

Efficacy of Commercially Available Ultrasonic Pest Repellent Devices to Affect Behavior of Bed Bugs (Hemiptera: Cimicidae)

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J. Econ. Entomol. 105(6): 2107–2114 (2012); DOI: <http://dx.doi.org/10.1603/EC12166>

ABSTRACT Little is known about the potential for acoustic communication in bed bugs, *Cimex lectularius* L. (Hemiptera: Cimicidae), or the use of sound as cues in host location, although many hemipterans are known to communicate with sound. Most behavioral research has focused on bed bug pheromones that are used in aggregation and as alarm signals. We investigated the influence of sound as a deterrent and as an attractant, either of which could ultimately be used to monitor and control bed bugs. Female bed bugs were tested in two-choice tests with four different commercially available ultrasonic repellent devices. We found that female bed bugs were equally likely to occur in arenas with or without sound produced by ultrasonic devices. These devices did not repel or attract bed bugs during choice trials. However, more bed bugs preferred the middle corridor between the test (sound) and control (no sound) arenas when the sound devices were played. Bed bugs were also more likely to exit the middle corridor during control trials compared with treatment trials with ultrasonic devices. Our results confirm that commercial devices producing ultrasound are not a promising tool for repelling bed bugs.

KEY WORDS bed bug, ultrasound, management, repellency, *Cimex lectularius*

Effective means of monitoring and controlling bed bugs, *Cimex lectularius* L. (Hemiptera: Cimicidae), have eluded researchers and pest management professionals (but see Anderson et al. 2009; Wang et al. 2009, 2011; Weeks et al. 2011). Many of the current approaches for bed bug control rely on chemical means, primarily pyrethroids (Doggett and Russell 2008), that act as neurotoxicants (Costa et al. 2008). These insecticides may have adverse effects on nontarget species (Wolansky and Harrill 2008), and some have resulted in insecticide-resistant strains of bed bugs (Mallis and Miller 1964, Romero et al. 2007). There remains a need for a nontoxic and economical technology to manage this urban pest, as its presence has increased significantly since the late twentieth century in developed countries such as the United States, Australia, and Britain (Boase 2008).

Bed bugs are known to communicate chemically via pheromones that facilitate aggregation, signal sex and age, and serve as alarm signals (Usinger 1966, Siljander et al. 2007, Ryne 2009, Harraca et al. 2010). Bed bugs release alarm signals when disturbed (Levinson et al. 1974), resulting in increased activity and dispersal (Ryne 2009). These same chemicals also serve as honest signals when released by males and nymphs to avoid harmful mating attempts by adult males (Ryne 2009, Harraca et al. 2010). The exploitation of chemical signals in bed bugs may prove fruitful in moni-

toring and management efforts (Benoit et al. 2009, Haynes et al. 2010).

Bed bugs do rely on sensory modalities other than chemoreception. Vision is used by bed bugs as males quickly orient toward and mount other bed bugs or similar shapes (Rivnay 1933, also from personal observations of bed bug attraction to similar-sized objects such as small microphones). Bed bugs are also positively thigmotactic (Rivnay 1932, Usinger 1966); this response was confirmed in our preliminary bioassays during which bed bugs preferred locations allowing maximum contact with the substrate. However, little is known of bed bug sensitivity to sound. Other blood-sucking hemipterans, such as female reduviid bugs, are known to produce sound via stridulation that functions to discourage unwanted male mating attempts (Roces and Manrique 1996). Many hemipterans use substrate-borne sound to communicate and function in courtship, mating, and species identification (Virant-Doberlet and Cokl 2004).

Alternative means of controlling urban insect pests, including bed bugs, by using ultrasonic frequencies are available and marketed to the public. However, few of these devices have been demonstrated as being effective in repelling insect pests such as mosquitoes, cockroaches, and ants (Schreck et al. 1984, Koehler et al. 1986, Huang et al. 2002). In fact, some ultrasonic devices aggravated the impact of pests by increasing the biting rates of mosquitoes (Andrade and Cabrini 2010). Despite the lack of evidence for the efficacy of

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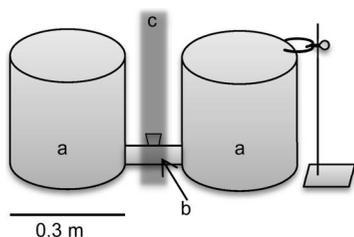


Fig. 1. Two choice test arenas (a) connected by a Plexiglas corridor (b). Ultrasonic devices were suspended at a depth of 10 cm within test arenas by using a ring stand. A 4-cm-wide sheet of foam (c) was placed midway over the corridor to acoustically isolate test arenas.

such devices, they continue to be sold and new versions targeting bed bugs are readily available.

We investigated the efficacy of four commercially available electronic pest repellent devices designed to repel insect and mammalian pests by using sound. One particular device is designed and marketed specifically for bed bugs. The efficacy of each device was assessed in two-choice tests with female bed bugs. The distribution of bed bugs throughout choice test arenas and the middle corridor also was compared among treatment and control trials. In addition, we describe the spectral and temporal characteristics of each device.

Materials and Methods

A laboratory strain of bed bugs was obtained from Dr. Dini Miller (Dodson Urban Pest Management Laboratory, Virginia Tech, Blacksburg, VA). This laboratory strain was originally obtained from the United Kingdom and is not pesticide resistant. Bed bugs were fed at the Dodson Urban Pest Management Laboratory 1 d before shipment. Subsequently, bed bugs housed at Northern Arizona University were not fed.

Bed bugs were maintained at 26°C, 40–50% RH, and a photoperiod of 14:10 (L:D) h. Upon receiving all shipments, bed bugs were placed on a reverse photoperiod (10:14 D:L) beginning at 9:00 a.m. Bed bugs were housed in 1-quart Kerr glass jars lined at the top with Fluon (Thermo Fisher Scientific, Denver, CO), each containing a folded 7-cm filter paper (Whatman 1 qualitative, Whatman, Maidstone, United Kingdom), to provide harborage for bed bugs. The metal lid of each jar was modified such that a 2-cm-diameter hole was removed and replaced with nylon mesh that was glued to the metal lid with epoxy to allow airflow into the jar.

Choice Test Arenas. A two-choice assay was used to test the influence of electronic devices on female bed bugs only (hereafter referred to as bed bugs), as control of female bed bugs alone would likely be effective at reducing populations. Bed bugs were used in bioassays \approx 2.5 wk from feeding to encourage host-seeking behaviors. Choice test arenas consisted of two 5-gallon buckets (29.85 cm in diameter, 36.8 cm in height, local Home Depot) joined at the bottom by a Plexiglas corridor (Fig. 1). The corridor (2.5 cm in height, 9 cm in width, 8 cm in depth) was attached

with epoxy at the bottom of each bucket so that the floor of the corridor was flush with the bottom of each bucket. A 2.5-cm hole was drilled through the top of the Plexiglas corridor for the release of bed bugs into a neutral space. The hole was sealed with a rubber stopper during bioassays. The corridor and interior floor of both buckets were painted with textured spray paint to provide adequate substrate for bed bug mobility. The interior of each bucket was lined with Fluon at the top and around the entryway to the middle corridor to prevent bed bugs from escaping. Insulation foam (4 cm in thickness; R-Tech Foam Insulation, Home Depot) was placed over the middle corridor, outside the buckets, to reduce noise contamination between the arenas.

Bioassay Procedures. Bed bug behavior was assessed in groups of 8–10 individuals. At the beginning of each bioassay, 10 individuals were placed into the middle corridor (Fig. 1) through the top opening. Each ultrasonic device was suspended down into an arena at a depth of 10 cm by using a ring stand. An ultrasonic device was turned on immediately after introducing the bed bugs and played for 30 min during each replicate, and the position of each bed bug was assessed as being in either arena or in the middle corridor. Each device and a control bioassay (without sound) were tested for 8–10 replicates. All bioassays were conducted in a dark room using a 60-W red light bulb positioned centrally over the apparatus, because a previous study (Romero et al. 2010) demonstrated normal activity levels under such conditions. Two different choice test arena apparatuses were used during bioassays and were both thoroughly wiped down with 70% alcohol after each use.

Ultrasonic Pest Repellent Devices. Devices were purchased online (Amazon.com 2011) and used according to manufacturers' instructions. Most devices had only one setting, on/off. The exception was device A that had multiple settings for different mammalian and invertebrate pests according to taxon groups and intensity. For this device, instructions were followed to target crawling insects. Only one device, D, was specifically designed to affect bed bugs. The following devices were used in two-choice tests: device A (Transonic Pro, BIRD-X, Chicago, IL), device B (SonicIQ Ultrasonic pest repeller model SB105, SmartWorks, Somerset, NJ), device C (Pest Free, ViaTEK, Orlando, FL), and device D (Riddex Anti bed bug killer, Global TV Concepts, Deerfield Beach, FL).

Each device was rerecorded using a TASCAM TM-STI electret condenser microphone attached to an HD-P2 TASCAM digital audio recorder at 96 kHz and 24-bit sampling rate. Thirty-second recordings were made in the sound and control arenas at the bottom of each arena. Three recordings were made for each device, as well as a control recording just before turning on each device. Sound pressure levels were taken using a digital sound level meter (Radio Shack model 33-2055) at the C weighting, a weighting that is sensitive to frequencies ranging from 32 to 10,000 Hz. Readings were averaged over 2-min intervals at dis-

Table 1. Number of female bed bugs in arenas with sound (S) and without sound (NS) for each device and control

	Control		Device A		Device B		Device C		Device D	
	Left	Right	S	NS	S	NS	S	NS	S	NS
Sum	31	23	17	15	19	18	14	12	14	16
Avg	3.1	2.3	1.7	1.5	1.9	1.8	1.4	1.2	1.75	2.0
Range	0-5	0-6	0-4	0-6	0-4	0-3	0-3	0-3	0-4	1-5
Replicates	10		10		10		10		8	
<i>t</i> (df)	-0.79 (9)		-0.41 (9)		-0.16 (9)		-4.5 (9) ^a		0.29 (7)	
<i>P</i>	0.45		0.69		0.88		0.78		0.78	

^a Test statistic for device C is Wilcoxon signed rank S-test statistic.

tances that approximated that experienced by bed bugs in bioassays, 28 cm, and closer at 1 cm.

Spectrographic Analysis. Spectrographic analysis was conducted using Raven Pro Interactive Sound Analysis software, version 1.4 (www.birds.cornell.edu/raven). Spectrograms were produced using a customized preset with the following parameters: Hann window with a 1,050 sample size, 105 Hop size, and 90% overlap. All recordings, including the controls, contained sound at low frequencies, ≈ 0 –1 kHz. Therefore, analysis of each device recording included a bandpass filter of 1–48 kHz to exclude frequencies up to 1 kHz. Most ultrasonic devices produced signals that alternated temporally or with two simultaneous components at low and high frequencies and are reported here individually.

Individual pulse trains produced by ultrasonic devices were identified using the band limited energy detector in Raven. Detectors were specialized for each device and sometimes for individual pulse trains or sound components within a recording. Preset band limited energy detectors were developed following the guidelines in the Raven Pro 1.4 user's manual (Charif et al. 2010) and were based on the duration and bandwidth of each signal, as well as the time intervals between signals. Spectral and temporal characteristics were measured from the resulting selections detected within each recording. Measurements reported here are peak frequency, median frequency, and duration. Peak frequency is the frequency within a pulse train with maximum power. Median frequency is the frequency about which equal amounts of energy lie above and below. Spectral profiles were constructed using the spectrogram slice view at the center of each pulse train. The center of each pulse train is the time at which energy is divided equally within the pulse train.

Device output occurring in the sound and control arenas was compared using the 30-s recordings (see previous paragraph for description). For devices with relatively continuous signals (A and D), 0.5-s selections were chosen at ≈ 5 , 10, 15, 20, and 25 s from recordings made in the sound and control arenas. For the remaining devices (B and C), five 0.5-s selections from each recording were chosen such that each included one pulse train and analogous selections were chosen from recordings made in the control arena. Selections were analyzed in Raven (see previous paragraph for discussion of spectrographic analysis) for

differences in amplitude. The root-mean-square (RMS) amplitude for each selection, reported here in generic units, assesses the average amplitude for a given selection.

Data were analyzed by comparing the number of bed bugs present in the arena with sound to the number of bed bugs present in the arena with no sound, as well as comparing overall distribution patterns for treatment and control trials. All data were analyzed using JMP Pro 9.0.2 (SAS Institute 2010). Paired-sample *t*-tests were used to test the effectiveness of each electronic device and in control trials. However, for device C, data were not distributed normally and the Wilcoxon signed rank test was used to test differences in bed bug presence in arenas with and without sound. Bed bugs tended to aggregate in the middle corridor and, consequently, we assessed bed bug distribution for devices as the total number of bed bugs present in both arenas during treatment and control trials. Distribution data for some devices were not normally distributed and so medians across treatment and control groups were compared using the Kruskal-Wallis rank sum test with chi-square approximation. Paired comparisons of bed bug distribution were conducted using the Wilcoxon multiple comparison method.

Because signals varied temporally, the number of signals within a recording varied from ≈ 30 to ≥ 400 . Therefore, in recordings with high numbers of signals (devices A and D), a random sample of 60 pulse trains each was chosen and reported. However, device B produced relatively few pulse trains within the thirty second recordings and only 29 pulse trains were available for analysis.

Results

Influence of Ultrasound Devices on Bed Bugs. There were no significant differences in the number of bed bugs observed in the control (no sound) and sound arenas (Table 1). Bed bugs were neither deterred nor attracted to the arena with the sound device. Bed bugs did exhibit strong tendencies to aggregate. At least half the bed bugs during a given trial were located in the neutral, middle corridor. More bed bugs remained in the neutral corridor when the sound devices were played than when no sound was played, suggesting that all of the sound devices stimulated aggregation behavior or reduced bed bug movement.

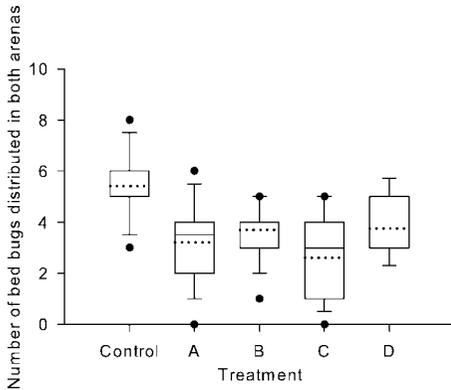


Fig. 2. Number of bed bugs distributed throughout both arenas was higher in the control trials compared with treatments with ultrasonic devices. Distribution of bed bugs ($N = 8-10$ /trial) was assessed as the total number of bed bugs observed in both choice arenas during bioassay trials. The solid line indicates the median, and the dotted line indicates the mean for each device.

The median number of bed bugs distributed in both arenas was significantly different for treatment and control trials (Fig. 2; Kruskal-Wallis: $\chi^2 = 13.28$, $df = 4$, $P < 0.01$). Multiple comparisons of bed bug distribution for treatment and control trials revealed that significantly more bed bugs were distributed throughout arenas in the control trials compared with all treatment trials (Wilcoxon nonparametric multiple comparisons: $P < 0.05$ for all comparisons between the control and treatment trials).

Spectral and Temporal Characteristics of Ultrasonic Devices. All ultrasonic devices produced repeating signals, varying in the interval between signals. Devices A and D produced rapidly repeating broadband signals (Figs. 3 and 4). Device A produced two different alternating signals (Fig. 3). The shorter duration signal spanned a range between 3 and 44.5 kHz, whereas the longer duration signal spanned a range between 3 and 42 kHz (Table 2). Device D produced repeating signals every 0.03 s, with a low- and a high-frequency component (Fig. 4; Table 2). Device B also showed sinusoidal amplitude modulation. Device B

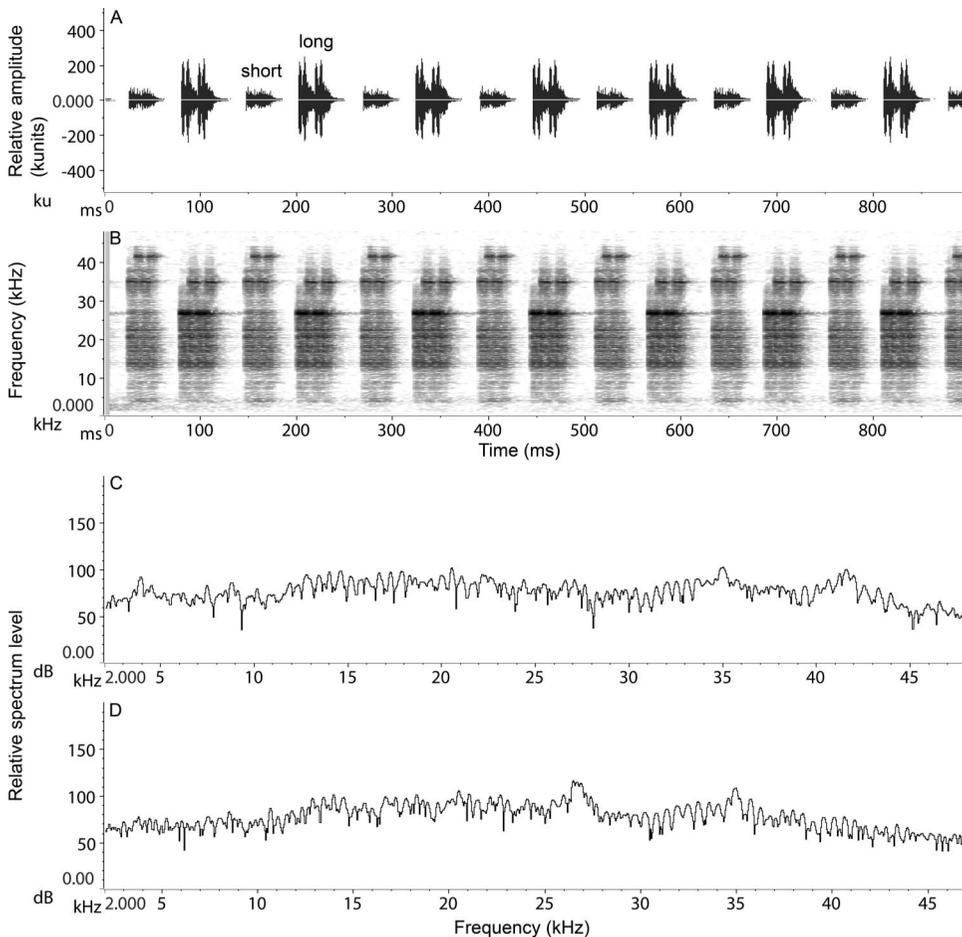


Fig. 3. Waveform (A), spectrogram (B), and spectral profiles (C, short pulse train; D, long pulse train) for device A. The waveform shows the relative amplitude, and the spectrogram shows frequency over time, with darker shades indicating higher relative energy. Examples of the short and long pulse trains are shown in the waveform and spectrogram.

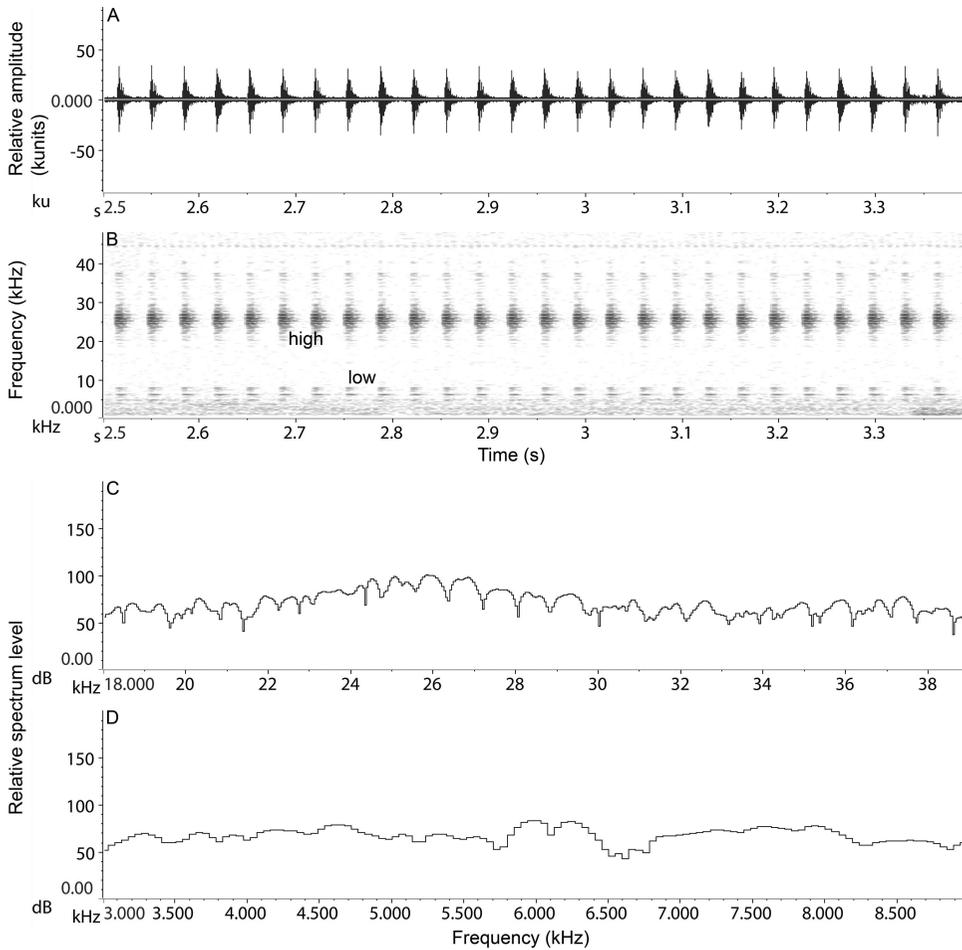


Fig. 4. Waveform (A), spectrogram (B), and spectral profiles (C, high-frequency component; D, low-frequency component) for device D. The waveform shows the relative amplitude and the spectrogram shows frequency over time with darker shades indicating higher relative energy.

produced simultaneous signals at high and low frequencies (Fig. 5; Table 2), spaced approximately every 3 s. The high-frequency signal was ≈60% longer com-

pared with the low-frequency component. Device C produced a relatively faint signal every 0.95 s at ≈19 kHz (Fig. 6; Table 2).

Table 2. Spectral and temporal characteristics of ultrasonic devices used in behavioral assays

Device	Max. frequency (mean ± SE, kHz)	Median frequency (mean ± SE, kHz)	Duration (mean ± SE, ms)	RMS amplitude ^a (mean ± SE, units)		Sound level ^b (mean dB)		Cost (US\$) ^c
				Sound arena	Control arena	1 cm	28 cm	
A	Short ^d	34.9 ± 5.68E-9	21.6 ± 0.108	36.80 ± 0.07	959.29 ± 10.91	64.67	63.00	29.84
	Long ^d	26.6	26.6					
B	Low ^e	5.1 ± 5.1E-10	5.0 ± 0.004	16.79 ± 0.18	342.12 ± 2.46	55.33	54.00	10.25
	High ^e	36.6 ± 0.003	36.4 ± 0.005					
C	19.6 ± 0.035	19.5 ± 0.039	256.59 ± 2.37	406.11 ± 9.14	349.7 ± 2.26	55.00	53.67	9.62
D	Low ^e	6.0 ± 0.002	6.0 ± 0.003	10.18 ± 0.05	1,128.13 ± 9.98	60.00	55.00	14.85
	High ^e	25.8 ± 0.006	25.7 ± 0.005					

^a RMS amplitude is reported generic units obtained from spectrographic analysis in Raven.

^b The mean sound pressure level for controls with no sound was 54 dB.

^c Prices from Amazon.com 2012.

^d The short and long signals produced by device A alternate sequentially throughout the recording.

^e The low and high signals reported for devices B and D occur simultaneously, although they might vary in duration.

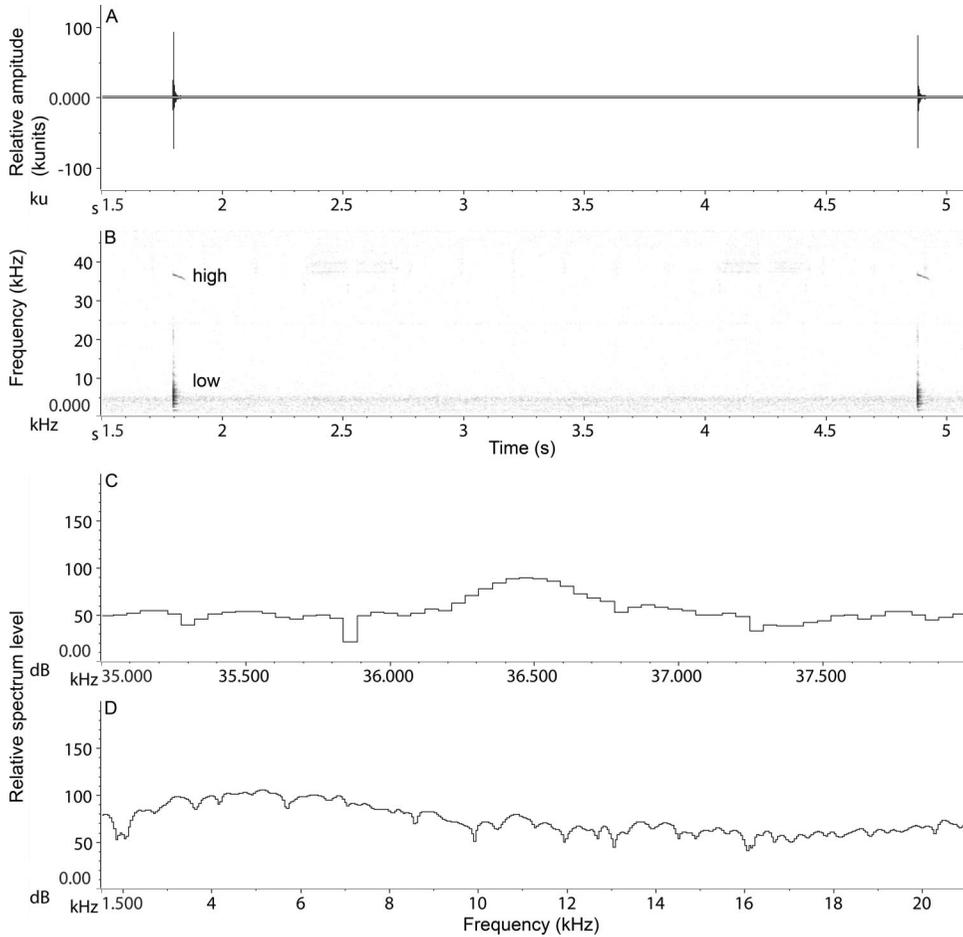


Fig. 5. Waveform (A), spectrogram (B), and spectral profiles (C, high-frequency component; D, low-frequency component) for device B. The waveform shows the relative amplitude, and the spectrogram shows frequency over time with darker shades indicating higher relative energy.

Discussion

Our bioassays indicate that bed bugs are not repelled or attracted to acoustic signals produced by commercially available ultrasonic devices. We found some evidence that these ultrasonic devices affect bedbug dispersal from the corridor or aggregation behavior. However, the practical importance of these observations is low because a significant number of bed bugs did not move away or to the arena where the ultrasound device was used.

The decreased number of bed bugs exiting the middle corridor during treatment trials compared with control trials requires further explanation. Two potential scenarios could account for changes in bed bug distribution in treatment trials. Upon introduction into the middle corridor some bed bugs may have responded to the ultrasonic devices by feigning death or quiescence. Death feigning, the sudden cessation of movement in animals when exposed to stimuli, has been shown to increase the likelihood of survival in some insects (Miyatake et al. 2004). However, con-

tinued exposure to quiescence inducing stimuli in Colorado potato beetles, *Leptinotarsa decemlineata* (Say), led to habituation, such that with increased exposure to stimuli potato beetles were less likely to respond (Acheampong and Mitchell 1997). Alternatively, bed bugs may have explored their surroundings, entering into either or both arenas, and returned back to the middle corridor in an attempt to seek harborage, as they are positively thigmotactic (Usinger 1966). The middle corridor was rectangular, whereas the choice arenas were circular. Therefore, bed bugs may have preferred the middle corridor to maximize the potential substrates for contact; such contact would have been greater in the middle corridor compared with the choice arenas. In either scenario, bed bugs would not effectively be repelled from potential hosts, only induced to remain quiescent and could potentially become habituated to external stimuli.

Elimination of chemical cues used and produced by bed bugs was not entirely possible and thus could influence our results. Within each individual bioassay,

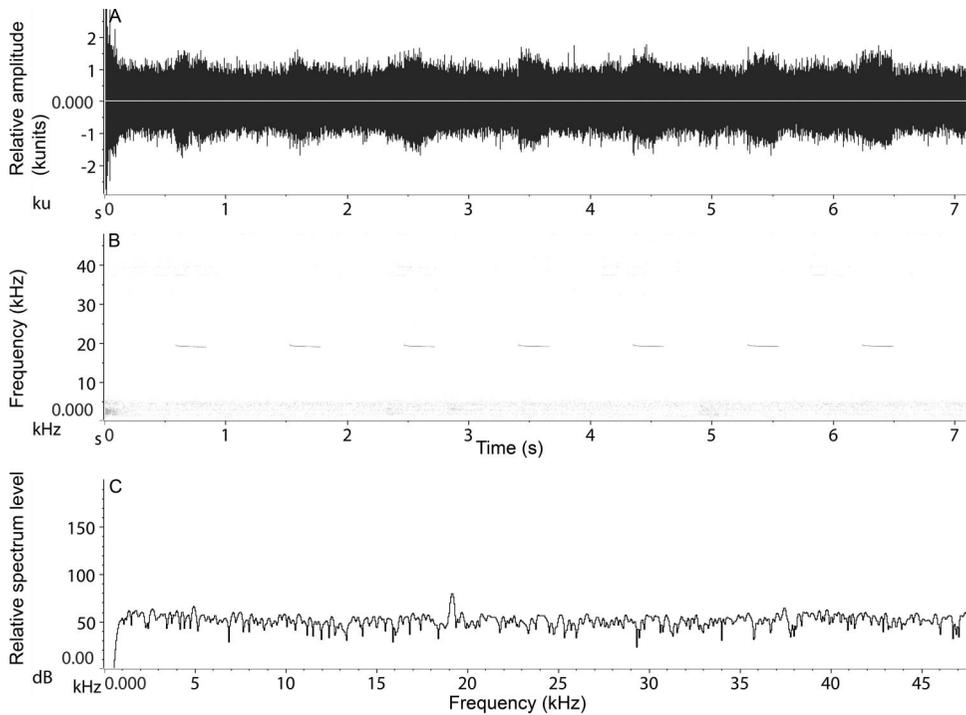


Fig. 6. Waveform (A), spectrogram (B), and spectral profile (C) for device C. The waveform shows the relative amplitude, and the spectrogram shows frequency over time with darker shades indicating higher relative energy.

aggregation pheromones could have been produced by bed bugs, resulting in the tendency for individuals to be found near one another in the middle corridor. However, that bed bugs still remained closer to the sound source than was necessary (meaning not moving to the farther choice arena) does seem to indicate that they were not deterred by the sound. That coupled with the fact that roughly equal numbers of bed bugs were found near the sound source compared with the opposite choice arena points to either a lack of device effectiveness or a lack of bed bug sensitivity to ultrasonic sounds.

That none of these ultrasonic devices repelled bed bugs is not surprising considering that similar devices have little effect on other insects such as mosquitoes, cockroaches, fleas, or ants (Ballard and Gold 1983, Schreck et al. 1984, Koehler et al. 1986, Huang et al. 2002). In fact, some devices have been shown to increase activity of insects. Koehler et al. (1986) reported a slight increase in the number of cockroaches in rooms and apartments with ultrasonic devices, although this difference was not statistically significant. Other studies show clear disadvantages of ultrasonic devices as they increase harmful activities such as biting rates among mosquitoes (Andrade and Cabrini 2010).

The ultrasonic devices we tested may not deter or attract bed bugs because they did not produce the right combination of frequencies. Bed bugs are commonly exposed to frequencies made by their host species, humans, and by appliances and machines found in homes. Therefore, it may be possible that bed bugs also would exploit sounds made by their hosts, such as breathing or snoring. Human snoring produces

sound with low frequencies ranging from 100 to 500 Hz (Fiz et al. 1996). These ultrasonic devices produced broadband signals and individual signals at high and low frequencies, spanning a bandwidth of ≈ 43 kHz. Future studies of bed bug bioacoustics may be served well by using low-frequency sounds produced by host species.

The lack of a behavioral change (other than the increase in aggregation) in bed bugs in this experiment may be because of a lack of attractive host cues such as high temperatures or human odors (Rivnay 1932, Harraca et al. 2012). Harraca et al. (2012) report that bed bugs are attracted to five different human volatiles at relatively low concentrations. Behavioral assays of bed bugs often include multimodal stimuli from hosts (Anderson et al. 2009, Wang et al. 2009), and tests with other urban pests directly use living hosts as stimuli in choice tests (Schreck et al. 1984, Andrade and Cabrini 2010). Andrade and Cabrini (2010) found an increase in biting rates of mosquitos when exposed to ultrasonic pest repellent devices. However, these bioassays included multiple host cues emanating from the host's hand, closely paired with the acoustic stimuli. Future studies of bed bugs should incorporate a combination of acoustic, chemical, and thermal host cues to test the potential behavioral responses to sound.

Acknowledgments

We are particularly thankful to Dini Miller and Timothy McCoy of the Dodson Urban Pest Management Laboratory, Virginia Tech, for providing well-fed bed bugs and valuable

advice in bed bug husbandry. We thank the Rocky Mountain Research Station for the use of laboratory facilities and Kaelyn Finley for assistance sorting bed bugs. Thanks also go to Nick Aflitto for the construction of bed bug choice arenas. This research was supported by Technology and Research Initiative Fund-Growing Biotechnology Initiative state of Arizona grant to R.H.H., Northern Arizona University. This research was also supported, in part, by McIntire-Stennis appropriations to NAU and the State of Arizona.

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Received 20 April 2012; accepted 17 August 2012.