

Lujo S, Hartman E, Norton K, Pregmon E, Rohde B, Mankin RW (2016) Disrupting mating behavior of *Diaphorina citri* (Liviidae). J Econ Entomol 109:2373–237

Mazzoni V, Presern J, Lucchi A, Virant-Doberlet M (2009) Reproductive strategy of the Nearctic leafhopper *Scaphoideus titanus* Ball (Hemiptera: Cicadellidae). Bull Entomol Res 99:401–413

Michelsen A, Fink F, Gogala M, Traue D (1982) Plants as transmission channels for insect vibrational songs. Behav Ecol Sociobiol 11:269–281

Mitomi M, Ichikawa T, Okamoto H (1984) Morphology of the vibration-producing organ in adult rice brown planthopper, *Nilaparvata lugens* (Stål) (Homoptera: Delphacidae). Appl Entomol Zool 19:407–417

Mizutani N (2006) Pheromones of male stink bugs and their attractiveness to their parasitoids. Jpn J Appl Entomol Zool 50:87–99. (In Japanese with English summary)

Mukai H (2016) Parental regulation for hatching plasticity. Jpn J Appl Entomol Zool 60:67–75 (In Japanese with English summary)

Mukai H, Hironaka M, Tojo S, Nomakuchi S (2012) Maternal vibration induces synchronous hatching in a subsocial burrower bug. Anim Behav 84:1443–1448.

Mukai H, Hironaka M, Tojo S, Nomakuchi S (2014) Maternal vibration: an important cue for embryo hatching in a subsocial shield bug. Plos One 9:e87932.

Mukai H, Hironaka M, Tojo S, Nomakuchi S (2018) Maternal hatching synchronization in a subsocial burrower bug mitigates the risk of future sibling cannibalism. Ecol Evol 8:3376–3381

Nishino H, Mukai H, Takanashi T (2016) Chordotonal organs in hemipteran insects: unique peripheral structures but conserved central organization revealed by comparative neuroanatomy. Cell Tissue Res 366:549–572

Nomakuchi S, Yanagi T, Baba N, Takahira A, Hironaka M, Filippi L (2012) Provisioning call by mothers of a subsocial shield bug. J Zool 288:50–56

Numata, H, Kon M, Fujii H, Hidaka T (1989) Sound production in the bean bug, *Riptortus clavatus* Thunberg (Heteroptera: Alydidae). Appl Entomol Zool 24:169–173

Percy DM, Taylor GS, Kennedy M (2006) Psyllid communication: Acoustic diversity, mate recognition and phylogenetic signal. Invertebr Syst 20:431–445

Polajnar J, Eriksson A, Lucchi A, Anfora G, Virant-Doberlet M, Mazzoni, V (2015) Manipulating behaviour with substrate-borne vibrations—potential for insect pest control. Pest Manag Sci 71:15–23

Polajnar J, Eriksson A, Virant-Doberlet M, Mazzoni V (2016a) Mating disruption of a grapevine pest using mechanical vibrations: from laboratory to the field. J Pest Sci

89:909–921

Polajnar J, Maistrello L, Bertarella A, Mazzoni V (2016b) Vibrational communication of the brown marmorated stink bug (*Halyomorpha halys*). Physiol Entomol, 41:249–259

Sakakibara M (2016) Introduction to true bug biology. Ann Rept Plant Prot North Japan 67:14–23 (In Japanese)

Schilman PE, Manrique G, Lazzari CR (2001) Comparison of disturbance stridulation in five species of triatominae bugs. Acta Tropica 79:171–178

Shimoda M, Honda K (2013) Insect reactions to light and its applications to pest management. Appl Entomol Zool 48:413–421

Söderberg O, Sozinov A, Lindroos VK (2005) Giant magnetostrictive materials In: Buschow KHJ, Cahn RW, Flemings MC, Ilschner B, Kramer EJ, Mahajan S, Veyssière P (eds) Encyclopedia of materials: science and technology, Elsevier, Amsterdam, pp 1–3

Stölting H, Moore TE, Lakes-Harlan R (2002) Substrate vibrations during acoustic signalling in the cicada *Okanagana rimosa*. J Insect Sci 2:1–7

Takanashi T, Fukaya M, Nakamuta K, Skals N, Nishino H (2016) Substrate vibrations mediate behavioral responses via femoral chordotonal organs in a cerambycid beetle. Zool Lett 2:18

Tishechkin DY (2003) Vibrational communication in Cercopoidea and Fulgoroidea (Homoptera: Cicadina) with notes on classification of higher taxa. Russ Entomol J 12:129–181

Tishechkin DY (2008) On the similarity of temporal pattern of vibrational calling signals in different species of Fulgoroidea (Homoptera: Auchenorrhyncha). Russ Entomol J 17:349–357

Tishechkin DY (2016) New data on vibrational calling signals of Fulgoroidea (Homoptera: Auchenorrhyncha) from the Asian part of Palaearctic with new records of three species of Cixiidae. Russ Entomol J 25:307–322

Travassos MA, Pierce NE (2000) Acoustics, context and function of vibrational signalling in a lycaenid butterfly-ant mutualism Anim Behav 60:13–26

Tsubaki R, Hosoda N, Kitajima H, Takanashi T (2014) Substrate-borne vibrations induce behavioral responses of a leaf-dwelling cerambycid *Paraglenea fortunei*. Zool Sci 31:789–794

Virant-Doberlet M, Čokl A (2004) Vibrational communication in insects. Neotrop Entomol 33:121–134

Virant-Doberlet M, Žežlina I (2014) Vibrational communication of *Metcalfa pruinosa* (Hemiptera: Fulgoroidea: Flatidae). Ann Entomol Soc Am 100:73–82

Wang Q (2017) Cerambycidae of the world: biology and pest management. CRC Press, Boca Raton

Wenninger EJ, Hall DG, Mankin RW (2009) Vibrational communication between the sexes in *Diaphorina citri* (Hemiptera: Psyllidae). Ann Entomol Soc Am 102:547–555

Wessel A (2006) Stridulation in the Coleoptera—an overview. In: Drosopoulos S, Claridge MF (eds) Insect sounds and communication: physiology, behaviour, ecology and evolution, Taylor and Francis, London, pp 397–404

Table 1 Vibrational communications and interactions in Hemiptera. Families reviewed by Virant-Doberlet and Čokl (2004) are included

Family	Species	Intra-species communication	Inter-species interaction	References
Heteroptera				
Alydidae	*Riptortus pedestris*	male courtship, communication between male and female		Numata et al. 1989
Coreidae	*Coreus marginartus*	courtship		Gogala 1990
Cydnidae	*Adomerus rotundus*, *Tritomegas bicolor*	male copulatory attempts, parent–embryo communication (synchronous hatching)		Gogala 1984; Mukai et al. 2012, 2018
Miridae	*Lygus rugulipennis*	courtship		Koczor and Čokl 2015
Parastrachiidae	*Parastrachia japonensis*	parent–embryo/offspring communication (synchronous hatching, provisioning call)		Mukai et al. 2014; Nomakuchi et al. 2012
Pentatomidae	*Halyomorpha halys*, *Nezara viridula*, *Nezara antennata*	male courtship, communication between male and female, embryo interaction (synchronous hatching)		Čokl et al. 1978, 1999, 2000; Endo and Numata 2017; Endo et al. 2018; Kon et al. 1988; Polajnar et al. 2016b
Reduviidae	*Rhodnius*	male copulatory	defense	Čokl and

	prolixus, Triatoma infestance	attempts	against predators or disturbance, detection of food	Virant-Doberlet 2003; Lazzari et al. 2006; Schilman et al. 2001
Auchenorrhyncha				
Aphrophoridae	*Aphrophora alni*	calling, male territorial and rivalry signals		Tishechkin 2003; Virant-Doberlet and Čokl 2004
Caliscelidae	*Acromega scurrilis, Peltonotellus turgidus*	calling		Tishechkin 2003, 2016
Cercopidae	*Cercopis vulnerata*	calling, territorial signals		Tishechkin 2003
Cicadellidae	*Scaphoideus titanus*	mate location, disturbance of rival males		Mazzoni et al. 2009
Cicadidae	*Cicada orni, Okanagana rimosa*	mate location (vibrational component of air-borne calling signal)		Stölting et al. 2002; Virant-Doberlet and Čokl 2004
Cixiidae	*Celebenna thomarosa*, *Cixius nervosus*	mating behavior		Hoch et al. 2011; Tishechkin 2003, 2008
Delphacidae	*Laodelphax striatellaus*, *Nilaparvata lugens*, *Sogatella furcifera*	communication between males and females		Ichikawa 1976; Ichikawa and Ishii 1974; Tishechkin 2008
Derbidae	*Cedusa*	calling		Tishechkin 2008

	sarmatica			
Dictyopharidae	*Dictyophara pannonica*	mating behavior, calling		Tishechkin 2003, 2016
Flatidae	*Metcalfa pruinosa*	mating behavior		Virant-Doberlet and Žežlina 2014
Issidae	*Alloscelis vittifrons*, *Scorlupella discolor*	calling		Tishechkin 2003, 2008
Machaerotidae	*Taichorina geisha*	calling		Tishechkin 2003
Meenoplidae	*Eponisiella paludicola*	calling		Tishechkin 2016
Membracidae	*Unbonia crassicornis*	mate location, mating	defense against predators	Cocroft 1996; Cocroft and Rodríguez 2005
Tettigarctidae	*Tettigarcta crinita*	courtship		Claridge et al. 1999
Tropiduchidae	*Trypetimorpha occidentalis*	calling, competition between males		Tishechkin 2003

Sternorrhyncha				
Aleyrodidae	*Aleurothrixus floccosus*, *Bemisia tabaci,* *Siphoninus phillyreae*, *Trialeurodes vaporariorum*	communication between males and females		Kanmiya 1996, 2006; Kanmiya and Sonobe 2002
Aphalaridae	*Aphalara affinis*	mate finding and courtship		Lubanga et al. 2014
Aphididae	*Aphis nerii*, *Toxoptera oadiiiae,* *Uroleucon hypochoeridis*		defense against predators	Gish et al. 2012; Hartbauer 2010
Carsidaridae	*Protyora sterculiae*	mate finding and courtship		Lubanga et al. 2014
Liviidae	*Diaphorina citri*	communication between males and females		Lubanga et al. 2014; Lujo et al. 2016; Wenninger et al. 2009
Psyllidae	*Cacopylla pyri*, *Macrohomotoma gladiata*	mate finding and courtship		Eben et al. 2014; Liao and Yang 2017
Triozidae	*Aacanthocnema dobsoni*, *Schedotrioza apicobystra*	mate finding and courtship		Percy et al. 2006

Table 2 Vibrational communication and interactions in Coleoptera. Proposed mechanisms for vibrational generation and responses to vibration are shown in parentheses.

Family	**Species**	**Intra-species communication**	**Inter-species interaction**	**References**
Anobiidae	*Xestobium rufovillosum*	male and female tapping (orientation)		Goulson et al. 1994
Tenebrionidae	*Onymacris plana plana*, *Psammodes striatus*, *Tribolium castaneum*	male tapping (orientation)	food movement by wind (orientation)	Hanrahan and Kirchner 1994; Kiyotake et al. 2014; Lighton 1987
Chrysomelidae	*Callosobruchus maculatus*, *Leptinotarsa decemlineata*	larval feeding (oviposition)	predator movement (tonic immobility)	Acheampong and Mitchell 1997; Guedes and Yack 2016
Cerambycidae	*Hylotrupes bajulus*, *Monochamus alternatus*, *Paraglenea fortunei*	male and female movement (startle, freezing)	predator movement (startle, freezing)	Breidbach 1986; Takanashi et al. 2016; Tsubaki et al. 2014
Scarabaeidae	*Trypoxylus dichotomus*	pupal tapping (freezing)	predator movement (freezing)	Kojima et al. 2012a, b, c
Nitidulidae	*Phenolia* (*Lasiodites*) *picta*		predator movement? (tonic immobility)	Kishi and Takanashi 2019
Curculionidae	*Dendroctonus ponderosae*	male stridulation (mating?)		Fleming et al. 2013

Figure legends

Fig. 1 Leg chordotonal organs in *Monochamus alternatus* (**a–c**) and *Plautia stali* (**d–f**). **a** Photograph of *M. alternatus* adult. **b** Diagram indicating the locations of femoral chordotonal organ (FCO): sensory neurons (scoloparium) (*red arrow*) and cuticular apodeme (*red line*) in prothoracic femur are shown. **c** Fluorescent retrograde labeling of FCO scoloparium viewed posteriorly. **d** *P. stali* adult. **e** FCO scoloparium (*red arrow*) in prothoracic femur and subgenual organ (*red arrowhead*) in prothoracic tibia are shown. **f** Fluorescent retrograde labeling of FCO scoloparium viewed anteriorly. Scale bars = 4 mm (**a, d**), 500 μm (**b, e**), 50 μm (**c, f**). **c** and **f** are reproduced from the work of Takanashi et al. (2016) and Nishino et al. (2016), respectively, with permission of the publishers. **e** Courtesy of H. Nishino (redrawn from Nishino et al. 2016).

Fig. 2 Thresholds of behavioral responses to vibrations in *Monochamus alternatus* and *Paraglenea fortunei*. Startle responses from a standstill (*solid lines*) in both species and freezing response during walk in *P. fortunei* (*dashed line*) are indicated. Adapted from the work of Takanashi et al. (2016) and Tsubaki et al. (2014).

Fig. 3 A vibration exciter made by using giant magnetostrictive materials, which generates vibration to induce behavioral responses from insects on a tree. The exciter is attached horizontally to the tree with black bands. Scale bar = 50 mm.