Acoustic Indicators for Targeted Detection of Stored Product and Urban Insect Pests by Inexpensive Infrared, Acoustic, and Vibrational Detection of Movement

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ABSTRACT Crawling and scraping activity of three stored-product pests, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), and *Stegobium paniceum* (L.) (Coleoptera: Anobiidae), and two urban pests, *Blattella germanica* (L.) (Blattodea: Blattellidae) and C*imex lectularius* L. (Hemiptera: Cimicidae), were monitored individually by infrared sensors, microphones, and a piezoelectric sensor in a small arena to evaluate effects of insect locomotory behavior and size on the ability of an inexpensively constructed instrument to detect insects and distinguish among different species. Adults of all species could be detected when crawling or scraping. The smallest insects in the study, first-fourth-instar *C. lectularius* nymphs, could not be detected easily when crawling, but could be detected when scraping. Sound and vibration sensors detected brief, 3–10-ms impulses from all tested species, often grouped in distinctive trains (bursts), typical of impulses in previous acoustic detection experiments. To consider the potential for targeting or focusing detection on particular species of interest, indicators were developed to assess the likelihood of detection of *C. lectularius*. Statistically significant differences were found between *C. lectularius* and other species in distributions of three measured variables: infrared signal durations, sound impulse-burst durations, and sound pressure levels (energy) of impulses that best matched an averaged spectrum (profile) of scraping behavior. Thus, there is potential that signals collected by an inexpensive, polymodal-sensor instrument could be used in automated trapping systems to detect a targeted species, 0.1 mg or larger, in environments where servicing of traps is difficult or when timeliness of trapping information is important.

KEY WORDS bed bug, cockroach, rice weevil, red flour beetle, drugstore beetle

Insect traps are highly varied in purpose, cost, and information they provide deployers (Epsky et al. 2008). Automated traps could be of particular benefit in circumstances where insect inspection is labor-intensive or servicing of traps is difficult (California Department of Food and Agriculture 2005, Wang et al. 2009), or when control measures could be enhanced by timely identification of an early infestation (Mankin et al. 2006). Efforts have been conducted by numerous researchers, including contributions from Spangler (1985), Shuman et al. (1997, 2004), Arbogast et al. (2000), Engel and Wyttenbach (2001),Tauber and Eberl (2003), Fleurat-Lessard et al. (2006), Frommolt et al. (2008), Dankert et al. (2009), and Siriwardena et al. (2010), to develop electronics, signal analyses, and decision tools for automated detection and monitoring. Widespread adoption of such technology for insect trapping has been limited, however, by factors such as high costs of instrumentation, high complexity, and uncertain reliability of automated detection technology and software, and by the significant training and understanding required to install and service automated traps and then to interpret the information they provide.

For this report, we addressed factors of instrumentation costs and complexity that have limited the incorporation of electronic and information technology into insect traps. An insect monitoring instrument was constructed using readily available infrared, acoustic, and vibration sensors and inexpensive high-gain amplifiers. Movements of different-sized stored-product and urban insect pests were monitored in a small arena to determine typical ranges of amplitudes, spectral patterns, and temporal patterns of detected signals.

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Table 1. Mean body length, width, and thickness, and mean lengths of femurs and tibias of three adults of each species in arena bioassays, ordered by increasing body length

Species	Dimensions (mm)								
	Body			Front leg		Middle leg		Rear leg	
	Length	Width	Height	Femur	Tibia	Femur	Tibia	Femur	Tibia
S. paniceum	2.80 ± 0.07	1.22 ± 0.03	1.06 ± 0.03	0.51 ± 0.01	0.48 ± 0.01	0.52 ± 0.01	0.48 ± 0.02	0.50 ± 0.00	0.48 ± 0.01
T. castaneum	3.69 ± 0.02	1.23 ± 0.03	0.86 ± 0.02	0.54 ± 0.01	0.50 ± 0.00	0.58 ± 0.02	0.55 ± 0.01	0.71 ± 0.01	0.64 ± 0.02
C. lectularius	4.15 ± 0.06	2.66 ± 0.08	0.67 ± 0.04	1.02 ± 0.04	1.05 ± 0.13	0.94 ± 0.03	0.92 ± 0.02	1.07 ± 0.02	1.32 ± 0.02
S. oryzae	4.19 ± 0.01	1.19 ± 0.04	0.95 ± 0.00	1.03 ± 0.03	0.74 ± 0.01	0.77 ± 0.03	0.50 ± 0.00	0.88 ± 0.04	0.57 ± 0.01
B. germanica	11.34 ± 0.55	4.15 ± 0.00	2.16 ± 0.17	1.94 ± 0.06	1.60 ± 0.06	2.60 ± 0.06	2.66 ± 0.00	3.10 ± 0.15	4.15 ± 0.2

Three types of movement were analyzed separately to consider whether visually distinctive activities produced correspondingly distinctive sounds: wriggling (rapid turning without net movement in any direction, or returning to an upright position after a fall), scraping (shuffling or other activities that involve tangential, frictional contact and movement across the arena surface), and crawling (running, walking, or tapping of feet, primarily involving normal or vertical impacts on the arena surface). The sound, vibration, and infrared signals were examined for their potential to distinguish among the different species tested using readily available signal processing software.

Insects tested in this study included adults of three stored-product pests (Hagstrum and Subramanyam 2006, Phillips and Throne 2010)—rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae); red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae); and drugstore beetle, *Stegobium paniceum* (L.) (Coleoptera: Anobiidae)—listed in order of decreasing size (Table 1), and adults of two urban insect pests—German cockroach, *Blattella germanica* (L.) (Blattodea: Blattellidae) (Schal and Hamilton 1990), and bed bug, *Cimex lectularius* L. (Hemiptera: Cimicidae) (Usinger 1966, Anderson et al. 2009). To consider the effects of size on detectability, unfed instars 1–5, as well as fed fifth instars of *C. lectularius* nymphs also were bioassayed. The occurrence of different combinations of sound, vibration, and infrared signal features then was used to assess the likelihood that a particular species, in this case, *C. lectularius,* was detected in the arena.

Materials and Methods

Insects, Bioassay Arena, and Sensors. The insects tested in this study covered a 10-fold range of weights, and approximately a five-fold range of body and leg sizes (Tables 1 and 2). Their different locomotory activities produced acoustic and vibrational signals of variable patterns with a ≈10-fold range of amplitudes, enabling comprehensive analysis of the range and sensitivity of the insect detection instrument. Adult *T. castaneum*, *S. oryzae*, and *S. paniceum* were obtained from rearing facilities at the Center for Medical, Agricultural, and Veterinary Entomology (CMAVE). Adult male C. *lectularius* and *B. germanica* were obtained from rearing facilities at North Carolina State University (NCSU) and the University of Florida (UF). Instars 1–5 of *C. lectularius* nymphs were obtained from the UF rearing facility.

Bioassays were conducted in a 150- by 20- by 15-mm arena whose four vertical walls were constructed from transparent, 1-mm-thick acrylic. A 150- by 20-mm by 2-mm piece of acrylic formed the base (Fig. 1). Two 15-mm-diameter holes (dotted circles in Fig. 1) were cut into the base so that they centered over two omnidirectional, electret condenser microphones (6 mm in diameter, 1.3 mm in height, −45-dB sensitivity; model WM-63-PR, Panasonic Corp., Osaka, Japan) mounted 32 mm apart on a customized circuit board (ExpressPCB, Mulino, OR). Plastic film was stretched over the holes to increase the effective sensitivity of the microphones to crawling movements that insects of all tested species were observed to perform. Two pairs of infrared emitters and matched phototransistor detectors (model 276-142, Radio Shack, Ft. Worth, TX) were mounted on the circuit board, positioned so that each emitter pointed directly across two arena walls to its matching detector, 20 mm opposite. The spacing between emitters (and detectors) was 8.5 mm, and both pairs were mounted 4 mm above the arena floor.

Table 2. Mean weights, body lengths, widths, and thicknesses, and mean lengths of femurs and tibias of three *C. lectularius* nymphs tested in arena bioassays, ordered by increasing body length

Instar; wt (mg)	Dimensions (mm)								
	Body			Front leg		Middle leg		Rear leg	
	Length	Width	Ht	Femur	Tibia	Femur	Tibia	Femur	Tibia
1; 0.08 ± 0.01	1.23 ± 0.05	0.73 ± 0.01	0.26 ± 0.01	0.38 ± 0.00	0.35 ± 0.00	0.38 ± 0.00	0.36 ± 0.01	0.39 ± 0.01	0.44 ± 0.01
2; 0.17 ± 0.01	1.48 ± 0.01	0.78 ± 0.05	0.27 ± 0.02	0.39 ± 0.01	0.36 ± 0.02	0.39 ± 0.02	0.39 ± 0.02	0.39 ± 0.01	0.48 ± 0.03
3; 0.28 ± 0.01	2.49 ± 0.25	1.39 ± 0.06	0.55 ± 0.03	0.65 ± 0.05	0.57 ± 0.01	0.57 ± 0.01	0.63 ± 0.03	0.65 ± 0.04	0.84 ± 0.05
4; 0.54 ± 0.12	3.06 ± 0.17	1.79 ± 0.12	0.67 ± 0.07	0.78 ± 0.04	0.70 ± 0.01	0.71 ± 0.04	0.75 ± 0.01	0.80 ± 0.00	1.03 ± 0.05
5; 1.15 ± 0.24	3.61 ± 0.06	2.17 ± 0.01	0.6 ± 0.00	0.84 ± 0.04	0.8 ± 0.00	0.88 ± 0.06	0.85 ± 0.01	1.01 ± 0.01	1.2 ± 0.00

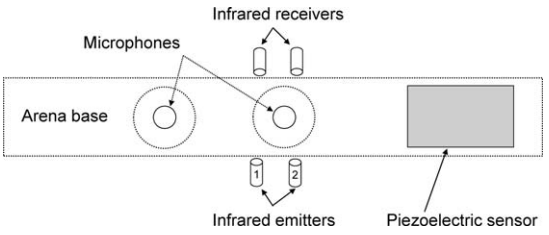

Fig. 1. Relative positions of microphone and infrared and piezoelectric sensors in bioassay arena.

A piezoelectric sensor (15 by 30 mm, 15 mV/μm displacement; Measurement Specialties Corp., Hampton, VA) was positioned horizontally at one end of the arena base. The sensor housing was clamped to the base with adhesive tape, enabling the piezoelectric element to float ≈1 mm above the base. Insects could crawl on the piezoelectric element or underneath on the floor, dorsally scraping the bottom of the element.

It should be noted that the infrared sensors detected only those insects that entered the infrared beam, the piezoelectric sensor detected primarily the insects that contacted it, and each microphone detected primarily the insects that crawled over the plastic film above it. In several bioassays, an infrared receiver and a microphone detected the insect simultaneously, and in bioassays with *B. germanica* or *S. oryzae*, the movements were vigorous enough to excite vibrations in the piezoelectric sensor without direct contact. In these instances, vibrations were induced where the piezoelectric element was attached to the arena base.

Signal Amplification and Recording. Integrated circuits (nine total), capacitors (20), potentiometers (10), and resistors (40), were mounted and connected on the circuit board (Fig. 2) to provide user-adjustable amplification of the sensor-produced signals. The microphone signals were combined by subtracting one from the other, as in Aubin et al. (2000), to cancel background noise detected at both sensors and enable amplification primarily of signals recorded at the microphone over which the insect was moving. As a result, it was possible to conduct tests in a typical office or laboratory environment by using a 100-Hz, high-pass filter to reduce low-frequency background noise, and by screening out speech using spectral profile techniques described under Digital Signal Processing.

An output connector was mounted on the circuit board with a matching cable that transmitted the infrared-, sound-, and vibration-sensor signals to a general-purpose data acquisition system (±10 V, 14-bit: USB-6009, National Instruments, Austin, TX). The amplifications of the infrared, sound, and vibration signals were set initially at levels that enabled detection of signals typically produced by *B. germanica* adults without exceeding the maximum input to the data acquisition system. These settings were used for the entire study.

Signals were collected at a sampling rate of 10 kHz and stored on computer using SignalExpress 2.0 (LabVIEW, National Instruments) software. A custom program, written in Matlab 7.7 (The MathWorks, Natick, MA), converted the digitized signals from .txt- or .tdms-format to .wav-format.

Bioassays were conducted for 30-s periods, beginning when an insect initiated movement after transfer by forceps to the center of the arena. The *B. germanica* and *S. paniceum* usually escaped rapidly from an open arena, so the top was secured with plastic film after these insects were transferred. The insects were monitored with a video camera (model HDR-SR1, Sony, Tokyo, Japan) after transfer, and in initial studies, insects that did not move toward a sensor within 1 min after being placed in the arena were discarded and

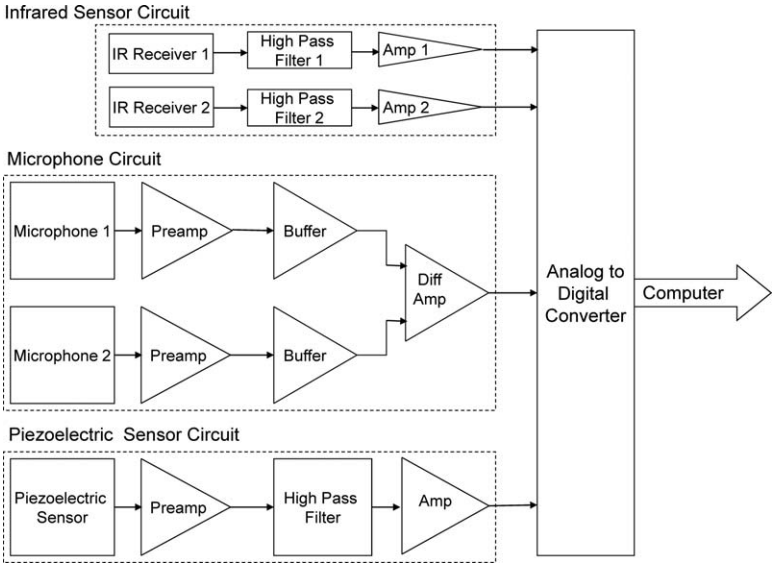

Fig. 2. Diagram of arena sensor circuits (IR, infrared; Amp, amplifier; Preamp, preamplifier; Buffer, voltage buffer for transfer from high to low impedance; Diff Amp, differential amplifier).

replaced, as well as those that were not detected by two or more sensors within 30 s. This procedure usually worked well for *B. germanica*, *S. paniceum*, and *S. oryzae* but resulted in failure of many tests with *C. lectularius* and *T. castaneum*, which often avoided the sensors or ceased movement for long periods. A revised procedure was implemented to reduce the number of failed tests by using a recording options feature of the SignalExpress software that triggered a 30-s period of recording beginning when the signal from any sensor exceeded a preset threshold. In these tests, the thresholds were set at 10% of maximum amplitude at the sound and vibration sensors.

Bioassays were conducted in several offices and laboratories at NCSU and CMAVE with different levels of background noise. In general, although we avoided testing during periods of extreme noise, the effects of background noise were minimal, due to subtraction of signals of one microphone from those of the other.

Ultimately, signals were collected and analyzed from 30 separate *C. lectularius*, 15 *B. germanica*, eight *S. oryzae*, six *T. castaneum*, and five *S. paniceum* adults, and 10 each of first–fifth-instar *C. lectularius* nymphs. In a significant fraction of trials with first–fourth instars, the crawling movements of the nymphs after initial triggering of a recording were too weak to produce sounds or vibrations adequate for feature identification analysis (see below). Consequently, to obtain enough replications for feature identification analyses, we merged the records from first–fourth-instar bioassays together into a single category.

For analyses of the effects of insect size on signal features, the body and leg sizes of three nymphs of each instar were measured using a stereo microscope (model X100, Olympus, Center Valley, PA) at magnifications between 16 and 50, and weights were measured with a microbalance (model UMT2, Mettler, Columbus, OH). It should be noted that the weights of *C. lectularius* nymphs and adults can increase 1.5–5-fold immediately after feeding (Usinger 1966), and these measurements were taken from individuals that did not have expanded abdomens indicative of recent feeding.

Digital Signal Processing and Feature Identification. Playbacks and signal overviews were performed using Raven 1.3 software (Charif et al. 2008) to discard intervals of background noise, talking, and other extraneous signals, and to identify signal features that distinguished different pest species. The acoustic and vibrational records of all tested species contained groups (trains) of brief, 3–10-ms impulses or ticks, similar to those described in previous insect acoustic detection studies (Zhang et al. 2003a,b; Mankin et al. 2008a,b). Trains of five or more impulses separated by >1-s intervals usually corresponded to separate passes of the insect across a sensor and were designated as bursts (Mankin et al. 2008a,b). The temporal patterns and spectral features of impulses and impulse trains detected in the acoustic and vibrational recordings were analyzed with custom-written software Digitize, Analyze, and Visualize Insect Sounds (DAVIS) Mankin 1994, Mankin et al. 2000).

Based on video monitoring and initial overviews of the infrared-, acoustic-, and vibration-sensor signals, analyses were conducted on acoustic signals associated with distinctive wriggling, scraping, and crawling behaviors that individuals of different species performed at different rates during bioassays. Individuals of all the tested species performed all of these behaviors, but *T. castaneum*, for example, produced a preponderance of wriggling behaviors, *B. germanica* crawled or ran primarily, and *C. lectularius* individuals scraped or shuffled more often than they crawled.

Three different profiles (averaged spectra of a series of insect sound impulses, see Mankin et al. 2000, Mankin and Benshemesh 2006) were calculated for analysis of sounds recorded during different behaviors. A profile of signals produced during wriggling behavior by a *T. castaneum* adult was calculated from 107 impulses recorded during a 2-s period free of background noise. A profile of signals produced by a scraping *C. lectularius* adult was calculated from 62 impulses recorded in 4 s. A profile of signals produced by a crawling *B. germanica* adult was calculated from 38 impulses recorded in a 5-s interval. For each profile, the spectrum of each impulse was constructed from a 6-ms time slice centered on the peak amplitude (Mankin et al. (2000).

Further analyses also were conducted on scraping vibrations produced by *C. lectularius* nymphs and adults. The piezoelectric sensor had greater sensitivity than the microphone; consequently, it detected more reliably the weak sounds produced by first–fourth instars. The signals detected by the sound and vibration sensors from *C. lectularius* nymphs and adults otherwise were similar in spectral and temporal pattern. Three additional profiles were calculated for analysis of scraping vibrations produced by *C. lectularius* first instars (178 impulses in a 23-s period), third instars (300 impulses in 8 s), and adults (64 impulses in 12 s).

The full set of records recorded by microphone from adult stored-product and urban pest species was analyzed in DAVIS by using the wriggling, scraping, and crawling profiles, discarding impulses whose spectra failed to match any profile within an empirically determined difference threshold, T_s (Mankin et al. 2008a). The impulse occurrence times were labeled by DAVIS according to which of the three profiles they matched best, and were saved in an impulse-sequence spreadsheet. The *C. lectularius* nymph and adult signals recorded with the vibration sensor were analyzed similarly, by using the first-instar, third-instar, and adult scraping vibration profiles.

Automated Assessment of Likelihood of *C. lectularius* Detection. A goal of the study was to identify easily measured features in signals from different sensors that could be used to automate detection of individuals of different species. The species, *C. lectularius*, was selected as an example of a potential target of interest that might be detected even when other species could enter the arena. Several char-

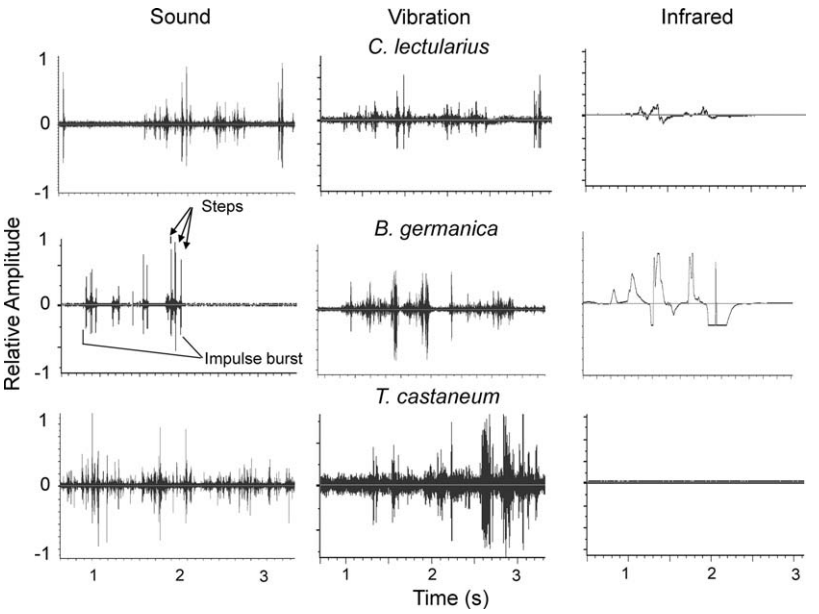

Fig. 3. Examples of separate 3-s intervals of signals produced by individual *C. lectularius*, *B. germanica*, and *T. castaneum* adults during 30-s recordings of sound, vibration, and infrared signals. A 1-s impulse burst is shown in the *B. germanica* sound trace.

acteristics of the signals were considered, including the durations of infrared signals and sound impulse bursts, the rates of impulses within sound impulse bursts, and impulse sound pressure levels (Mankin et al. 2000). Preliminary analyses of the bioassay results suggested that, for each 30-s bioassay, the magnitudes of the median infrared signal duration, *MIRD* (s), the longest impulse burst duration, *LIBD* (s), and the mean sound pressure level of sound impulses that matched the *C. lectularius* scraping profile, *SPLC* (dB), were distributed nonuniformly across species, and consequently were candidates for acoustic indicators that could automate assessment of detection likelihood.

To consider an initial example of the feasibility of using the detection instrument for automated assessment, we constructed an indicator (Mankin et al. 2007) for each nonuniformly distributed signal feature above and summed the three indicators to obtain an overall assessment of the likelihood of *C. lectularius* detection, i.e.,

$$i_{MRD} = \begin{cases} 1 & \text{if } MIRD < \text{MIRD}_{\min} \\ 0 & \text{if } MIRD \geq \text{MIRD}_{\min} \text{ and} \leq \text{MIRD}_{\max} \\ -1 & \text{if } MIRD > \text{MIRD}_{\max}, \end{cases}$$

$$i_{LIBD} = \begin{cases} -1 & \text{if } LIBD > \text{LIBD}_{\max} \\ 0 & \text{otherwise, and} \end{cases}$$

$$i_{SPLC} = \begin{cases} 1 & \text{if } SPLC < \text{SPLC}_{\max} \\ 0 & \text{otherwise.} \end{cases} \quad [1]$$

$$i_{CL} = \begin{cases} \text{l}_{\text{ow}} & \text{if } i_{MIRD} + i_{LIBD} + i_{SPLC} < 1 \\ \text{m}_{\text{edium}} & \text{if } i_{MIRD} + i_{LIBD} + i_{SPLC} = 1 \\ \text{h}_{\text{igh}} & \text{if } i_{MIRD} + i_{LIBD} + iSPLC > 1, \end{cases} \quad [2]$$

where i_{MIRD} is the indicator variable for median infrared signal duration (MIRD), $\text{MIRD}_{\min}$ and $\text{MIRD}_{\max}$ are lower and upper MIRD threshold values, respectively; i_{LIBD} is the indicator value for longest impulse burst duration (LIBD), and $\text{LIBD}_{\max}$ is the LIBD upper threshold value; i_{SPLC} is the indicator variable for the mean sound pressure level of sound impulses that matched the *C. lectularius* scraping profile (SPLC), and $\text{SPLC}_{\max}$ is the upper SPLC threshold value; and i_{CL} is the indicator variable for the likelihood that a *C. lectularius* is detected in the arena, taking the values l_{ow}, m_{edium}, and h_{igh}. The selections of these particular indicators and thresholds are described more completely in Results. It should be noted that other indicators and thresholds might be preferable if the goal was to detect a species other than *C. lectularius.*

Finally, the distributions of l_{ow}, m_{edium}, and h_{igh} likelihood of *C. lectularius* detection were compared across bioassays with or without *C. lectularius* using the Wilcoxon two-sample exact test (Proc NPAR1WAY, SAS Institute 2004) under the null hypothesis that the distributions were independent of whether the arena contained a *C. lectularius.*

Results

Observations of the bioassays during recordings from all tested species revealed frequent occurrences

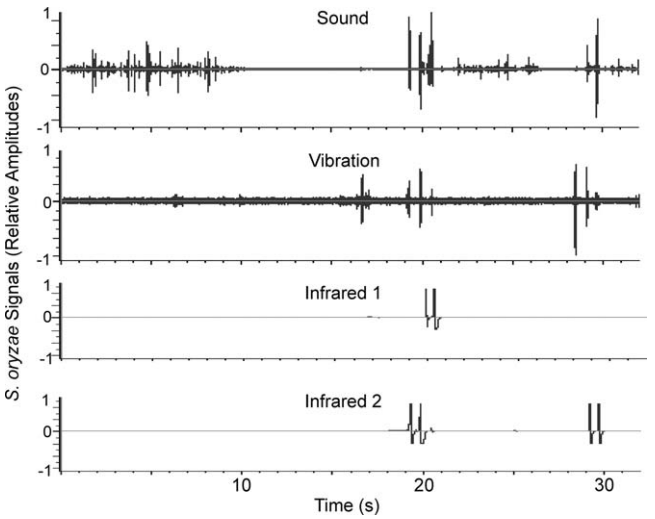

Fig. 4. Traces of sounds, vibrations, and infrared signals detected over a 32-s period from an adult *S. oryzae* in bioassay arena.

of wriggling, scraping, and crawling movements that produced distinctive acoustic and vibrational signals. Examples of each behavior are shown in Fig. 3. The signals in the three columns were from three separate 3-s intervals in a 30-s bioassay of a scraping *C. lectularius*, a running *B. germanica*, and a wriggling *T. castaneum*. In the *T. castaneum* bioassay, the beetle never crossed the infrared beam, and the signal displayed is from the last 3 s of the recording.

At least one adult of all species except *T. castaneum* triggered infrared signals during their bioassays by crawling on the arena base or walls. None of the *C. lectularius* nymphs, however, crossed the infrared beam during their bioassays. They were too short to reach the bottom of the sensor field of view (Table 2), and they never climbed high enough on a wall.

All of the species tested in the arena produced at least a few sound-impulse and vibration-impulse bursts similar to those in Fig. 3. During many of the observed crawling periods, including the sound trace from *B. germanica* in Fig. 3, individual steps or footfalls often were distinguishable as short, high-amplitude ticks. More steps were observed from the larger, *B. germanica*, *S. oryzae*, and *C. lectularius* adults, than from the smaller, *T. castaneum* and *S. paniceum* adults and the *C. lectularius* nymphs. The smallest, first–third instars sometimes did not trigger the microphone while crawling, especially the first instars, but usually triggered a signal if they performed wriggling or scraping behaviors on a microphone or vibration sensor.

The behaviors observed most frequently in the arena were intermittent crawling and resting, examples typical of which are shown in Fig. 4, recorded from an *S. oryzae*. Particularly vigorous activity by an insect near the center of the arena often triggered sounds and vibrations simultaneously. The *B. germanica* triggered vibrations whenever they ran or crawled quickly anywhere in the arena. Signals collected simultaneously with the sound and vibration sensors from a crawling *S. paniceum* adult are displayed in Fig. 5, where impulse trains in the traces from each sensor are expanded in 0.3-s insets. Individual steps or other impacts appear distinctly in the impulse train in the sound inset, but equivalent impacts are not easily discerned in the vibration inset because the durations of impulses were longer than the intervals between them. Profiles of the vibration impulses (mean of 113), and sound impulses (mean of 104) are displayed in Fig. 6. Only minor differences appear in the spectral patterns of the profiles except in a range between 400 and 800 Hz, where the relative signal level was higher for the vibration than the sound profile.

Similarly, minor differences appear in comparisons of the spectral patterns of sounds by different species performing crawling, wriggling, and scraping behaviors, as seen in the spectral profiles of Fig. 7. The crawling sounds produced by *B. germanica* are very similar to the *S. paniceum* crawling sounds in Fig. 6. The sounds produced by a wriggling *T. castaneum* and a scraping *C. lectularius* have slightly greater energy than in the crawling signals at frequencies between 800 and 3,000 Hz, but these differences are not enough to reliably distinguish the three behaviors. Consequently, when the sound impulses from all insects were tested against the three profiles in Fig. 7 by using DAVIS, multiple matches of each profile were found in each recording.

Although wriggling was visually distinctive as a behavior, the similarity of the wriggling and scraping spectra in Fig. 7, and the finding that adults of all tested species produced multiple sounds that matched wriggling, scraping, and crawling profiles, suggested that wriggling and scraping were acoustically indistinguishable and led us to focus subsequent analyses primarily on crawling and scraping behaviors. For *C. lectularius*, we focused analysis primarily on scraping behaviors, given that the crawling sounds produced by

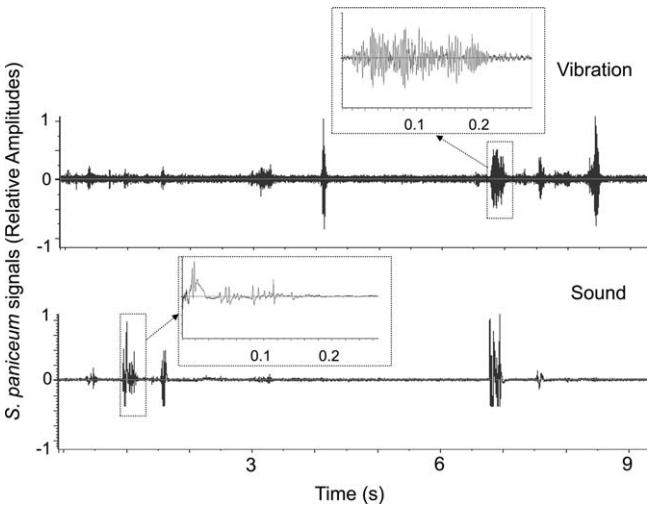

Fig. 5. Comparison of vibrations and sounds recorded simultaneously from an *S. paniceum* adult, with insets showing 0.3-s expansions of impulse bursts recorded from each sensor.

small nymphs did not always produce analyzable signals.

An effect of insect size is seen in Fig. 8 in comparisons of profiles of scraping vibrations produced by a *C. lectularius* first instar, third instar, and adult. The adult produced relatively lower frequency impulses than the first instar. Also, in comparisons across *C. lectularius* stages, the mean vibration level of impulses that best matched the first-instar scraping profile was lower for instars 1–4 (69.8 ± 1.2 dB, $N = 6$) and fifth-instar nymphs (69.4 ± 0.5 dB, $N = 8$) than for adults (77.1 ± 2.3 dB, $N = 10$) under the Waller–Duncan K-ratio test ($F = 6.59$; df = 2, 21; $P = 0.006$) (SAS Institute 2004). The fraction of impulses that matched the adult profile was significantly lower for instars 1–4 (0.16 ± 0.05, $N = 6$) than for the fifth-instar nymphs (0.48 ± 0.08, $N = 8$) and the adults (0.48 ± 0.05, $N = 10$) under the Waller–Duncan K-ratio test ($F = 5.82$; df = 2, 21; $P = 0.01$) (SAS Institute 2004).

Given the observed similarities of sound and vibration spectra, and the observed similarities of sound spectra from adults of different insect species performing different behaviors, it did not seem likely that these could be used to distinguish among the different species in the arena. We therefore considered whether signals from different species might be distinguished on the basis of other signal features, including those from the infrared sensors.

Signal Feature Analyses. Several easily measured characteristics of the signals were tested as potential features for distinguishing among the different insect species in the arena, including median infrared signal duration, *MIRD;* longest impulse burst duration, *LIBD;* and magnitude of *C. lectularius* profile sound pressure level, *SPLC.* The magnitudes of these signal measures were not distributed uniformly across species, as can be seen in the *MIRD*, *LIBD*, and *SPLC* columns of Tables 3, 4, and 5; consequently, it was feasible to set thresholds for indicators, i_{MIRD}, i_{LIBD}, and i_{SPLC}, that assessed the likelihood of *C. lectularius* detection (see

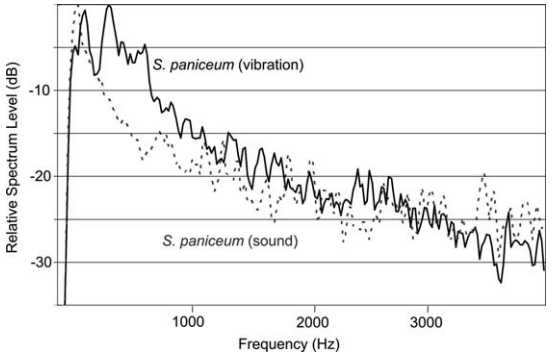

Fig. 6. Spectral profiles of signals of a crawling *S. paniceum* adult detected by sound and vibration sensors.

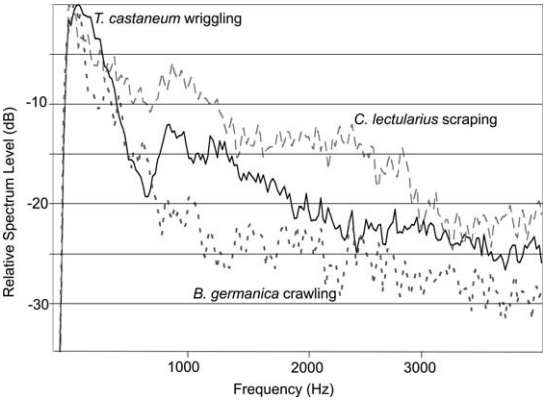

Fig. 7. Spectral profiles of sounds associated with wriggling, scraping or shuffling, and crawling or running. Sound pressure levels of the *C. lectularius* scraping profile were used in assessing likelihood of *C. lectularius* detection (i_{CL}).

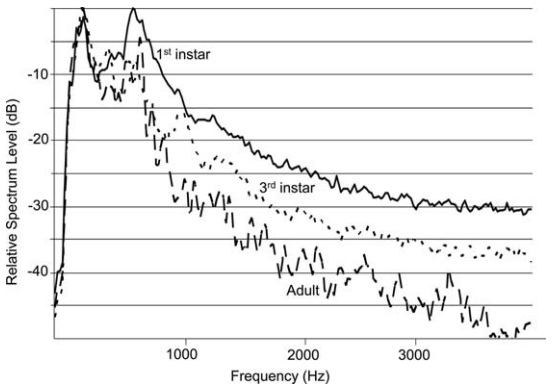

Fig. 8. Spectral profiles of vibrations produced by a *C. lectularius* first instar, third instar, and adult.

equations 1 and 2). The *MIRD* of *C. lectularius* was typically $<\text{MIRD}_{\text{min}} = 0.2$ s and exceeded $\text{MIRD}_{\text{max}} = 0.75$ s in only one of 30 tests. The *LIBD* of *C. lectularius* exceeded $\text{LIBD}_{\text{max}} = 10$ s in only four tests, and the *SPLC* exceeded $\text{SPLC}_{\text{max}} = 70$ dB in only two tests. The magnitudes of these signal features were often outside such thresholds in bioassays with other species.

Table 3. Features of *C. lectularius* sounds considered for automated species identification (median infrared signal duration, MIRD; longest impulse burst duration, LIBD; and magnitude of *C. lectularius* profile sound pressure level, SPLC); their associated indicator values (i_{MIRD}, i_{LIBD}, and i_{SPLC}); and the assessed likelihood of *C. lectularius* detection in arena, i_{CL}, arranged in order of increasing likelihood, i_{CL}, and SPLC

MIRD (s)	*LIBD* (s)	*SPLC* (dB)	i_{MIRD}	i_{LIBD}	i_{SPLC}	i_{CL}
0.825	3	59.91	−1	0	1	l_{ow}
0.352	3	55.13	0	0	1	m_{edium}
0.21	4	60.12	0	0	1	m_{edium}
0.553	4	62.82	0	0	1	m_{edium}
0.169	19	63.57	1	−1	1	m_{edium}
0	15	63.82	1	−1	1	m_{edium}
0	17	64.5	1	−1	1	m_{edium}
0.546	9	64.76	0	0	1	m_{edium}
0.569	5	64.88	0	0	1	m_{edium}
0.598	9	64.94	0	0	1	m_{edium}
0.585	4	65.7	0	0	1	m_{edium}
0	14	67.01	1	−1	1	m_{edium}
0	5	70	1	0	0	m_{edium}
0	5	71.67	1	0	0	m_{edium}
0	5	61.15	1	0	1	h_{igh}
0	3	62.48	1	0	1	h_{igh}
0	5	62.54	1	0	1	h_{igh}
0	3	62.93	1	0	1	h_{igh}
0	9	63.7	1	0	1	h_{igh}
0	7	63.8	1	0	1	h_{igh}
0.175	2	64.32	1	0	1	h_{igh}
0	6	64.68	1	0	1	h_{igh}
0.171	8	65.39	1	0	1	h_{igh}
0.022	7	65.49	1	0	1	h_{igh}
0	4	65.55	1	0	1	h_{igh}
0	3	65.69	1	0	1	h_{igh}
0	6	66.17	1	0	1	h_{igh}
0	2	67.63	1	0	1	h_{igh}
0.195	1	68.34	1	0	1	h_{igh}
0	3	68.62	1	0	1	h_{igh}

Table 4. Signal features of *B. germanica* sounds (see Table 3); their associated indicator values (i_{MIRD}, i_{LIBD}, and i_{SPLC}); and the assessed likelihood of *C. lectularius* detection in arena, i_{CL}, arranged in order of increasing likelihood, i_{CL}, and SPLC

MIRD (s)	*LIBD* (s)	*SPLC* (dB)	i_{MIRD}	i_{LIBD}	i_{SPLC}	i_{CL}
1.208	5	65.37	−1	0	1	l_{ow}
0.888	9	66.73	−1	0	1	l_{ow}
0.762	7	67.76	−1	0	1	l_{ow}
0.875	8	68.59	−1	0	1	l_{ow}
0.586	9	70.01	0	0	0	l_{ow}
0.504	5	70.32	0	0	0	l_{ow}
0.577	6	71.07	0	0	0	l_{ow}
0.442	3	72.05	0	0	0	l_{ow}
0.993	4	73.13	−1	0	0	l_{ow}
0.633	7	73.3	0	0	0	l_{ow}
0.717	3	73.45	0	0	0	l_{ow}
0.963	5	73.7	−1	0	0	l_{ow}
0.641	5	74.04	0	0	0	l_{ow}
0.925	3	74.07	−1	0	0	l_{ow}
0	3	65.4	1	0	1	h_{igh}

The values of i_{MIRD}, i_{LIBD}, and i_{SPLC} based on the above thresholds of MIRD_{min}, MIRD_{max}, LIBD_{max}, and SPLC_{max}, and the resultant assessments of the likelihood of *C. lectularius* detection, i_{CL}, are listed in the last four columns of Tables 3–5. Inspection of the tables suggests that the three indicators distinguish individually between the presence of *C. lectularius* and other insects less reliably than does the sum of the indicators, i_{CL}. Considering values of i_{CL} and i_{MIRD} for example, more than 50% of the *C. lectularius* tests were ranked h_{ign} for i_{CL}, and similarly were ranked at the highest level of i_{MIRD}. However, <10% of tests with other species were ranked h_{ign} for i_{CL}, although 50% of other species tests were ranked at the highest level of i_{MIRD}, a considerably higher fraction of false positives. The indicator for i_{MIRD} is not sufficient by itself to distinguish between species in the arena, and similar arguments can be presented for i_{LIBD}, and i_{SPLC}.

Table 5. Signal features of stored product insect sounds (see Table 3); their indicator values (i_{MIRD}, i_{LIBD}, and i_{SPLC}); and the assessed likelihood of *C. lectularius* detection in arena, i_{CL}, arranged in order of increasing likelihood, i_{CL}, and *SPLC*

Species	*MIRD* (s)	*LIBD* (s)	*SPLC* (dB)	i_{MIRD}	i_{LIBD}	i_{SPLC}	i_{CL}
S. oryzae	0.203	21	66.24	0	−1	1	l_{ow}
S. oryzae	0.3	10	67.33	0	−1	1	l_{ow}
S. paniceum	0.317	6	70.28	0	0	0	l_{ow}
S. oryzae	0.308	8	71.34	0	0	0	l_{ow}
S. paniceum	0.243	8	72.18	0	0	0	l_{ow}
T. castaneum	0	29	61.56	1	−1	1	m_{edium}
S. oryzae	0	14	63.86	1	−1	1	m_{edium}
S. oryzae	0.31	9	64.48	0	0	1	m_{edium}
T. castaneum	0	29	65.45	1	−1	1	m_{edium}
S. oryzae	0	14	65.48	1	−1	1	m_{edium}
S. paniceum	0.232	5	65.91	0	0	1	m_{edium}
T. castaneum	0	29	66.29	1	−1	1	m_{edium}
T. castaneum	0	20	66.94	1	−1	1	m_{edium}
T. castaneum	0	23	67.04	1	−1	1	m_{edium}
S. paniceum	0.229	4	67.61	0	0	1	m_{edium}
T. castaneum	0	33	67.65	1	−1	1	m_{edium}
S. oryzae	0.145	14	69.91	1	−1	1	m_{edium}
S. paniceum	0.184	3	67.22	1	0	1	h_{igh}
S. oryzae	0.187	2	68.49	1	0	1	h_{igh}

Using the Wilcoxon two-sample exact test (SAS Institute 2004) to compare values of i_{CL} in bioassays where *C. lectularius* or another species was present in the arena, the probability that i_{CL} was independent of *C. lectularius* presence in the arena was $P < 0.001$ ($S = 1319.5$, $Z = 4.9225$, $N = 30$). That is, the results do not support a null hypothesis that tests with and without *C. lectularius* produce the same distribution of values of the *C. lectularius* detection likelihood indicator, i_{cl}, and suggest, instead that i_{cl} is associated with the presence or absence of *C. lectularius* in the arena.

Discussion

The size and species of the insects and the nature of the movements they performed all affected the signals detected by the sensors in the bioassays. The walls were too slippery for *C. lectularius* nymphs and *T. castaneum* adults to crawl on easily, for example, and these insects also were too short to crawl across the infrared beam at the 4-mm height set in this study. If these sensors were to be incorporated into a practical insect trap, either multiple infrared sensor pairs would be placed at different heights, or the height would be set at the expected crawling height of the target insect. For the sound or vibration sensors, the trap geometry and substrate surface could be selected carefully to optimize the likelihood that the target insect contacted the sensors and produced easily detected movements. If *C. lectularius* is the target insect, for example, a rough or fabric trap surface may be preferable to a hard, slippery surface (Usinger 1966).

The smallest insect reliably detected with the piezoelectric sensor was the 0.17–0.3-mg second–third-instar nymph, similar in size to *Cryptolestes ferrugineus* (Stephens) adults that were bioassayed in Mankin et al. (1997). An effect of insect size on the amplitudes and rates of sounds and vibrations that are produced has been observed frequently in previous studies (Vick et al. 1988, Pittendrigh et al. 1997, Mankin et al. 1997, Goerlitz et al. 2008). In a small arena or trap with fixed amplification of acoustic or vibrational signals, the amplitude or sound pressure level is thus an easily measured signal feature that can be used to target particular species.

The effects of different behaviors on the signal spectra in Fig. 7 were probably the result of differences in the relative contribution of normal forces (direct vertical impacts) and tangential forces (sideways frictional forces) in the movements of the insects during these behaviors. The frictional forces of scraping behaviors produce sounds with a broader, higher frequency spectrum than the direct impacts caused by steps (e.g., Ekimov and Sabatier 2006). The magnitudes of the steps and scrapes are known to be significantly affected by the substrate surface as well (e.g., Silva et al. 2010).

It should be noted that many of the insects transferred into the arena performed a variety of escape (Hiraguchi and Yamaguchi, 2000), exploratory (Durier and Rivault 2003), or death-feigning (Miyatake et al. 2008) behaviors that were not detected by any of the sensors. Significant customizations of a monitoring arena structure and sensor placement would be required to maximize detection of a particular targeted species. Likewise, careful attention to the behavioral patterns of target insects as well as attractive and repellent stimuli may be necessary to employ these sensors most effectively in an insect trap. In the case of *C. lectularius*, our knowledge of attractive and repellent stimuli is limited (Anderson et al. 2009, Wang et al. 2009), but attractants are known for *B. germanica* and many stored product insect species. This suggests that if an insect other than *C. lectularius* were targeted, the specific indicators estimated for its detection likelihood would need to be customized.

Initially, we expected that the intervals between impulses (steps) during crawling activities might be distributed nonuniformly across different species. However, significant variation was observed both among individuals and species, and the impulse-interval feature was subsequently dropped from further analysis. Others also have found a wide variety in the speeds of various crawling activities among individuals of a given species, e.g., Li et al. (2009) with crawling rates of *Diabrotica virgifera virgifera* LeConte adults. Complete analysis of the different gaits and behaviors of different insects would require a more comprehensive array of sensors, such as those used for human gait analysis (Best and Begg 2006), with a concomitant increase in instrumentation costs.

The costs of the instrumentation were considerably lower than equivalent commercial instrumentation. The greatest single component expense was the amplifier circuit board, ≈$100. The total of the resistors, potentiometers, capacitors, integrated circuits, and miscellaneous switches and connections was less than $100. The total of the sensors was less than $30. Although we used a laptop computer connected to the instrument to collect and analyze the signals, low-cost technology is available to transmit the signals wirelessly to a remote location instead. Even allowing for nonrecurring engineering design and prototyping costs, we estimate that the total component costs are two orders of magnitude less than for some of the original instrumentation developed for automated insect detection (Shuman et al. 1993) and movement analysis (Gorczyca and Hall 1987), but they still exceed the typical costs of a pheromone or pitfall trap. Nevertheless, the additional benefits of timely notification may outweigh these additional costs in a variety of urban insect and stored product insect management environments.

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References Cited

Anderson, J. F., F. J. Ferrandino, S. McKnight, J. Nolen, and N. Miller. 2009. A carbon dioxide, heat and chemical lure trap for capturing bed bugs, *Cimex lectularius.* Med. Vet. Entomol. 23: 99–105.

Arbogast, R. T., P. E. Kendra, D. K. Weaver, and D. Shuman. 2000. Insect infestation of stored oats in Florida and field evaluation of a device for counting insects electronically. J. Econ. Entomol. 93: 1035–1044.

Aubin, T., F. Rybak, and B. Moulin. 2000. A simple method for recording low-amplitude sounds. Application to the study of the courtship song of the fruit fly *Drosophila melanogaster.* Bioacoustics 11: 51–67.

Best, R., and R. Begg. 2006. Overview of movement analysis and gait features, pp. 1–69. *In* R. Begg and M. Palaniswami (eds.), Computational intelligence for movement sciences. Neural networks and other emerging techniques. Idea Group Publishing, Hershey, PA.

California Department of Food and Agriculture. 2005. Insect trapping guide. (http://www.cdfa.ca.gov/phpps/PDEP/Insect_Trapping_Guide_web.pdf).

Charif, R. A., A. M. Waack, and L. M. Strickman. 2008. Raven Pro 1.3 user's manual. Cornell Laboratory of Ornithology, Ithaca, NY.

Dankert, H., L. Wang, E. D. Hoopfer, D. J. Anderson, and P. Perona. 2009. Automated monitoring and analysis of social behavior in *Drosophila.* Nat. Methods 6: 297–303.

Durier, V., and C. Rivault. 2003. Exploitation of home range and spatial distribution of resources in German cockroaches (Dictyoptera: Blattellidae). J. Econ. Entomol. 96: 1832–1837.

Ekimov, A., and J. M. Sabatier. 2006. Vibration and sound signatures of human footsteps in buildings. J. Acoust. Soc. Am. 120: 762–768.

Engel, J. E., and R. A. Wyttenbach. 2001. An optoelectronic sensor for monitoring small movements in insects. Fla. Entomol. 84: 336–343.

Epsky, N. E., W. L. Morrill, and R. W. Mankin. 2008. Traps for capturing insects, pp. 3387–3901. *In* J. L. Capinera (ed.), Encyclopedia of entomology, 2nd ed., volume 4. Springer, New York.

Fleurat-Lessard, F., B. Tomasini, L. Kostine, and B. Fuzeau. 2006. Acoustic detection and automatic identification of insect stages activity in grain bulks by noise spectra processing through classification algorithms, pp. 476–486. *In* I. Lorini, B. Bacaltchuk, H. Beckel, D. Deckers, E. Sundfeld, J. P. Dos Santos, J. D. Biagi, J. C. Celaro, L. R. D'A Faroni, L. de., and O. F. Bortolini (eds.), Proceedings of the 9th International Working Conference on Stored Product Protection, 15–18 October 2006, Sao Paulo Brazil.

Frommolt, K.-H., R. Bardeli, and M. Clausen. 2008. Computational bioacoustics for assessing biodiversity. *In* Proceedings of the International Expert Meeting on IT-based Detection of Bioacoustical Patterns, 7–10 December 2007, Vilm, Germany. (http://www.bfn.de/0502_skripten.html).

Goerlitz, H. R., S. Greif, and B. J. Siemers. 2008. Cues for acoustic detection of prey: insect rustling sounds and the influence of walking substrate. J. Exp. Biol. 211: 2799–2806.

Gorczyca, M., and J. C. Hall. 1987. The INSECTAVOX, an integrated device for recording and amplifying courtship song. Drosophila Inf. Serv. 66: 157–160.

Hagstrum, D. W., and Bh. Subramanyam. 2006. Fundamentals of stored-product entomology. AACC International, St. Paul, MN.

Hiraguchi, T., and T. Yamaguchi. 2000. Escape behavior in response to mechanical stimulation of hindwing in cricket, *Gryllus bimaculatus.* J. Insect Physiol. 46: 1331–1340.

Li, H., S. Toepfer, and U. Kuhlmann. 2009. Flight and crawling activities of *Diabrotica virgifera virgifera* (Coleoptera: Chrysomelidae) in relation to morphometric traits. J. Appl. Entomol. 131: 254–263.

Mankin, R. W. 1994. Acoustical detection of *Aedes taeniorhynchus* swarms and emergence exoduses in remote salt marshes. J. Am. Mosq. Control Assoc. 10: 302–308.

Mankin, R. W., and J. Benshemesh. 2006. Geophone detection of subterranean termite and ant activity. J. Econ. Entomol. 99: 244–250.

Mankin, R. W., J. Brandhorst-Hubbard, K. L. Flanders, M. Zhang, R. L. Crocker, S. L. Lapointe, C. W. McCoy, J. R. Fisher, and D. K. Weaver. 2000. Eavesdropping on insects hidden in soil and interior structures of plants. J. Econ. Entomol. 93: 1173–1182.

Mankin, R. W., J. L. Hubbard, and K. L. Flanders. 2007. Acoustic indicators for mapping infestation probabilities of soil invertebrates. J. Econ. Entomol. 100: 790–800.

Mankin, R. W., R. Machan, and R. Jones. 2006. Field testing of a prototype acoustic device for detection of Mediterranean fruit flies flying into a trap, pp. 165–169. *In* Proceedings of the 7th International Symposium on Fruit Flies of Economic Importance, 10–15 September 2007, Salvador, Brazil.

Mankin, R. W., A. Mizrach, A. Hetzroni, S. Levsky, Y. Nakache, and V. Soroker. 2008a. Temporal and spectral features of sounds of wood-boring beetle larvae: identifiable patterns of activity enable improved discrimination from background noise. Fla. Entomol. 91: 241–248.

Mankin, R. W., D. Shuman, and J. A. Coffelt. 1997. Acoustic counting of adult insects with differing rates and intensities of sound production in stored wheat. J. Econ. Entomol. 90: 1032–1038.

Mankin, R. W., M. T. Smith, J. M. Tropp, E. B. Atkinson, and D. Y. Jong. 2008b. Detection of *Anoplophora glabripennis* (Coleoptera: Cerambycidae) larvae in different host trees and tissues by automated analyses of sound-impulse frequency and temporal patterns. J. Econ. Entomol. 101: 836–849.

Miyatake, T., K. Tabuchi, K. Sasaki, K. Okada, K. Katayama, and S. Moriya. 2008. Pleiotropic antipredator strategies, fleeing and feigning death, correlated with dopamine levels in *Tribolium castaneum.* Anim. Behav. 75: 113–121.

Phillips, T. W., and J. E. Throne. 2010. Biorational approaches to managing stored-product insects. Annu. Rev. Entomol. 55: 375–397.

Pittendrigh, B. R., J. E. Huesing, R. E. Shade, and L. L. Murdock. 1997. Monitoring of rice weevil, *Sitophilus oryzae,* feeding behavior in maize seeds and the occurrence of supernumerary molts in low humidity conditions. Entomol. Exp. Appl. 83: 225–231.

SAS Institute. 2004. SAS/STAT 9.1 user's guide. SAS Institute, Cary, NC.

Schal, C., and R. L. Hamilton. 1990. Integrated suppression of synanthropic cockroaches. Annu. Rev. Entomol. 35: 521–551.

Shuman, D., J. A. Coffelt, K. W. Vick, and R. W. Mankin. 1993. Quantitative acoustical detection of larvae feeding inside kernels of grain. J. Econ. Entomol. 86: 933–938.

Shuman, D., R. G. Larson, and N. D. Epsky. 2004. A quantitative stored-product insect monitoring system using sensor output analog processing (SOAP). Trans. ASAE 47: 1857–1864.

Shuman, D., D. K. Weaver, and R. W. Mankin. 1997. Quantifying larval infestation with an acoustical sensor array and cluster analysis of cross-correlation outputs. Appl. Acoustics 50: 279–296.

Silva, J., A. M. Lima, H. Neff, and J. S. Rocha Neto. 2010. Vibration analysis based on hammer impact for fouling detection using microphone and accelerometer as sensors. Sensors Transducers 112: 10–23.

Siriwardena, K.A.P., L.C.P. Fernando, N. Nanayakkara, K.F.G. Perera, A.D.N.T. Kumara, and T. Nanayakkara. 2010. Portable acoustic device for detection of coconut palms infested by *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae). Crop Prot. 29: 25–29.

Spangler, H. G. 1985. Detecting lesser wax moths acoustically. Gleanings Bee Cult. 113: 207–209: 218.

Tauber, E., and D. F. Eberl. 2003. Acoustic communication in *Drosophila.* Behav. Processes 64: 197–210.

Usinger, R. 1966. Monograph of Cimicidae. Entomological Society of America, College Park, MD.

Vick, K. W., J. C. Webb, D. W. Hagstrum, B. A. Weaver, and C. A. Litzkow. 1988. Sound detection of stored product insects that feed inside kernels of grain. J. Econ. Entomol. 81: 1489–1493.

Wang, C., T. Gibb, G. W. Bennett, and S. McKnight. 2009. Bed bug (Heteroptera: Cimicidae) attraction to pitfall traps baited with carbon dioxide, heat, and chemical lure. J. Econ. Entomol. 102: 1580–1585.

Zhang, M., R. L. Crocker, R. W. Mankin, K. L. Flanders, and J. L. Brandhorst-Hubbard. 2003a. Acoustic identification and measurement of activity patterns of white grubs in soil. J. Econ. Entomol. 96: 1704–1710.

Zhang, M., R. L. Crocker, R. W. Mankin, K. L. Flanders, and J. L. Brandhorst-Hubbard. 2003b. Acoustic estimation of infestations and population densities of white grubs (Coleoptera: Scarabaeidae) in turfgrass. J. Econ. Entomol. 96: 1770–1779.

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