

# Inaudible Noise Pollution of the Invertebrate World

*Maggie Raboin*

## Introduction

Anthropogenic sound is widely recognized as an issue of environmental concern (Shannon et al., 2016). Produced by human activities like those associated with urbanization, economic development, transportation networks, and recreation, anthropogenic sound now penetrates some of the quietest places on Earth (Buxton et al., 2017). In fact, over 60% of US protected lands experience noise levels double those of background noise, despite their distance from major metropolitan areas (Buxton et al., 2017). For vertebrates, the consequences of noise in natural landscapes have been found to be multifaceted, impacting mating, movement, predator-prey dynamics, and physiology (Shannon et al., 2016). However, research has mostly focused on the impacts of pressure waves on vertebrates, with the impact of anthropogenic sound on invertebrates and the acoustic modalities they rely on (mainly particle motion and substrate-borne sound) remaining largely unstudied.

Indeed, when evaluated in 2016, only 4% of the work on the impact of anthropogenic sound on animals had been on invertebrates, despite their comprising 97% of species on Earth (Shannon et al., 2016). However, recent research investigating anthropogenic sound and invertebrates suggests that the impact of noise on invertebrate behavior, physiology, and communities is likely diverse and complicated. The goal of this article is to introduce readers to invertebrates, their bioacoustics, and the potential effects of anthropogenic sound on invertebrates.

## Invertebrate Decline

In natural history museums, you can find millions of individual invertebrates, from ants and anemones to stoneflies and shrimp. All are collected with care, meticulously analyzed by morphology, labeled, and stored on a shelf. These animals were once so abundant that their swarms darkened skies, fields, and intertidal zones.

Perhaps most telling, invertebrates were once so numerous that their services to ecosystems were once incalculable and their disappearance inconceivable. However, in the last decade, the scientists that collect and identify invertebrates began to notice a concerning trend, a precipitate drop-off in the number of invertebrates visiting their traps. In fact, in parts of the world such as Germany, Puerto Rico, and the United States mainland, scientists have reported up to a 90% loss in the abundance of some invertebrate populations (Goulson, 2019).

To talk about invertebrates as a single group (defined as organisms lacking a backbone) in many ways obscures the diversity of organisms within. Invertebrates range from insects, spiders, and worms in terrestrial ecosystems to corals, clams, and squid in marine ecosystems. They are often considered valuable because of their propensity to be eaten by more charismatic fauna. Although they make up a substantial portion of the diets of many vertebrates, like amphibians, reptiles, birds, and mammals, they also perform other vital roles in ecosystems. From nutrient cycling in soils and marine environments to pollination and controlling pest populations, invertebrates are the little engines that make ecosystems go. Dramatic declines in their abundances are predicted to result in major consequences for the world's ecosystems and economies (Cardoso et al., 2020).

We are still in the early days of understanding the magnitude and consequences of historic invertebrate declines. Recent changes in their populations have been attributed to several factors, including climate change, habitat loss, and pesticide use (Goulson, 2019). However, most models of invertebrate decline fail to account for the extent of loss. Traditional strategies for the conservation of species, stopping decline and restoring populations, often hinge on understanding an animal's habitat and population structure, with less attention paid to the animal's "habit," their way of being in and sensing the world.

But a handful of conservation biologists have recently been making appeals to consider the sensory ecology, the way organisms acquire, process, and share information, of species (Dominoni et al., 2020). These investigators implore us to transition away from questions like “What do these organisms eat?” and “Who eats them?” toward questions that ask, “In what ways do these animals find food or avoid being eaten?” For many invertebrates, the ubiquitous answer to questions concerning the mechanism for finding food or mates, avoiding predators, choosing suitable habitats, or communicating with conspecifics is “sound.”

It just so happens that over the past century, while invertebrate populations have been in free fall, sound from increased human activity has been rising (Buxton et al., 2017; Goulson, 2019). For vertebrates, anthropogenic sound has been found to impact behavior and physiology, leading, in some cases, to reductions in vertebrate species abundances (Shannon et al., 2016). However, much less is known about the impact of anthropogenic sound on invertebrates. Results from recent research aiming to bridge the gap between two fields of study, invertebrate bioacoustics and anthropogenic sound, suggest that in searching for the major contributors to invertebrate decline, we might look first to anthropogenic sound.

### Invertebrate Bioacoustics

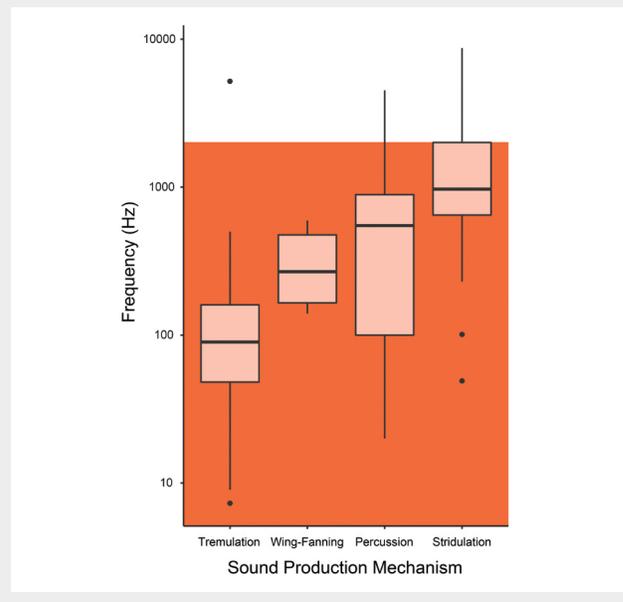
Once submerged in alcohol and placed on a museum shelf, little attention is paid to the sensory life that defined the day to day of a living invertebrate. At first glance, they would appear to be too strange and void of emotion to interact with sound in a meaningful way and, therefore, disqualified from being impacted by anthropogenic sound. Moreover, in contrast to mammals, most invertebrates lack protruding folds that are identifiable as ears. They don’t delight us with their audible praise of the morning sun the way that birds do. Their anguish isn’t conveyed through familiar bellows. But invertebrates have rich sensory lives that are much different from our own and are often dominated by sound.

Recall the cacophony of crickets singing on a warm summer night (available at [youtu.be/fh3uNUrAnss](https://youtu.be/fh3uNUrAnss)). Crickets, like humans and vertebrates, rely on airborne pressure waves to sense and convey acoustic information. However, the audibility of a cricket’s song to human ears is an exception among invertebrates. In fact, most of the invertebrate sounds you know, like those produced by

crickets, cicadas, katydids, and grasshoppers, are departures from the invertebrate rules of sound production. (For more on the bioacoustics of these animals, see Pollack, 2017.) Few invertebrates are large enough to efficiently move air (Bennet-Clark, 1998) and thus resort to transmitting information through particle oscillations (particle motion) or vibrations of solids (substrate-borne sound), modalities of sound out of the sensory reach of humans.

Invertebrates sense and convey information through not only air but also through water, soils, rocks, leaves, and plant stems. Many marine invertebrates have hearing organs that are highly sensitive to low-frequency particle motion rather than pressure waves (Popper and Hawkins, 2018). Among terrestrial invertebrates, over 90% use some type of substrate-borne sound for communication

**Figure 1.** Average frequency of signals by mechanism for 97 invertebrate species that communicate with substrate-borne sound. Included are the four most common mechanisms that invertebrates use for producing substrate-borne sound: tremulation (oscillations of a body part), wing-fanning (rapid oscillation of wings), percussion (transient impacts of an appendage against another appendage or against the substrate), and stridulation (rubbing of two rigid structures against one another) (Raboin and Elias, 2019). Nearly all species that communicate with substrate-borne sound use frequencies that overlap with the highest energy anthropogenic sound (<2,000 Hz; orange box). Pink boxes, 1st to 3rd quartile; black lines, 95% confidence intervals; black circles, points outside the confidence interval.



## INAUDIBLE NOISE POLLUTION

(Cocroft and Rodriguez, 2005). Using a variety of mechanisms, substrate-borne signalers produce sounds with frequencies below about 2,000 Hz because low frequencies experience little attenuation in solids (**Figure 1**) (Bennet-Clark, 1998).

### Sound in Survival and Reproduction

In his 1881 publication *The Formation of Vegetable Mould Through the Action of Worms*, Charles Darwin provides one of the earliest recognitions of an inaudible invertebrate acoustic world, one in which sound is communicated through substrates. He reports, "...if the ground is beaten or otherwise made to tremble, worms believe that they are pursued by a mole and leave their burrows" (Darwin, 1881, p. 28). Worm charming, a popular technique for collecting earthworms by transmitting vibrations through the soil with a metal rod or machine engine, repeated Darwin's observation by the thousands throughout the twentieth century. When faced with human-produced low-frequency vibrations (<1,000 Hz), earthworms race to the soil's surface to avoid being eaten by an imaginary subterranean rodent, allowing worm charmers the ability to quickly collect hundreds of them to sell for fish bait (Catania, 2008) (see video at [youtu.be/IGviTYCFksE](https://youtu.be/IGviTYCFksE)) Like many invertebrates, earthworms rely on substrate-borne vibrations, in part, to avoid predators.

As prey, invertebrates use sound to identify, avoid, and deter predators. As predators, they use sound to distinguish, localize, and lure prey. A single web in an East African forest may include an orb-weaver spider listening intently to the vibrations of each silken strand of a web so that it might reveal the capture and identity of a flying insect (Landolfi and Barth, 1996). But this web might also attract another kind of invertebrate predator. *Portia*, a jumping spider that prefers to hunt other spiders, employs a creative vibratory technique in its pursuit of a meal (see [youtu.be/U2WHZGpdghc](https://youtu.be/U2WHZGpdghc)). On entering the web of an unwitting spider, *Portia* plucks the strings so that they vibrate with frequencies that mimic an ensnared and struggling insect, thereby catching the attention of the web's owner and luring them to investigate (Tarsitano et al., 2000). When the resident spider approaches, *Portia* seizes and eats it. For each spider, their ability to hear and translate vibratory pulses into useful information has critical consequences for survival.

The overall fitness of an individual organism is, in part, determined by its ability to reproduce. Crucial to this endeavor



**Figure 2.** Male *Habronattus pugillis* jumping spiders (order Araneae, family Salticidae) attract mates by producing courtship songs made up of substrate-borne sound paired with visual displays. Photograph courtesy of Marshal Hedin.

is communication with conspecifics about reproductive status, quality, and location. Invertebrates as diverse as crickets, lobsters, and mosquitoes, among many others, rely on sound to attract and find mates. Just as crickets, katydids, and grasshoppers advertise their location and willingness to mate through airborne song, wolf and jumping spiders (**Figure 2**) (see [youtu.be/AZszAaJyVTc](https://youtu.be/AZszAaJyVTc)), treehoppers, and crabs encode their ability to produce quality offspring through composed arrangements of substrate-borne syllables channeled to potential mates (Hill, 2009). Mosquitoes and fruit flies buzz their wings to transmit similar information through particle motion (Albert and Göpfert, 2015; Menda et al., 2019). The mechanisms, modalities, and context by which invertebrates use sound for reproduction may be specific to each species but, when taken broadly, it is clear that sound is a primary vehicle for sexual selection and evolution across invertebrates.

What reproducing is to the fitness of solitary invertebrates, collaboration via communication is to the fitness of social invertebrates. Bees, termites, and ants communicate information within communities and sometimes across species, in part, with sound. When an intruder enters or threatens an ant or termite colony, observing members beat their heads against the substrate, producing percussive vibrations that alert the rest of the colony of an imminent attack (Hill, 2009). Ants and bees convey instructions about where and when to find food in vibrations, as in the remarkable waggle dance of honeybees (Michelsen, 2003). In an indication of the importance of acoustic communication, even some caterpillars that live

in a commune with ants produce stridulations to exploit the acoustic sensitivities of their tenders and gain access to more care and protection (DeVries, 1990).

Finally, but no less important, is the reliance of invertebrates on sound for its ability to carry general information about the environment. Environmental processes like wind, rain, fire, and moving water (e.g., streams, rivers) all produce sound with specific acoustic characteristics. In a recent study, forest patches with broadcasted sounds of a white water river were found to be home to more web-building spiders than similar forest patches without these sounds (Gomes et al., 2020). It is likely that each ecosystem, with its unique makeup of soils, plants, animals, and environmental processes, has an acoustic signature that invertebrates pick up on to make decisions or determine habitat quality. Just as the broadcasted crackle of a healthy coral reef was found to attract a diversity of fishes to a depopulated reef (Gordon et al., 2019), so too might sounds emanating from ecosystems inform invertebrates of their quality.

In these collected reports of invertebrate behavior, researched by hundreds of investigators, published over decades, and randomly assembled, are the beginning brushstrokes to a complete picture of invertebrate bioacoustics that is in every way as vibrant as the one that's been painted for vertebrates. Invertebrate bioacoustics suggests, with emphasis, the first step to understanding sound in the natural world: human perceptions are limiting. Acoustics are penetrating, diverse, time warping, alien, and complex. The ubiquity of a sound makes it a reliable and ever-present source of information accessible to even the smallest organisms. It is no wonder that many invertebrates rely on sound to perform important daily activities and thus are vulnerable to the impact of anthropogenic sound.

### Invertebrates and Anthropogenic Sound

When the idea and threat of anthropogenic sound took hold in the first decade of the twenty-first century (Shannon et al., 2016), it brought to attention the acoustic vulnerabilities of vertebrate animals that had previously eluded ecologists. Excited scientists established acoustic monitoring programs, created sound libraries, and began documenting the acoustics of ecosystems. Ostensibly, this was and continues to be an effort to create an acoustic record of nature before it disappears. Like any attempt to describe the nature of things, though, it omitted the inconvenient aspects of doing so.

Baseline values for ecosystem acoustics in the form of particle motion or substrate-borne vibrations were ignored and remain nonexistent.

One such example, a 2015 attempt to create awareness of noise pollution in Grand Teton National Park, WY (GTNP; see [nps.gov/grte/index.htm](https://nps.gov/grte/index.htm)), involved noise meters installed along Park roadsides (National Park Service, 2015). The meters penetrated the quiet of each vehicle's interior with a green-yellow-red visualization of the airborne pressure wave drivers introduced into the ecosystem. Missing from these meters was an indication of the particle motion and substrate-borne vibrations emanating from vehicles as they progressed through the Park: the granite pebbles, aspen leaves, sagebrush stems, and pine boughs rattling long after they passed and the millions of disrupted invertebrate individuals who depend on sound for survival and reproduction.

Noise from human activities is dominated by frequencies below 2,000 Hz, which happens to correspond with those frequency sensitivities of the majority of terrestrial and marine invertebrates (Popper and Hawkins, 2018; Raboin and Elias, 2019). As sound radiates out from a source, it encounters invertebrates of all kinds and intrudes into their acoustic worlds as a novel stimulus, abundant in time, space, and modality. For example, noise from vehicles passing an aspen stand in the GTNP may encounter a tree, a branch, a leaf and with them, a single female planthopper sitting atop its matte surface (Figure 3). Vibrations from the vehicles

**Figure 3.** *Planthoppers (order Hemiptera, family Tropiduchidae) send and receive substrate-borne vibrations along plant stems and leaves to identify, locate, and assess potential mates. Photograph courtesy of Marshal Hedin.*



## INAUDIBLE NOISE POLLUTION

swamp out any courtship pulses from male planthoppers, reducing the female's ability to perceive, locate, or assess the caller. In the height of the summer, when mating season is in full swing, vehicles may pass her leaf every few seconds, reducing her many mating opportunities to just a few. When she finally finds a mate, she may be less discerning in her choice, impacting generations to come.

### *Noise Impacts Behavior and Physiology*

Masking, where an acoustic signal of interest (natural environment stimulus) and pollutant sound occur simultaneously in time and space and with similar characteristics, is, perhaps, the most often observed impact of anthropogenic sound to vertebrates and invertebrates alike. Of the many invertebrates that rely on sound to communicate during courtship and mating, few have encountered masking sound under scientific observation and experimentation. For those that have, such as crickets, katydids, grasshoppers, fruit flies, stink bugs, and leafhoppers, anthropogenic sound tends to drown out any information encoded in calls, reducing the receiver's ability to identify, locate, and assess potential mates (Raboin and Elias, 2019).

For *Ormea ochracea*, a tiny parasitoid fly, the presence of masking sound means that they are unable to find a cricket host in which to deposit their larvae. Females of this species have exquisitely sensitive ears tuned to the frequencies of calling crickets that allows them to locate individuals with accuracy. On arriving at a calling cricket, *O. ochracea* deposits her larvae so that they might feed on the cricket as they grow from larva to pupa. When anthropogenic sound overlaps with cricket calling, *O. ochracea*'s accuracy in finding a host plummets, potentially limiting her ability to successfully raise offspring (Lee and Mason, 2017).

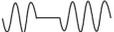
Burying beetles are scavenging invertebrates that scour the landscape in search of dead and decomposing animals. On locating one, paired burying beetles cooperate to excavate a grave beneath the carcass, eventually lowering it to a depth at which it can be easily covered with soil (see [youtu.be/Ua1wC59phpk](https://youtu.be/Ua1wC59phpk)). They remain with the carcass underground for weeks to lay eggs and work side by side in caring for the young. Beetles facilitate carcass burial, courtship, and care for the young with their partner via stridulatory vibrations. However, low-frequency anthropogenic sound disrupts cooperation, possibly through masking, and results in fewer offspring for pairs (Phillips et al., 2020).

Sensory pollutants can also mislead animals into invoking inappropriate responses when the animal wrongly attributes the sensory pollutant as being a natural stimulus. Anthropogenic sound is misleading when it is similar in acoustic characteristics to natural stimuli but occurs differently in time or space. Misleading sensory pollutants often lead to maladaptive behaviors or ecological traps that result in increased mortality, predation, or decreased reproductive success of individuals. Worm charming can be thought of as a misleading stimulus because it mimics the acoustic frequencies of earthworm predators. The worms, having evolved behavioral responses to these frequencies, respond predictably and yet still find themselves in the hands of a predator, humans.

But anthropogenic sound need not overlap in location, characteristics, or even sensory modality to cause harm. Distraction occurs when a pollutant stimulus occupies the limited attention of an individual, thereby involuntarily diverting their attention from some other stimulus or task. Through distraction, anthropogenic sound can penetrate deep (higher level) cognitive processes of animals, such as risk assessment, navigation, memory retrieval, and learning. Hermit crabs retreat inside their shells when predators approach. They rely, in part, on sound to identify when external conditions merit withdrawal, but in the presence of sound from boats, distracted hermit crabs allow predators to get closer before retreating, exposing themselves to increased risk of predation (Chan et al., 2010).

Finally, anthropogenic sound does not only impact the ways that invertebrates send, receive, and process information (by masking, misleading, or distracting), it can also impact basic physiological and developmental processes. Some sounds have long been considered stressors for humans. Similarly, road sound raised the heart rates of monarch caterpillars (Davis et al., 2018), and boat sound elicited an immune response in lobsters consistent with a stress response (Celi et al., 2015). When exposed to chronic anthropogenic sound during development, crickets took longer to reach maturity and had shorter life spans (Gurule-Small and Tinghitella, 2019). Interestingly, diverse stress responses of a small group of sediment-dwelling marine invertebrates in the presence of anthropogenic sound altered the behavior and physiology in a such a way that impacted overall ecosystem nutrient cycling (Solan et al., 2016).

Among the many lingering questions surrounding invertebrates and anthropogenic sound, some of the

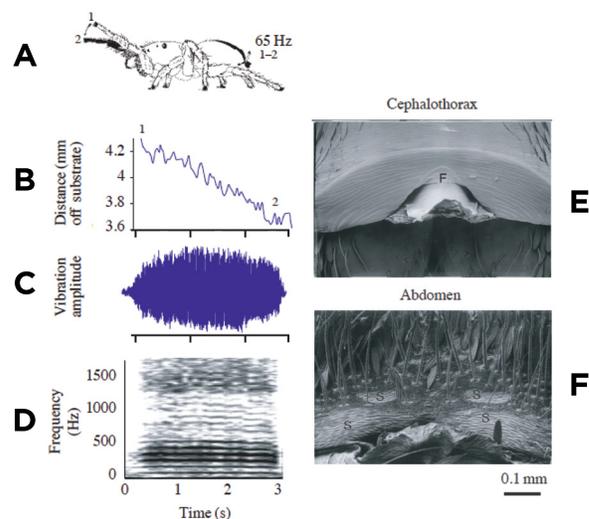
Signal Characteristic	Potential for Conveying Information in Noise	
	Weak	Strong
Amplitude	Quiet 	Loud 
Bandwidth	Broadband 	Narrowband 
Temporal Structure	Continuous 	Intermittent 
Modulation	Constant 	Modulated 
Repetition	No repetition 	Repetition 
Dimensionality	Unidimensional 	Multidimensional 
Multimodality	Unimodal 	Multimodal 

**Figure 4.** Signal characteristics and their hypothesized robustness to masking noise. **Left column:** signal information can be conveyed across multiple acoustic characteristics. **Right column:** certain variations of each characteristic are predicted to be better at conveying information in the presence of masking noise than others (**right to left**, respectively). Information can be conveyed using temporal, amplitudinal (waveforms in **white boxes**), and spectral (spectrograms in **gray boxes**) properties. Modified from Raboin and Elias, 2019.

most consequential involve whether or not invertebrates will habituate to anthropogenic sound or adapt via plasticity or evolution. For now, we can only guess at the answers. First, invertebrates can avoid anthropogenic sound by migrating away from areas with human activity. Although this may be an especially useful strategy for those species with wings, migration may be out of the question for others, such as soil-dwelling species. Second, they can avoid a masking sound by shifting the times of day at which they communicate away from peak human activity. However, this strategy comes with the potential costs of communicating at nonoptimal times of day. Finally, they can adjust the acoustic characteristics of calls that contain information, such as amplitude, frequency and bandwidth, temporal structure, dimensionality, and modality, to avoid overlap with anthropogenic sound or increase their signal-to-noise ratio (**Figure 4**).

This last strategy, modification of acoustic characteristics, holds ample opportunity for adaptation but also backs up against constraints specific to invertebrates. The sound production and receiving mechanisms and related exoskeleton features of many invertebrates (e.g., insects, spiders), which are manifestations of the sort represented by ripples in a hardened cuticle, are molded and set in place at the time of an organism's final molt, the one in which they reach maturity (**Figure 5**). Herein lies a problem: on reaching maturity, many invertebrates have little room to plastically adjust the sounds they produce through structural adjustments. Additionally, many invertebrates are small and face size constraints in shifting the frequencies of their calls (Bennet-Clark, 1998).

**Figure 5.** Substrate-borne “buzz” courtship signal and corresponding stridulating structure of the male jumping spider, *Habronattus dossenus* (order Araneae, family Salticidae). Front legs come down (1→2) as the abdomen oscillates at 65 Hz (1-2). This signal has a fundamental frequency at 65 Hz, with several harmonic frequencies (130, 195, and 260 Hz). **A:** body position, with numbers (1 and 2) illustrating movements of the forelegs and abdomen. **B:** position of one of the forelegs (in millimeters above the substrate). **C:** oscillogram of the substrate-borne signal. **D:** frequency characteristics of the substrate-borne signal. **B-D** are shown in the same time scale, with numbers (1 and 2) corresponding to the body movements illustrated in **A**. **E** and **F:** scanning electron micrographs (SEM) of the stridulating structure on the exoskeleton of a male *H. dossenus*. **E:** SEM of the posterior end of the head (cephalothorax). **F:** ridged file. **F:** SEM of the anterior end of the abdomen. **S**, locations of the scrapers. Adapted from Elias et al., 2003.



As is the trend for most human activities that produce sound, visitation in the GTNP has increased manifold in recent years and with it the number of cars, trucks, and motorcycles entering its gates. Although the sound meters were only temporary on the landscape, anthropogenic sound in the form of pressure waves, particle motion, and substrate-borne sound, are ever present. The stories and studies recounted here highlight newly formed connections between penetrating anthropogenic sound and invertebrate communication, behavior, and physiology. However, the question of the role anthropogenic sound might play in shaping invertebrate populations and communities remains. Future research must seek to identify and make visible connections between sound from human activities and broad trends in invertebrate decline in ecosystems.

## Conclusion

In the face of worldwide invertebrate decline that touches nearly every tip of the invertebrate family tree, one commonality shared by the majority of its members is their reliance on sound for survival and reproduction. Concurrent with invertebrate decline has been an increase in human activities that produce anthropogenic sound, now a ubiquitous sensory pollutant in ecosystems. It is, perhaps, in recognizing the acoustic lives of invertebrates, in recording and mapping anthropogenic sound in particle motion and substrate-borne sound, and in understanding how these interact to impact invertebrate species, populations, and communities that we might find the keys to understanding invertebrate declines.

## Acknowledgments

I thank Damian O. Elias, Malcolm Rosenthal, Ambika Kamath, Trinity Walls, and Arthur Popper for their helpful comments and Marshal Hedin for kindly contributing photographs.

## References

- Albert, J. T., and Göpfert, M. C. (2015). Hearing in *Drosophila*. *Current Opinion in Neurobiology* 34, 79-85. <https://doi.org/10.1016/j.conb.2015.02.001>.
- Bennet-Clark, H. C. (1998). Size and scale effects as constraints in insect sound communication. *Philosophical Transactions of the Royal Society. Series B: Biological Sciences* 353(1367), 407-419. <https://doi.org/10.1098/rstb.1998.0219>.
- Buxton, R. T., McKenna, M. F., Mennitt, D., Frstrup, K. M., Crooks, K., Angeloni, L., and Wittemyer, G. (2017). Noise pollution is pervasive in U.S. protected areas. *Science* 356, 531-533. <https://doi.org/10.1177/1757913914566549>.
- Cardoso, P., Barton, P. S., Birkhofer, K., Chichorro, F., Deacon, C., Fartmann, T., Fukushima, C. S., Gaigher, R., Habel, J. C., Hallmann, C. A., and Hill, M. J. (2020). Scientists' warning to humanity on insect extinctions. *Biological Conservation* 242, 1-12. <https://doi.org/10.1016/j.biocon.2020.108426>.
- Catania, K. C. (2008). Worm grunting, fiddling, and charming—Humans unknowingly mimic a predator to harvest bait. *PLoS ONE* 3(10), e3472. <https://doi.org/10.1371/journal.pone.0003472>.
- Celi, M., Filiciotto, F., Vazzana, M., Arizza, V., Maccarrone, V., Ceraulo, M., Mazzola, S., and Buscaino, G. (2015). Shipping noise affecting immune responses of European spiny lobster (*Palinurus elephas*). *Canadian Journal of Zoology* 93(2), 113-121. <https://doi.org/10.1139/cjz-2014-0219>.
- Chan, A. A. Y., Giraldo-Perez, P., Smith, S., and Blumstein, D. T. (2010). Anthropogenic noise affects risk assessment and attention: The distracted prey hypothesis. *Biology Letters* 6, 458-461.
- Cocroft, R. B., and Rodriguez, R. L. (2005). The behavioral ecology of insect vibrational communication. *BioScience* 55(4), 323-334. [https://doi.org/10.1641/0006-3568\(2005\)055\[0323:TBEOIV\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2005)055[0323:TBEOIV]2.0.CO;2).
- Darwin, C. (1881). Chapter 1: Habits of worms. In *The Formation of Vegetable Mould Through the Action of Worms with Observations on Their Habits*. John Murray, London, UK, pp. 8-54.
- Davis, A. K., Schroeder, H., Yeager, I., and Pearce, J. (2018). Effects of simulated highway noise on heart rates of larval monarch butterflies, *Danaus plexippus*: Implications for roadside habitat suitability. *Biology Letters* 14(5), 20180018. <https://doi.org/10.1098/rsbl.2018.0018>.
- DeVries, P. J. (1990). Enhancement of symbioses between butterfly caterpillars and ants by vibrational communication. *Science* 248(4959), 1104-1106.
- Dominoni, D. M., Halfwerk, W., Baird, E., Buxton, R. T., Fernández-Juricic, E., Frstrup, K. M., McKenna, M. F., Mennitt, D. J., Perkin, E. K., Seymoure, B. M., and Stoner, D. C. (2020). Why conservation biology can benefit from sensory ecology. *Nature Ecology and Evolution* 4(4), 1-10. <https://doi.org/10.1038/s41559-020-1135-4>.
- Elias, D. O., Mason, A. C., Maddison, W. P., and Hoy, R. R. (2003). Seismic signals in a courting male jumping spider (Araneae: Salticidae). *Journal of Experimental Biology* 206(22) 4029-4039. <https://doi.org/10.1242/jeb.00634>.
- Gomes, D. G. E., Hesselberg, T., and Barber, J. R. (2020). Phantom river noise alters orb-weaving spider abundance, web size and prey capture. *Functional Ecology* 35(3), 717-726. <https://doi.org/10.1111/1365-2435.13739>.
- Gordon, T. A. C., Radford, A. N., Davidson, I. K., Barnes, K., McCloskey, K., Nedelec, S. L., Meekan, M. G., McCormick, M. I., and Simpson, S. D. (2019). Acoustic enrichment can enhance fish community development on degraded coral reef habitat. *Nature Communications* 10(1), 1-7. <https://doi.org/10.1038/s41467-019-13186-2>.
- Goulson, D. (2019). The insect apocalypse, and why it matters. *Current Biology* 29(19), R967-R971. <https://doi.org/10.1016/j.cub.2019.06.069>.
- Gurule-Small, G. A., and Tinghitella, R. M. (2019). Life history consequences of developing in anthropogenic noise. *Global Change Biology* 25(6), 1957-1966. <https://doi.org/10.1111/gcb.14610>.
- Hill, P. S. M. (2009). How do animals use substrate-borne vibrations as an information source? *Naturwissenschaften* 96(12), 1355-1371. <https://doi.org/10.1007/s00114-009-0588-8>.
- Landolfá, M. A., and Barth, F. G. (1996) Vibrations in the orb web of the spider *Nephila clavipes*: Cues for discrimination and orientation. *Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology* 179(4), 493-508. <https://doi.org/10.1007/BF00192316>.
- Lee, N., and Mason, A. C. (2017). How spatial release from masking may fail to function in a highly directional auditory system. *eLife* 6, 1-24. <https://doi.org/10.7554/elife.20731>.
- Menda, G., Nitzany, E. I., Shamble, P. S., Wells, A., Harrington, L. C., Miles, R. N., and Hoy, R. R. (2019). The long and short of hearing in the mosquito *Aedes aegypti*. *Current Biology* 29(4), 709-714.e4. <https://doi.org/10.1016/j.cub.2019.01.026>.
- Michelsen, A. (2003). Signals and flexibility in the dance communication of honeybees. *Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology* 189(3), 165-174. <https://doi.org/10.1007/s00359-003-0398-y>.

National Park Service (2015). *Soundscape Awareness Efforts Underway with Temporary Roadside Noise Meter*. Press Release, National Park Service, August 10, 2015. Available at <https://acousticstoday.org/NPS-roadside-noise>.

Phillips, M. E., Chio, G., Hall, C. L., ter Hofstede, H. M., and Howard, D. R. (2020). Seismic noise influences brood size dynamics in a subterranean insect with biparental care. *Animal Behaviour* 161, 15-22. <https://doi.org/10.1016/j.anbehav.2019.12.010>.

Pollack, G. S. (2017). Insect bioacoustics. *Acoustics Today* 13(2), 26-34.

Popper, A. N., and Hawkins, A. D. (2018). The importance of particle motion to fishes and invertebrates. *The Journal of the Acoustical Society of America* 143(1), 470-488. <https://doi.org/10.1121/1.5021594>.

Raboin, M., and Elias, D. O. (2019). Anthropogenic noise and the bioacoustics of terrestrial invertebrates. *Journal of Experimental Biology* 222(12), 1-11. <https://doi.org/10.1242/jeb.178749>.

Shannon, G., McKenna, M. F., Angeloni, L. M., Crooks, K. R., Fristrup, K. M., Brown, E., Warner, K. A., Nelson, M. D., White, C., Briggs, J., and McFarland, S. (2016). A synthesis of two decades of research documenting the effects of noise on wildlife. *Biological Reviews* 91(4), 982-1005. <https://doi.org/10.1111/brv.12207>.

Solan, M., Hauton, C., Godbold, J. A., Wood, C. L., Leighton, T. G., and White, P. (2016). Anthropogenic sources of underwater sound can modify how sediment-dwelling invertebrates mediate ecosystem properties. *Scientific Reports* 6, 1-9. <https://doi.org/10.1038/srep20540>.

Tarsitano, M., Jackson, R. R., and Kirchner, W. H. (2000). Signals and signal choices made by the araneophagic jumping spider *Portia fimbriata* while hunting the orb-weaving web spiders *Zygiella x-notata* and *Zosis geniculatus*. *Ethology* 106(7), 595-615. <https://doi.org/10.1046/j.1439-0310.2000.00570.x>.

## About the Author



### Maggie Raboin

[Maggie.raboin@berkeley.edu](mailto:Maggie.raboin@berkeley.edu)

Department of Environmental  
Sciences, Policy, and Management  
University of California, Berkeley  
140 Mulford Hall  
Berkeley, California, 94720, USA

Maggie Raboin is a PhD candidate in the Environmental Science, Policy, and Management Department at the University of California, Berkeley (Berkeley). Her research seeks to uncover the ways that invertebrates are affected by human-created environmental change. Specifically, her work investigates the impact of substrate-borne anthropogenic noise on invertebrates in the Greater Yellowstone Ecosystem.

## The Journal of the Acoustical Society of America

### JASA Call For Submissions:

JASA is currently accepting manuscripts for the following Special Issues:

- COVID-19 Pandemic Acoustic Effects
- Education in Acoustics
- Noise-Induced Hearing Disorders: Clinical and Investigational Tools
- Ocean Acoustics in the Changing Arctic

Special Issue articles are free to read for one year after publication and don't incur any mandatory page charges.

Find out more at  
[asa.scitation.org/jas/info/specialissues](https://asa.scitation.org/jas/info/specialissues)

# JASA EXPRESS LETTERS

Rapidly publishing  
gold **open access**  
research in acoustics

[asa.scitation.org/journal/jel](https://asa.scitation.org/journal/jel)

# Simulation of Perforates: An Application of Nonlinear Thermo-viscous Acoustics

*M. Herring Jensen*

Whether designing a concert hall, an earbud microspeaker, or virtual reality sound (Vorländer, 2020), acoustics simulation has gained a foothold in many commercial and academic settings. For electronic products especially, the competition between companies is fierce, because consumers have many options to choose from when they are looking to spend money on the latest and greatest devices. Product experts race to design the next viral product in a market where even a small competitive advantage can have a big impact on a company's success. In this climate, many teams turn to simulation to develop that advantage.

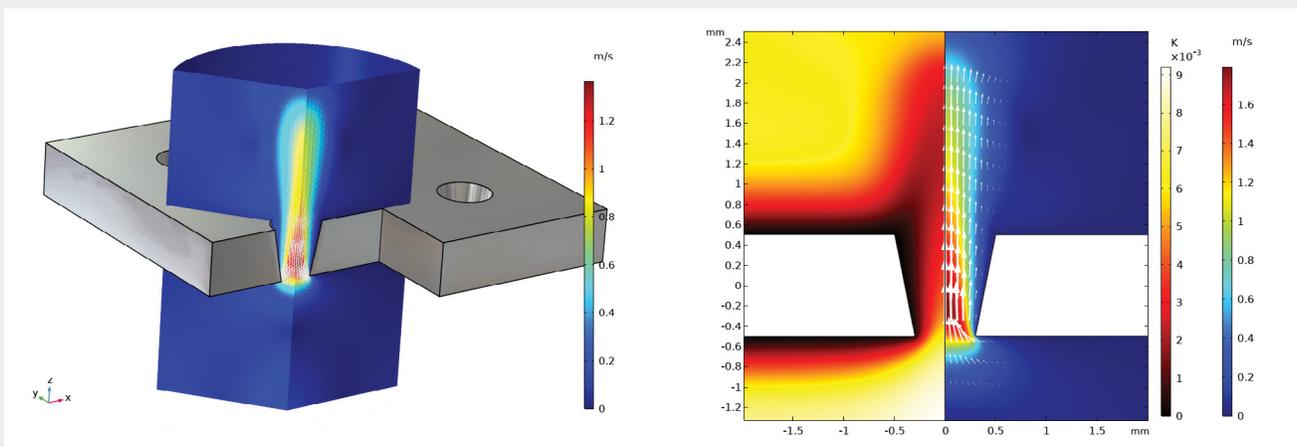
Simulation is becoming even more important as new design challenges arise. Optimizing designs, minimizing weight, and making devices as small and compact as possible are some

examples. And where many designs would previously rely on analytical inputs, like Webster's horn equation used for a tweeter waveguide design, it is now possible to include more details in the simulation model and explore new designs. One example is the ability to conduct a numerical simulation of all relevant physics and how they interact, to simultaneously study electromagnetics, structural deformation, and acoustic fields in multiphysics simulations of loudspeakers. Another example is how simulation and better computers allow the inclusion of smaller-scale or microfeatures.

The example studied here is microperforated plates (MPPs) or perforates, used in many acoustics applications where controlled damping is necessary. Perforates are found in room acoustic treatments for sound control and absorption, in duct acoustics for muffler systems, in various microphone applications, and in grills in front of loudspeakers.

Damping occurs as a result of thermal and viscous dissipation in the acoustic boundary layer. In microperforated plates, the boundary layer thickness is comparable to the perforation diameter, which leads to a larger amount of damping. A full thermoviscous acoustics description is necessary to capture the losses in detail. In general, as sound pressure levels increase in the devices, nonlinear effects start to kick in. An increase in dissipation occurs and the value of the transfer impedance becomes level dependent. The importance of nonlinear effects can be related to the Strouhal number,

**Figure 1.** Acoustic velocity magnitude in a tapered perforate showing the onset of vortex shedding: 3D view (left) and cross section (right) with acoustic temperature fluctuations and velocity.



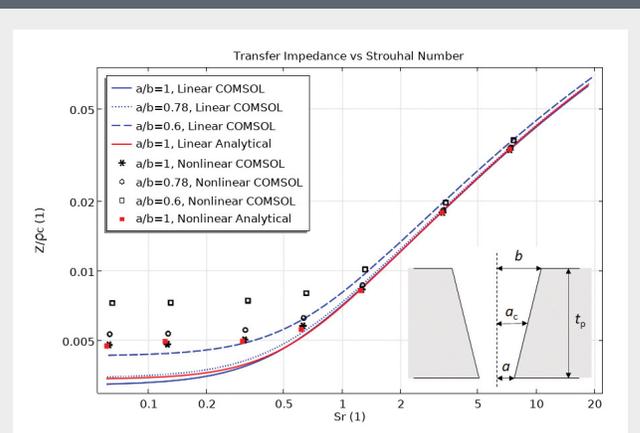
$Sr$  (a nondimensional measure of the degree of nonlinearity, where a smaller  $Sr$  represents a more nonlinear system). The number also depends on the excitation frequency and the dimension of the perforate. Nonlinear effects will be more important at lower frequencies and for smaller perforations.

For some simple perforation geometries, such as cylinders in a regular pattern, there are analytical and semianalytical models for computing the transfer impedance. The models include descriptions of the viscous (and thermal) losses, end correction approximations, hole-hole interaction models, approximate nonlinear effects, and the presence of a bias or grazing flow.

Using a detailed thermoviscous acoustics simulation model, the analytical approximations and the restrictions on the geometry can be surpassed. Detailed transfer impedance data can be simulated within minutes, for example, if the perforations are tapered, as seen in **Figure 1** (COMSOL, 2021). There is generally no restriction on the geometric configuration. The system of equations is solved with the COMSOL Multiphysics® software using the *Thermoviscous Acoustics* physics interface for the linear analysis (COMSOL, 2020). Nonlinear effects can be included using the *Nonlinear Thermoviscous Acoustic Contributions* feature. The model is based on the finite element formulation using a Galerkin least square stabilization technique. The governing equations are the full set of acoustic nonlinear first-order perturbation equations.

The transfer impedance for a specific setup (0.4 mm perforation center radius  $a_c$  and 1 mm plate thickness  $t_p$ ) for the tapered perforation geometry is depicted in **Figure 2**. The impedance is depicted as a function of the Strouhal number. The results are given for three tapering angles defined by the ratio of  $a/b$  (see inset in **Figure 2**). The COMSOL Multiphysics® simulation results comprise linear and nonlinear model results (blue lines and black symbols). For comparison, linear and nonlinear (Temiz et al., 2016) analytical models are also depicted (red line and red dots). The analytical models are only valid for a cylindrical perforate (when  $a/b = 1$ ).

For many acoustics applications, it is important to know the transfer impedance of a perforate in order to control the damping properties. Using simulation, it is possible to get highly accurate transfer impedance data for all perforate configurations and



**Figure 2.** The transfer impedance as a function of the Strouhal number for a plate thickness  $t_p = 1$  mm and a perforation center radius  $a_c = 0.4$  mm. The blue lines represent the linear simulation results (three tapering configurations) and the red line represents the nontapered analytical model. The black symbols represent the nonlinear simulation results (three tapering configurations) and the red dots represent the nontapered semianalytical model.

hole geometries in a short amount of time. Acquiring the same experimental data is time consuming, and variations in the geometry require many test specimens. Analytical models are fast but restricted to a few simple geometries. The computed transfer impedance values can then, for example, be tabulated and used in a larger system simulation as a boundary condition or in a lumped model. The flexibility of simulations gives engineers the possibility to test and optimize many designs in a time-efficient manner.

## References

- COMSOL (2020). Acoustics Module, COMSOL Multiphysics, Version 5.6, 2020. <https://www.comsol.com/acoustics-module>. Accessed April 29th 2021.
- COMSOL (2021). "Nonlinear Transfer Impedance of a Perforate", COMSOL, 2021. <https://www.comsol.com/model/99471>. Accessed April 29th 2021.
- Temiz, A., Tournadre, J., Arteaga, I.L., and Hirschberg, A. (2016). "Non-linear acoustic transfer impedance of micro-perforated plates with circular orifices?" *The Journal of Sound and Vibration*, 366, 418-428.
- Vorländer, M. (2020). "Are Virtual Sounds Real," *Acoustics Today*, 16(1), 46-54.

## About the Author



### Mads Herring Jensen

mads@comsol.dk

COMSOL A/S

Diplomvej 373, 2000 Kgs. Lyngby,  
Denmark

Mads Herring Jensen joined COMSOL in 2011 and is the technology manager

for the acoustics products. Mads has a PhD in computational fluid dynamics from the Technical University of Denmark. Before joining COMSOL, Mads worked in the hearing aid industry for five years as an acoustic finite element expert.