

STORED-PRODUCT ENTOMOLOGY

Comparison of Acoustical Detection of Several Species of Stored-Grain Beetles (Coleoptera: Curculionidae, Tenebrionidae, Bostrichidae, Cucujidae) Over a Range of Temperatures

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ABSTRACT Acoustical detection of five species of adult stored-product insects in 1-kg samples of wheat was compared. Sitophilus oryzae (L.) and Tribolium castaneum (Herbst) were detected during more 10-s intervals than Rhyzopertha dominica (F.); Cryptolestes ferrugineus (Stephens) and Oryzaephilus surinamensis (L.) were detected less frequently than other species. These species were also distinguishable by differences between the probability distributions of the numbers of sounds per 10-s interval. The probability distributions decreased logarithmically with increasing numbers of sounds. The number of sounds for three species varied with temperatures between 17.5 and 37.5°C. The number of sounds of S. oryzae increased as the temperature increased from 17.5 to 35°C and then decreased at higher temperatures. The number of sounds of T. castaneum tended to be lowest at <25°C and then increased steadily as temperature increased. The number of sounds of R. dominica increased as temperature increased from 17.5 to 30°C and then became level at higher temperatures. We also investigated the possibility of finding larger differences in acoustical signals between species by using different instrument settings for the filter which eliminates sounds above and below a selected frequency range and the counter which determines the number of sounds producing voltages above a selected threshold. Widening the filter frequency range increased the number of background sounds as much as it increased the number of insect sounds; thus, it did not increase our ability to distinguish between species. Raising the counter voltage threshold resulted in a logarithmic decrease in the number of sounds for all insect species. These data should make it possible to distinguish between some species of adult insects using acoustical detection data, and to adjust the estimates of insect density made using acoustical detection by removing the effects of temperature.

KEY WORDS sampling, stored-product beetles, insect sounds

AUTOMATED INSECT MONITORING can improve pest management by providing more timely and reliable information about insect density. Automated monitoring of insects with acoustical sensors on cables that are installed in stored grain provides accurate estimates of insect density (Hagstrum et al. 1991). The numbers of sounds produced by insects feeding or moving around in grain are strongly correlated with insect density.

Two problems with the automated monitoring of insect populations by acoustical detection are that species of insects cannot be identified by the usual morphological characteristics, and that insect activity (and thus detectability) can vary with temperature. Several studies have provided some information on the variation in the acoustical signal detected. Vick et al. (1988b) found

that the strength of acoustical signal detected from Sitophilus oryzae (L.) and Sitotroga cerealella (Oliver) larvae averaged 3.57 and 1.15 times that detected from Rhyzopertha dominica (F.) larvae. The peak frequency of insect sounds was 1,200 Hz for all three species on wheat. Vick et al. (1988b) also showed that the strength of acoustical signal increased with larval size.

For Callosobruchus maculatus (F.), Shade et al. (1990) also found that the strength of the acoustical signal increased with instar. They showed that the number of sounds of feeding larvae increased as temperature increased from 13 to 25°C, became level between 25 and 38°C, then decreased as temperatures increased from 38 to 45°C. Hagstrum et al. (1988, 1990, 1991) found that the strength of acoustical signals from adults of R. dominica and Tribolium castaneum (Herbst) were 37 and 80 times greater than those detected with larvae of the same species. They found that the relationship between number of

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insects and number of sounds was similar at 22, 27, and 32°C. However, differences in the detectability of different species of adult stored-product insects over a range of temperatures have not been compared. Estimates of insect numbers with an automated insect monitoring system might be improved by adjusting for differences in detectability because of insect species or temperature. When insect densities are low (i.e., early in the storage period) and the volume of grain around a sensor in which insects can be detected is likely to contain only one insect, insect sounds may also provide some information about which insect species are present.

Here we present results of studies done to compare the detectability of sounds of five species of adult stored-grain insects. For three species, the effects of temperatures on detectability are studied. The settings for counter voltage thresholds and filter frequency ranges are varied to investigate the possibility of finding larger differences in acoustical signal between species.

#### Materials and Methods

Tests were conducted with one adult in 1 kg of hard red winter wheat (12% moisture content) at 25°C for *Cryptolestes ferrugineus* (Stephens), *Oryzaephilus surinamensis* (L.), *R. dominica*, *S. oryzae* and *T. castaneum*. For the last three species, tests were also done at 2.5°C temperature increments between 17.5 and 37.5°C. The grain was poured into the sample chamber (Fig. 1) through the funnel at the top and was released through the bottom of sample chamber at the end of each test. The grain was vibrated for 20 s each time the grain was poured into the sample chamber to reduce the sounds caused by grain settling.

Data collection was begun immediately after 20 s of vibrating. Background sounds were further reduced by suspending the sample chamber on size 14 Masterflex silicone tubing (Cole-Palmer, Chicago, IL) inside a sound-insulated box made of 3/4" (1.9 cm) thick plywood. The box was lined with Nx4 Sonex sound proofing foam (Illbruck, Minneapolis, MN); the outside was covered with PSP-9 Prospec sound barrier (Illbruck). The sample chamber was equipped with eight piezoelectric microphones (#9D0576 BNF Enterprises, Peabody, MA). The signal processing equipment was the same as that described in an earlier study (Hagstrum et al. 1991). An eight-channel multiplexer (Bruel & Kjaer Model 2811, Marlborough, MA) switched to the next of eight microphones every 10 s. The signal from the microphones was amplified 10,000 times (Bruel & Kjaer Model 2610) and filtered (Krohn-Hite Model 3700 variable band-pass filter, Avon, MA), and the numbers of sounds were counted (Hewlett-Packard universal counter model 5316A, Wichita, KS). An IBM-PC compat-

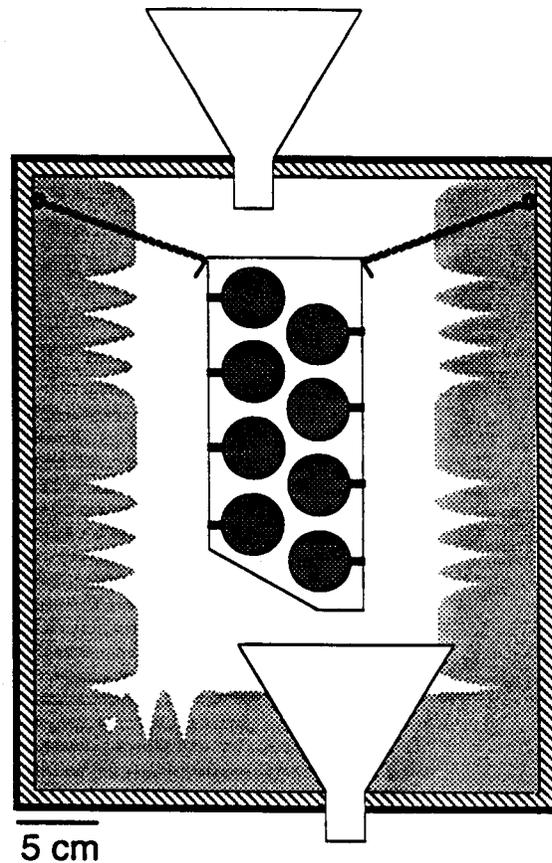


Fig. 1. Cross section of sound-insulated box and grain sample chamber inside box. See *Materials and Methods* for further details.

ible computer stored the data, switched the multiplexer to the next microphone, and reset the counter using software developed by Webb et al. (1988).

For each insect, data were collected during three 12-min periods at 25°C. Between 12-min data collections, the grain was removed and poured into the sample chamber again to reposition the beetle in the chamber. Data were collected during only one 12-min period for tests of the effects of temperature. For each species, the test was replicated 10–30 times with different beetles each time. A narrow filter setting of 3–3.5 KHz and a minimum detectable voltage threshold of 0.15 V were used except for tests of the effects of instrument settings.

Differences in the number of 10-s intervals with sounds between insect species were tested using analysis of variance (ANOVA) and Tukey's studentized range test (HSD)(PROC ANOVA, SAS Institute 1985). For each beetle, a nonlinear model was fit to the cumulative probabilities of fewer counts as a function of number of counts with PROC NLIN (SAS Institute 1985). Models

were fit to the data for each beetle so that CIs could be based on the variation in the frequency distributions of different beetles from model predictions rather than being based on the deviations in the sizes of frequency classes from model predictions. This procedure is important because individual frequency classes are derived by repeated measures on the same population; thus, the sizes of frequency classes are not independent of one another. The CIs were calculated based on the variation in estimates of model parameters between beetles. The SEs are provided to show the variability of each of the model parameters but no significance testing was done because, as a result of the interactions among the three parameters of models, the overall models could be significantly different even if the parameters were not significantly different. In addition, the lack of fit test (Draper & Smith 1981) could not be used because there is no replication of an independent variable when models are fit for each beetle. Instead, significant differences in the number of sounds produced between species were identified by finding regions of CI that did not overlap. Locating regions of nonoverlapping CIs has the advantage of showing where models are significantly different. The effect of temperature on the mean total number of counts was described by linear regression for *R. dominica* and *T. castaneum* (PROC REG, SAS Institute 1985) or nonlinear regression for *S. oryzae* (PROC NLIN, SAS Institute 1985). Logan et al. (1976) used this nonlinear equation to describe the effects of temperature on insect developmental rate.

For *R. dominica*, *S. oryzae*, and *T. castaneum*, tests with 0.15, 0.45, 0.75, 1.3, and 1.8-V threshold settings on the counter were replicated twice with different beetles. The logarithm of the total number of counts per 36-min period was regressed (PROC REG, SAS Institute 1985) against the logarithm of the voltage threshold. Differences in the number of sounds produced between species were tested with a model comparison procedure (Draper & Smith 1981). With these species, tests with low (0.35–3 Khz), high (3–20 Khz), and wide (0.35–20 Khz) frequency filter ranges were also replicated twice with different beetles. Different voltage thresholds had to be used with different filter settings to maintain similar levels of background sounds. For low, high, and wide frequency ranges of filter, counter voltage thresholds were 0.35, 0.35, and 0.5 V, respectively. For each beetle, a nonlinear model was fit to the cumulative probability of fewer counts as a function of the number of counts using PROC NLIN (SAS Institute 1985). For comparison, regression lines with average model parameters were plotted, along with the CIs of models for narrow filter frequency range.

Table 1. Number of 10-s intervals in which sounds were detected with different insect species

| Insect species         | n  | Mean no. intervals <sup>a</sup> | SD    |
|------------------------|----|---------------------------------|-------|
| Background             | 10 | 31.60a                          | 12.35 |
| <i>C. ferrugineus</i>  | 10 | 31.60a                          | 9.51  |
| <i>O. surinamensis</i> | 16 | 55.81b                          | 14.32 |
| <i>R. dominica</i>     | 10 | 100.80c                         | 33.06 |
| <i>S. oryzae</i>       | 10 | 179.60d                         | 19.47 |
| <i>T. castaneum</i>    | 10 | 156.90d                         | 17.37 |

<sup>a</sup> Means followed by the same letter are not significantly different ( $P = 0.05$ ; Tukey's studentized range test (SAS Institute 1985)).

### Results

The mean number of 10-s intervals in which sounds were detected was significantly different ( $F_{5,60} = 120.47$ ,  $P < 0.0001$ ) among insect species (Table 1). The mean number of intervals for *C. ferrugineus* was not significantly higher than that for background, and the mean number of intervals for *S. oryzae* was not significantly different from that for *T. castaneum*. However, the means for *O. surinamensis* and *R. dominica* were significantly different from the means for background and other species.

The numbers of sounds counted per 10-s interval also differed among species. Probability distributions for *R. dominica* and *S. oryzae* show that >10 counts were detected in 27 and 66% of intervals, respectively (Fig. 2). For both species,

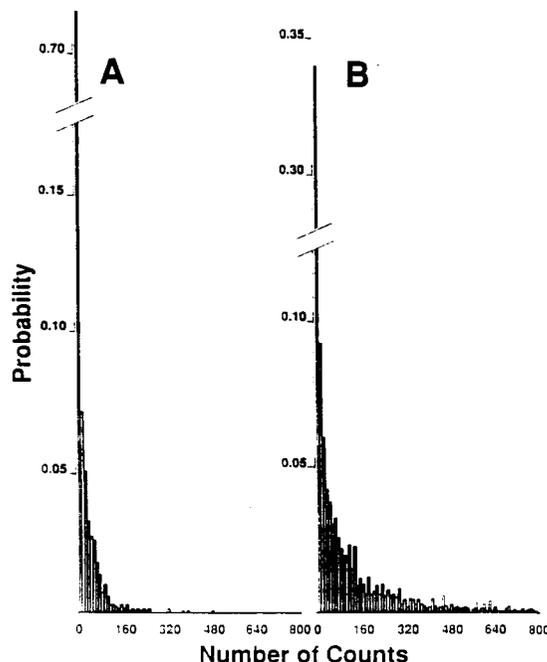


Fig. 2. Probability distributions of number of counts per 10-s interval for *R. dominica* (A) and *S. oryzae* (B).

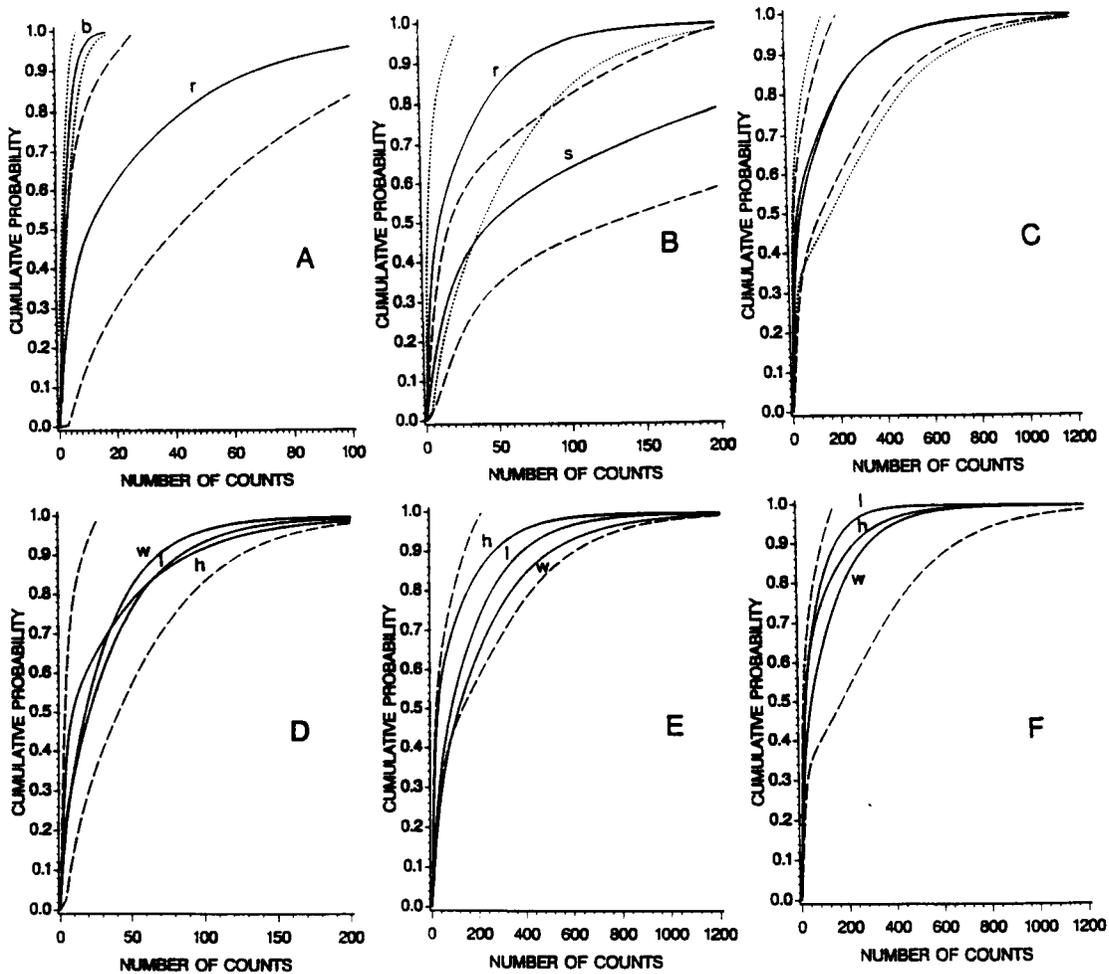


Fig. 3. Predicted cumulative probabilities of fewer counts as the number of counts per 10-s interval increased (solid line), and CIs (dotted line) for background and *R. dominica* (A), *R. dominica* and *S. oryzae* (B), and *S. oryzae* and *T. castaneum* (C). Low, high, and wide filter setting curves are shown to fall within the CIs for narrow filter setting with *R. dominica* (D), *S. oryzae* (E) and *T. castaneum* (F). Lowercase letters b, r, s, l, h, and w are used to label background, *R. dominica*, and *S. oryzae*, and low, high, and wide filter settings, respectively.

the probability of an interval having a given number of counts decreased logarithmically with increasing numbers of counts per 10-s interval. The probability distribution for *T. castaneum* was similar to that for *S. oryzae* and is not shown. For background (no insect), *C. ferrugineus*, and *O. surinamensis*, only 0.42, 0.74, and 2.00% of intervals had counts of >10, respectively.

As the numbers of counts per 10-s interval increased, we detected a progressively slower increase in the cumulative probability (Fig. 3). The relationship between the cumulative probability ( $y$ ) and the number of counts ( $x$ ) is well described by the equations  $y = 1 - (A \cdot \exp^{-Bx})$  for background, *C. ferrugineus* and *O. surinamensis* ( $r^2 = 0.95-0.99$ ), and  $y = 1 - (A \cdot \exp^{-Bx} + (1 - A) \cdot \exp^{-Cx})$  for *R. dominica*, *S. oryzae* and *T. castaneum* ( $r^2 > 0.99$ ). Estimates of the parameters  $A$ ,  $B$ , and  $C$  are given in Table 2. Above six

counts, the CIs for background and *R. dominica* did not overlap (Fig. 3A). Regression lines for *C. ferrugineus* and *O. surinamensis* fell within CIs for background and are not shown in Fig. 3. The CIs for *R. dominica* and *S. oryzae* did not overlap between 85 and 190 counts per 10-s interval (Fig. 3B). The CIs for *T. castaneum* were wider than those for *S. oryzae* (Fig. 3C). In 20% of 10-s intervals, the counts for *S. oryzae* and *T. castaneum* were higher than those for *R. dominica*. In 52% of 10-s intervals, the counts for *R. dominica* were above background counts.

The number of counts ( $y$ ) for adults of three species varied with temperatures ( $x$ ) between 17.5 and 37.5°C. The number of counts of *S. oryzae* (Fig. 4) increased as temperature increased from 17.5 to 35°C and then decreased at higher temperatures ( $y = 24.17 \text{ Exp}^{0.159x} - \text{Exp}^{-1.16 - 0.35 - x/1.11}$ ,  $\text{MSE} = 230.00$ ,  $r^2 = 0.91$ ).

Table 2. Parameters of models predicting the cumulative probability of fewer counts for a given number of counts

| Filter setting         | n  | A ± SE <sup>a</sup> | B ± SE <sup>a</sup> | C ± SE <sup>a</sup> |
|------------------------|----|---------------------|---------------------|---------------------|
| Background             |    |                     |                     |                     |
| Narrow                 | 10 | 1.10148 ± 0.14751   | 0.36946 ± 0.08490   | — —                 |
| <i>C. ferrugineus</i>  |    |                     |                     |                     |
| Narrow                 | 10 | 0.81313 ± 0.12496   | 0.31941 ± 0.09266   | — —                 |
| <i>O. surinamensis</i> |    |                     |                     |                     |
| Narrow                 | 16 | 0.91067 ± 0.14395   | 0.29119 ± 0.07493   | — —                 |
| <i>R. dominica</i>     |    |                     |                     |                     |
| Narrow                 | 10 | 0.34202 ± 0.18296   | 0.29203 ± 0.15684   | 0.02772 ± 0.01309   |
| Low                    | 2  | 0.15618 ± 0.07240   | 0.79004 ± 0.64609   | 0.02569 ± 0.00887   |
| High                   | 2  | 0.43437 ± 0.25831   | 0.35568 ± 0.24868   | 0.01947 ± 0.00387   |
| Wide                   | 2  | 0.12661 ± 0.01212   | 0.37749 ± 0.13896   | 0.03193 ± 0.02307   |
| <i>S. oryzae</i>       |    |                     |                     |                     |
| Narrow                 | 10 | 0.62107 ± 0.10606   | 0.00536 ± 0.00233   | 0.06820 ± 0.03628   |
| Low                    | 2  | 0.77249 ± 0.14697   | 0.00538 ± 0.00362   | 0.04891 ± 0.03862   |
| High                   | 2  | 0.52554 ± 0.16986   | 0.00638 ± 0.00247   | 0.08561 ± 0.04278   |
|                        |    | 0.79867 ±           |                     |                     |
| Wide                   | 2  | 0.09533             | 0.00414 ± 0.00079   | 0.03942 ± 0.01316   |
| <i>T. castaneum</i>    |    |                     |                     |                     |
| Narrow                 | 10 | 0.56003 ± 0.08336   | 0.00504 ± 0.00266   | 0.08614 ± 0.03268   |
| Low                    | 2  | 0.58606 ± 0.01224   | 0.01149 ± 0.00936   | 0.10112 ± 0.10734   |
| High                   | 2  | 0.45752 ± 0.01417   | 0.00656 ± 0.00631   | 0.06732 ± 0.04205   |
| Wide                   | 2  | 0.67037 ± 0.11459   | 0.00655 ± 0.00287   | 0.07896 ± 0.05646   |

<sup>a</sup> A, B, and C are parameter in the equations  $y = 1 - (A \cdot \exp^{-Bx})$  for background, *C. ferrugineus* and *O. surinamensis*, and  $y = 1 - (A \cdot \exp^{-Bx} + (1 - A) \cdot \exp^{-Cx})$  for *R. dominica*, *S. oryzae*, and *T. castaneum*.

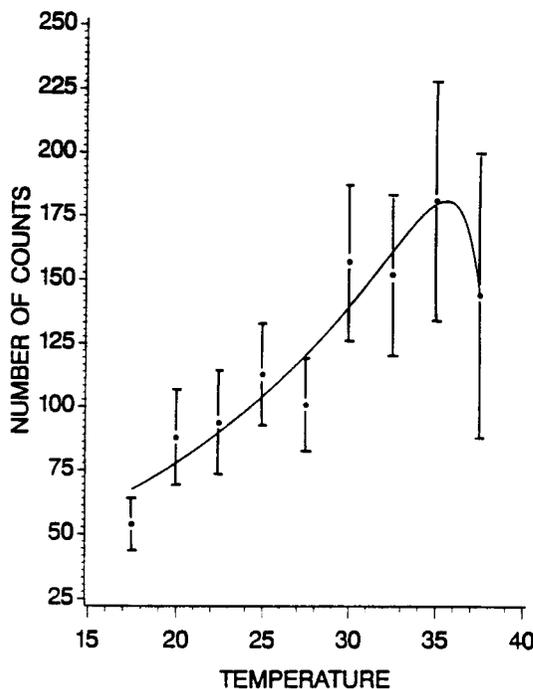


Fig. 4. Effect of temperature (°C) on the predicted (solid line) and observed (●) mean total number of sounds of *S. oryzae* counted per 12-min period. Vertical lines show the SEs for means at each temperature.

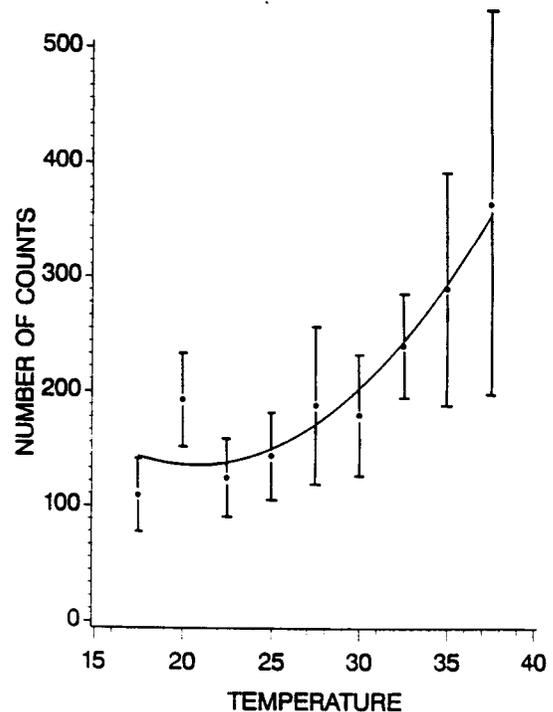


Fig. 5. Effect of temperature (°C) on the predicted (solid line) and observed (●) mean total number of sounds of *T. castaneum* counted per 12-min period. Vertical lines show the SEs for means at each temperature.

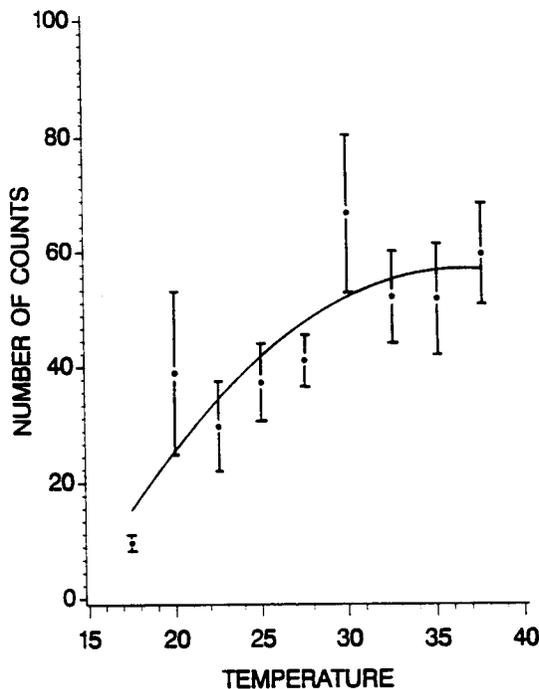


Fig. 6. Effect of temperature ( $^{\circ}\text{C}$ ) on the predicted (solid line) and observed ( $\bullet$ ) mean total number of sounds of *R. dominica* counted per 12-min period. The vertical lines show the SEs for means at each temperature.

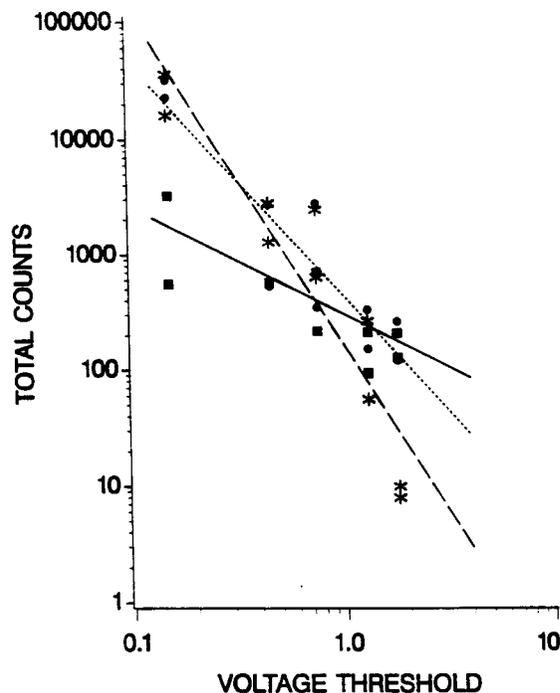


Fig. 7. Decrease in logarithm of total number of counts per 36-min period with increase in logarithm of voltage threshold of counter for *R. dominica* ( $\blacksquare$ ), *S. oryzae* ( $\bullet$ ), and *T. castaneum* (\*).

The SEs for these four model parameters were 8.44, 0.013, 3.81, and 1.64, respectively. The number of counts of *T. castaneum* (Fig. 5) tended to be lowest at  $<25^{\circ}\text{C}$  and then increased steadily as temperatures increased ( $y = 465.39 - 31.87x + 0.77x^2$ ,  $\text{MSE} = 931.57$ ,  $r^2 = 0.90$ ). The SEs of the three model parameters were 203.76, 15.39, and 0.28, respectively. The number of counts of *R. dominica* (Fig. 6) increased as temperature increased from 17.5 to  $30^{\circ}\text{C}$  and then became level at higher temperatures ( $y = 8.48x - 0.12x^2 - 97.43$ ,  $\text{MSE} = 92.08$ ,  $r^2 = 0.76$ ). The SEs of the three model parameters were 4.84, 0.087, and 64.06, respectively.

The regression lines for high, low, and wide filter frequency ranges fell within the CIs for the narrow filter frequency range (Fig. 3 D-F). The total counts detected during a 36-min period decreased logarithmically as the counter voltage threshold was raised (Fig. 7). The relationship between the total counts ( $y$ ) and the voltage threshold ( $x$ ) is described by the equations  $\log y = 2.49 - 0.92 \cdot \log x$  with  $N = 9$ ,  $r^2 = 0.69$ ,  $\text{SE}_{\text{intercept}} = 0.094$ ,  $\text{SE}_{\text{slope}} = 0.22$ , and  $\text{MSE} = 0.071$ ;  $\log y = 2.65 - 2.01 \cdot \log x$  with  $N = 9$ ,  $r^2 = 0.85$ ,  $\text{SE}_{\text{intercept}} = 0.12$ ,  $\text{SE}_{\text{slope}} = 0.30$ , and  $\text{MSE} = 0.13$ ; and  $\log y = 2.22 - 2.91 \cdot \log x$  with  $N = 9$ ,  $r^2 = 0.87$ ,  $\text{SE}_{\text{intercept}} = 0.17$ ,  $\text{SE}_{\text{slope}} = 0.39$ , and  $\text{MSE} = 0.22$  for *R. dominica*, *S. oryzae*, and *T.*

*castaneum*, respectively. Equations for *S. oryzae* and *T. castaneum* were not significantly different ( $F_{2,16} = 2.64$ ,  $P = 0.10$ ), but the equation for *R. dominica* was significantly different from those for *S. oryzae* ( $F_{2,16} = 7.62$ ,  $P = 0.0047$ ) and *T. castaneum* ( $F_{2,16} = 9.78$ ,  $P = 0.0017$ ). Total counts decreased more slowly for *R. dominica* than for the other two species. *C. ferrugineus* and *O. surinamensis* were detected when the voltage threshold for the counter was set at 0.15 V, but these species were not detected when the voltage threshold was set at 0.45 V.

### Discussion

Although we could not distinguish all of the five species (Table 1), *S. oryzae* and *T. castaneum* were detected during more 10-s intervals than *R. dominica*. *C. ferrugineus* and *O. surinamensis* were detected less frequently than other species. These species groups were also distinguishable by differences between the probability distributions of the numbers of sounds per 10-s interval (Fig. 2), and by nonoverlapping CIs and the percentage of counts above those of another species (Fig. 3). The magnitude of the beetle-to-beetle variation is evident from SDs shown in Table 1, the width of CIs in Fig. 3, the SEs in Figs. 4-6, and the spread of data

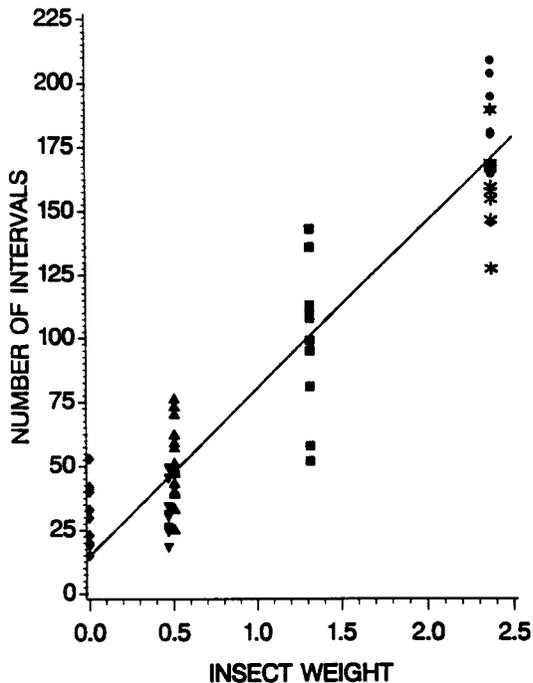


Fig. 8. Number of 10-s intervals with sounds as a function of mean insect weight (mg). For the best fit regression line, the slope is 65.32 with a SE of 3.24, the intercept is 14.89 with a SE of 5.05,  $n$  is 55,  $r^2$  is 0.88, and MSE is 420.76. Data are given for background ( $\diamond$ ), *C. ferrugineus* ( $\nabla$ ), *O. surinamensis* ( $\blacktriangle$ ), *R. dominica* ( $\blacksquare$ ), *S. oryzae* ( $\bullet$ ), and *T. castaneum* (\*). Background data are given for reference but are not included in regression.

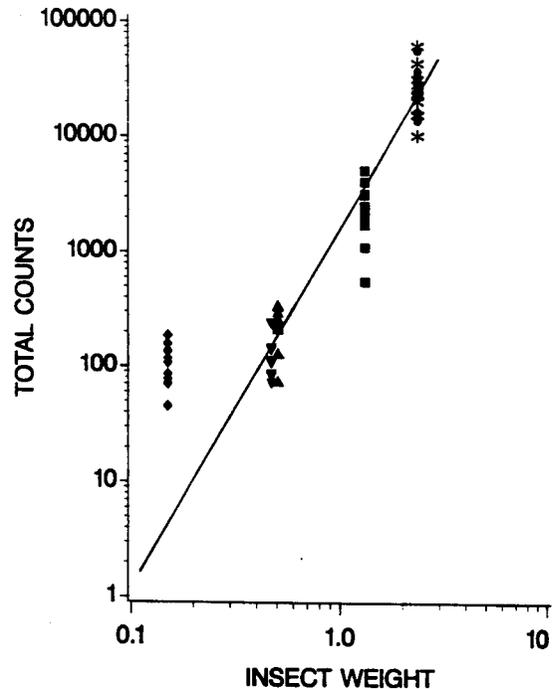


Fig. 9. Increase in the logarithm of total counts per 36-min period as a function of the logarithm of mean insect weight (mg). For the best fit regression line, the slope is 3.11 with a SE of 0.11, the intercept is 3.20 with a SE of 0.034,  $n$  is 49,  $r^2$  is 0.95, and MSE is 0.055. Data are given for background ( $\diamond$ ), *C. ferrugineus* ( $\nabla$ ), *O. surinamensis* ( $\blacktriangle$ ), *R. dominica* ( $\blacksquare$ ), *S. oryzae* ( $\bullet$ ), and *T. castaneum* (\*). Background data are given for reference but are not included in regression.

points in Figs. 7–9. This beetle-to-beetle variation makes elaborate data analysis necessary to distinguish between species and to estimate insect densities.

The number of intervals with sounds increased linearly (Fig. 8) and the total number of counts during a 36-min period increased logarithmically (Fig. 9) as a function of the mean weight of species. This logarithmic increase compared with the linear increase in the percentage of intervals with sounds means that insect weight has a larger influence on the number of sounds than on the probability of detection. Both relationships are caused by the sounds made by heavy insects reaching a microphone more often than those made by light insects. Previous studies by Vick et al. (1988a) and Hagstrum et al. (1990) have shown that the number of sounds decreased logarithmically as the distance increased between the microphone and *S. oryzae* larvae or *T. castaneum* adults. To be detected, small insects probably must be closer to the microphone than large insects; therefore they are detected less frequently.

Species causing the most damage to grain also tend to be the most readily detected. *S. oryzae* and *R. dominica* cause the most damage and *C. ferrugineus* and *O. surinamensis* cause the least damage (Hurlock 1967, Campbell & Sinha 1976). However, the less damaging species, *T. castaneum* (Simwat & Chahal 1981) will be confused with the more damaging *S. oryzae*. Further separation of species may be possible using differences in insect distribution in the grain storage bin and differences in population growth rates between species.

Unfortunately, the differences between species could not be enhanced by using different instrument settings. Widening the filter frequency range did not improve detection because background sounds increased as much as insect sounds, and the voltage threshold had to be raised to eliminate additional background sounds. The separation of medium and heavy weight classes became less distinct as the counter voltage threshold was increased. Raising the voltage threshold reduces the number of sounds detected because weaker sounds are not detected. The logarithmic

decrease in the number of counts as the voltage threshold is raised may be caused by insects having to be closer to the microphone for the same number of sounds to be detected.

Automation of stored-grain insect monitoring can improve pest management by providing more timely and reliable information on insect density. Results presented here will allow acoustical data to be interpreted better for use in pest management programs. Early in the storage period, when few insects are present and each microphone generally detects only one insect during each 10-s interval, our results should allow us to determine which insect species are present. The effects of the distance between an insect and a microphone on the number of sounds detected can be averaged by using data from many time intervals. If >10 sounds are detected during >72% of 10-s intervals with insect sounds, the microphone is likely to be listening to *S. oryzae* or *T. castaneum*. If >10 sounds are detected during 47–72% of 10-s intervals with insect sounds, the microphone is likely to be listening to *R. dominica*. If >10 sounds are detected during <2% of 10-s intervals with insect sounds, the microphone is probably listening to *C. ferrugineus* or *O. surinamensis*. Equations predicting the number of insect sounds over a range of temperatures can be used to adjust estimates of insect population density by removing the effects of temperature.

We are currently coupling the acoustical detection system with an expert system developed by Flinn & Hagstrum (1990) for stored-grain insect management so that the recommendations of the expert system can be based upon more current and accurate estimates of insect density. Our current study provides part of the information needed to develop a rule base with which the expert system can estimate insect density from acoustical detection data. Results presented should make it possible to distinguish between some species and to remove the effects of temperature on insect density estimates.

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