

Effects of Shelf Architecture and Parasitoid Release Height on Biological Control of *Plodia interpunctella* (Lepidoptera: Pyralidae) Eggs by *Trichogramma deion* (Hymenoptera: Trichogrammatidae)

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ABSTRACT The effects of shelving type, packaging, and release height on success of *Trichogramma deion* Pinto & Oatman (Hymenoptera: Trichogrammatidae) parasitizing *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae) eggs was studied under laboratory conditions. In trials on multiple-tiered gondola-type or open shelving units, with or without packaging, foraging success was evaluated by comparing parasitism and total mortality rates of sentinel egg disks among shelves after a single point-release of *T. deion*. Results showed that *T. deion* parasitized more egg disks and killed more total eggs on open shelves than on gondola shelving. The presence of packaging had no effect on parasitoid foraging on open shelves; however, packaging did interfere with parasitism of *P. interpunctella* eggs on gondola shelving. Egg parasitism and mortality patterns among shelves were not as evenly distributed on gondola-type shelving compared with open shelving. On gondola shelves without packages, changing the release point of *T. deion* from the middle to the lowest shelf shifted the distribution of parasitism toward the floor. Gondola shelving, especially in the presence of packaging, reduced foraging efficiency of *T. deion* for *P. interpunctella* eggs. Thus, to attain adequate control of *P. interpunctella*, it may be necessary to use two release heights on gondola shelving.

KEY WORDS habitat complexity, stored products, biological control

Augmentative biological control by using trichogrammatid wasps offers a promising new approach for managing stored-product moths. Previous studies with *Trichogramma* species have demonstrated marked reductions in moth captures and infestations in bulk peanut, *Arachis hypogaea* L., storage (Brower 1988); bulk wheat, *Triticum aestivum* L., storage (Schöller et al. 1996); and bakeries (Prozell and Schöller 1998, Steidle et al. 2001) as well as in warehouses and retail stores (Prozell et al. 1996).

The Indianmeal moth, *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae), is one of the most serious pests in retail stores and warehouses, infesting a variety of products, including raw and processed cereals, dried fruit, pulses, and garlic, *Allium* L. (Cox and Bell 1991, Perez-Mendoza and Aguilera-Pena 2004). A major obstacle to the development of augmentative biological control for *P. interpunctella* in retail stores and warehouses is the absence of practical guidelines

about when, where, and how many *Trichogramma* to release so that maximum pest control is achieved at minimal expense. An important consideration when developing release guidelines is to define and understand how habitat complexity influences *Trichogramma*. For example, a high level of habitat complexity has been shown to negatively affect *Trichogramma* in a variety of natural and artificial systems, including tree branches and crowns (McCravy and Berisford 1998); maize, *Zea mays* L., and wax paper models (Andow and Prokrym 1990, Andow and Olson 2003); pine needles and paper models (Lukianchuk and Smith 1997); and artificial plant models of varying structural complexity (Gingras et al. 2002, Gingras and Boivin 2002). In stored grain, Schöller et al. (1994) demonstrated that *Trichogramma* were unable to penetrate more than several centimeters into bulk wheat. A related study by Grieshop (2005) showed that although good suppression of *P. interpunctella* by *Trichogramma deion* Pinto & Oatman (Hymenoptera: Trichogrammatidae) occurred on packaged cornmeal, virtually no suppression was evident on bulk cornmeal.

On a larger scale, variation in habitat complexity pertaining to shelf architecture (i.e., size, type, and presence and type of packaging) may be one of the most relevant factors to consider when making decisions about the location and magnitude of *Trichogramma* releases. A previous study showed that

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gondola shelving seems to negatively affect host-foraging and parasitism by *Trichogramma pretiosum* Riley compared with open shelving (Grieshop 2005). These findings indicate that guidelines for releasing *Trichogramma* species in stored-product facilities need to take into account variability in the structural environment, which consists of different types of shelving, the presence and type of packaging stocked on those shelves, and patches of spilled products that may harbor concentrations of host eggs. In addition, tests to determine how to choose the release point for *Trichogramma* are needed because reduced foraging efficiency caused by structural characteristics of retail stores and warehouses may be avoided or hindered further depending on how parasitoids disperse from the release point.

In general, *Trichogramma* are released on or in proximity to the products to be protected, typically at 1-m distances laterally (Schöller et al. 2006). However, little is known about how rates of parasitism are affected by the type of shelving on which *Trichogramma* are released may affect rates of parasitism. Because making multiple uniform releases is labor-intensive, inconvenient, and costly, the optimization of release rates on different types of shelving is of economic importance. Thus, the objectives of this study were to investigate the effects of shelf type, presence, or absence of packaging, and release point of *T. deion* on percentage of parasitism and adjusted mortality of *P. interpunctella* eggs.

Materials and Methods

Insects. Insect colonies were maintained in walk-in growth chambers at the USDA-ARS, Grain Marketing and Production Research Center (GMPCRC) in Manhattan, KS. The Mediterranean flour moth, *Ephestia kuehniella* Zeller (Lepidoptera: Pyralidae), served as a rearing host for *T. deion*, whereas *P. interpunctella* was used in experiments. Larvae of both moths were reared on a standard diet of cracked wheat, wheat shorts, honey, and glycerin described in McGaughey and Beeman (1988). *T. deion* were reared on sterilized eggs of *E. kuehniella*. *Ephestia* eggs were sterilized by exposing them to UV light (6-W Spectronics BLE 6254s) for 1 min (eggs were placed ≈ 2.5 cm from the bulb). Colonies of *T. deion* and *E. kuehniella* were originally obtained from Beneficial Insectaries (Redding, CA) in April 2003 and February 2002, respectively (Kansas State University Entomology voucher no. 171). The *P. interpunctella* used in experiments were obtained from a colony maintained in continuous production for more than a decade at the GMPCRC (Manhattan, KS). Rearing conditions for *T. deion* and *P. interpunctella* were $\approx 26^{\circ}\text{C}$ and 60% RH.

Experimental Design. Experiments were conducted in two walk-in growth chambers located at the GMPCRC. Experiments were conducted at $23 \pm 1^{\circ}\text{C}$ and $45 \pm 5\%$ RH, with a photoperiod of 16:8 (L:D) h. Temperature and relative humidity settings for the chambers were based on means calculated from 6 mo

of data collected between April and November 2002 from four retail stores in Manhattan, KS. Open-shelf trials were run between 1 July and 5 November 2003, whereas gondola-shelf trials were run between 13 February and 7 December 2004. Sentinel egg disks were used to map parasitism. Disks consisted of 1-cm-diameter cardstock punch outs with four viable *P. interpunctella* eggs (<18 -h-old) attached using an inert glue, Traganth gum (Merck, Whitehouse Station, NJ). *T. deion* were released as late-stage pupae inside eggs of *E. kuehniella* glued onto cardstock. The number and timing of each release was adjusted so that ≈ 500 female wasps emerged within 1 h of the cards being placed on the shelves.

Separate comparisons were made to test the influence of shelving type, the presence or absence of packages, and the shelf height at which parasitoids were released, on the host-foraging success of *T. deion*. The first trial consisted of four treatments made up of two factors: shelving type and either empty shelves or shelves with packaging. Each treatment was replicated five times for a total of 20 experimental units. In treatments that included packaging, an assortment of empty breakfast cereal boxes was used. These boxes were placed on the shelves between sentinel disks in four columns, with six boxes per column and boxes spaced equidistant to fill the width of the shelf. Total surface area of the packages on each shelf was 3.97 m^2 . The second trial consisted of two treatments with the release point either on the third (middle) or first (lowest) shelf of gondola shelves without packages.

The open shelving units (Fig. 1) consisted of 1.27-cm-thick particleboard shelves and painted sheet metal risers. A 3 by 5 grid of sentinel egg disks was placed on each shelf and on the floor directly beneath the shelving unit, with the exception of the third shelf from the bottom, which had the center sentinel egg disk replaced with the *T. deion* release point (Fig. 1). The resulting three-dimensional grid consisted of six tiers of 15 egg disks/tier with the third (central) shelf consisting of 14 egg disks. The inter-disk spacing for sentinel egg grids measured 33 by 28.6 cm. Figure 1 shows the layout of the open shelves, grids of sentinel egg disks, and the *T. deion* release point.

The gondola units (Fig. 2) consisted of five painted sheet metal shelves on either side of two pegboard (fiberboard) dividers that extended from the lowest shelf to the highest. A 2 by 4 grid of sentinel egg disks was placed on each shelf on either side of the divider and on the floor directly beneath the shelving unit. The resulting three-dimensional grid consisted of six tiers of 16 egg disks per tier (Fig. 2). The interdisk spacing for sentinel egg grids on gondola shelves measured 38.1 by 22.9 cm per shelf with 0.1 m (the pegboard divider) between the two sides of the shelf. *T. deion* were released at the center of shelf three or shelf one on two 375-egg cards, one on either side of the divider. Packaging was laid out in four columns of three boxes on either side of the central divider.

An additional 30–40 sentinel egg disks (120–160 eggs) were kept for each replicate. These disks were kept in sealed petri dishes within the test chambers

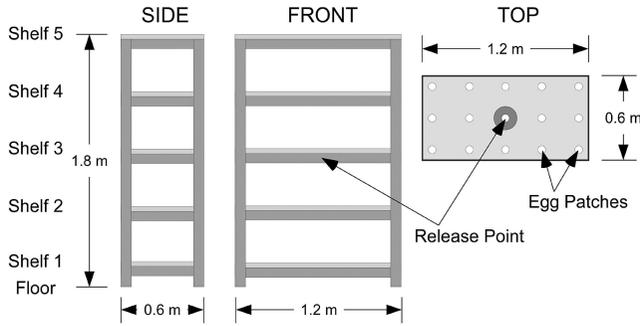


Fig. 1. Diagram of open shelving unit showing 3 × 5 sentinel egg disk (egg patches) layout and the central *Trichogramma* release point. Sentinel egg disks were spaced in a 33- × 28.6-cm grid.

and were used to calculate incidental *P. interpunctella* egg mortality. Replications with >20% incidental mortality were excluded from the experiment. Replicates were run at least 5 d apart to allow adequate time for *T. deion* from the previous experiment to die.

Data Collection. Sentinel egg disks were collected after 48 h and held for 7 d in a growth chamber set at 26 ± 1°C and 60 ± 7% RH to allow any live parasitoids to develop and emerge. Subsequently, the eggs on each sentinel egg disk were individually inspected using a stereomicroscope (original magnification 160–240×), to count the number of eggs hatched, parasitized, or dead. We calculated percentage of parasitism per shelf, percentage of egg disks attacked, and corrected total mortality per shelf. Corrected total mortality (parasitized eggs + dead eggs) was calculated as (experimental percentage of mortality – control percentage of mortality) / (1 – control mortality) (Abbott 1925).

Data Analysis. Data were analyzed using the mixed, GLM, and frequency procedures (SAS Institute 2000). All percentages were transformed by using arcsine square root [$\arcsin(x^{0.5})$] before analyses to stabilize variance. Complete factorial mixed model analysis of variance (ANOVA) were run for percentage of eggs parasitized, percentage of disks attacked, and percentage of corrected total mortality for the shelving type and packaging trial, and for the lower release point on

gondola shelving trial. For the shelving type and packaging experiment, to account for the time factor, shelving type and packaging were nested within experimental run as the random factor, and shelving type, packaging, and shelf were analyzed as fixed factors. For the release point on gondola shelving experiment, to account for the time factor, release point was nested within experimental run as the random factor, and release point and shelf level were analyzed as fixed factors. In addition, a series of mixed model *t*-test comparisons were made within packaging treatment and shelf level by using percentage of parasitism, percentage of disks attacked, and percentage of corrected total mortality as response variables. We used shelving type nested within run as the random factor and shelving type as the fixed factor. Degrees of freedom were adjusted using the Kenward–Rodgers correction for mixed models to account for nesting in the designs. Finally, five one-way ANOVA models by using the GLM procedure were used to compare percentage of parasitism, percentage of disks attacked, and percentage of corrected total mortality among shelf levels within individual treatments with Tukey–Kramer adjusted least significant difference (LSD) multiple comparisons used to separate means.

Further analysis consisted of chi-square goodness-of-fit-tests performed using the frequency procedure; the distribution of parasitism across the six shelves was

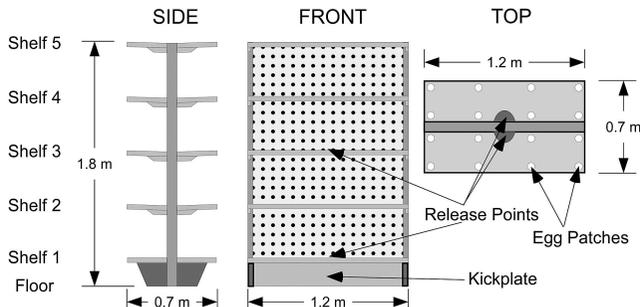


Fig. 2. Diagram of gondola shelving unit showing four × four sentinel egg disk layout across a pair of shelves and the split central or lowest shelf *Trichogramma* release point. Sentinel egg disks (egg patches) were spaced in two 2 × 4 38.1- × 22.9-cm grids.

Table 1. Mixed model ANOVA results for percentage of parasitism, percentage of egg disks attacked, and percentage of Abbott's adjusted mortality between packaging treatments and shelving type

Effect	df	% parasitism		% egg disks parasitized		% total corrected mortality	
		F	P	F	P	F	P
Packages	1, 16	0.01	0.99	0.11	0.74	0.02	0.88
Shelf level	5, 80	12.98	0.01	14.56	0.01	21.86	0.01
Packages × shelf level	5, 80	4.35	0.01	3.80	0.01	2.68	0.03
Shelving type	1, 16	19.24	0.01	11.59	0.01	31.06	0.01
Shelving type × packages	1, 16	0.61	0.44	0.66	0.43	0.17	0.69
Shelving type × shelf level	5, 80	4.61	0.01	4.84	0.01	4.20	0.01
Shelving type × packages × shelf level	5, 80	0.29	0.92	0.64	0.67	0.47	0.80

tested to determine whether it was significantly different from a uniform distribution.

Results

Shelving and Packaging. Significant treatment effects for percentage of parasitism, percentage of egg disks parasitized, and percentage of corrected mortality were detected for shelf level and shelf type, and for the shelf level × shelf type and shelf level × packaging interactions in the three-way mixed model ANOVA (Table 1). For shelves without packages, the

overall mean ± SEM percentage of parasitism was 56.16 ± 2.97% on open shelves versus 40.94 ± 4.4% on gondola shelves; overall mean ± SEM percentage of egg disks attacked was 68.75 ± 4.21% on open shelves versus 42.37 ± 5.23% on gondola shelves; and overall mean percentage of corrected total mortality was 79.1 ± 2.85% on open shelves versus 69.38 ± 2.94% on gondola shelves. On shelves with packages, the overall mean percentage of parasitism was 60.06 ± 5.96% on open shelves versus 37.03 ± 3.6% on gondola shelves; overall mean percentage of disks attacked was 71.45 ± 7.38% on open shelves versus 40.05 ± 3.48% on gondola

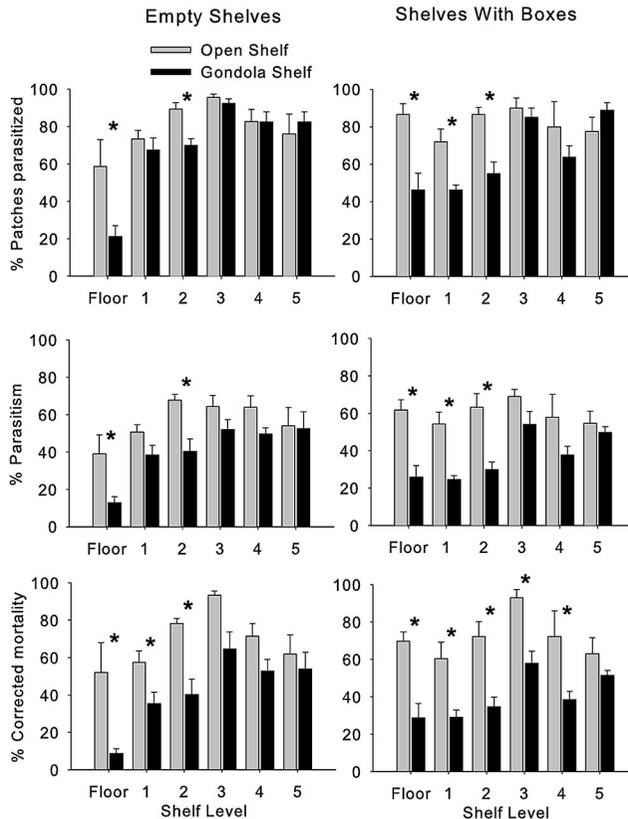


Fig. 3. Mean ± SEM percentage of parasitism, percentage of egg disks parasitized, and percentage of corrected total mortality of *P. interpunctella* eggs for open and gondola shelves with empty shelves presented in the left column and shelves with packages presented in the right column. Asterisk (*) indicates significant difference between treatments at that shelf level (*t*-test: *df* = 8, *P* < 0.05).

Table 2. Effect of packages on parasitism of *P. interpunctella* by *T. deion* on open-type shelving

Treatment	% parasitism	% egg disks parasitized	% total corrected mortality
Without packages			
Floor	39.00 ± 10.08a	58.67 ± 13.47a	52.04 ± 16.00b
Shelf 1	50.67 ± 3.89a	73.33 ± 5.33a	57.46 ± 6.04b
Shelf 2	67.67 ± 3.10a	89.33 ± 3.40a	78.16 ± 2.70ab
Shelf 3 ^a	64.29 ± 5.84a	95.71 ± 1.75a	93.22 ± 2.43a
Shelf 4	64.00 ± 6.07a	82.67 ± 4.00a	71.45 ± 6.85ab
Shelf 5	54.00 ± 9.77a	76.00 ± 10.19a	61.83 ± 10.33ab
With packages			
Floor	61.67 ± 5.55a	86.67 ± 5.58a	69.71 ± 4.96ab
Shelf 1	54.33 ± 6.25a	72.00 ± 6.80a	60.34 ± 8.85b
Shelf 2	63.33 ± 7.13a	86.67 ± 3.65a	72.13 ± 7.93ab
Shelf 3 ^a	68.93 ± 3.94a	90.00 ± 5.35a	92.81 ± 4.48a
Shelf 4	58.00 ± 12.07a	80.00 ± 13.50a	72.19 ± 13.67ab
Shelf 5	54.67 ± 6.46a	77.33 ± 7.77a	62.97 ± 8.62ab

Values (mean ± SEM) within the same column and treatment followed by a different letter are significantly different (LSD with Tukey-Kramer adjustment [$P < 0.05$]).

^a Parasitoid release shelf.

shelves; and overall mean percentage of corrected total egg mortality was $82.02 \pm 5.41\%$ on open shelves versus $62.17 \pm 3.44\%$ on gondola shelves. In almost all cases, the highest rates of egg parasitism, percentage of disks attacked, and egg mortality were observed on the release shelf (shelf 3), with the exception of percentage of parasitism on open shelves without packages, where shelf 2 had the highest rate.

Significant differences in percentage of parasitism, percentage of disks attacked, and percentage of corrected total mortality were detected within shelves with packages, among shelves, and between shelving types (Fig. 3). For shelves without packages, percentage of parasitism, and percentage of disks attacked were significantly greater for open shelves on the floor and on shelf 2, and percentage of corrected total egg mortality was significantly greater for open shelves on the floor and on shelves 1–3 (Fig. 3).

For shelves with packages, percentage of parasitism and percentage disks attacked were significantly greater for open shelves on the floor, shelf 1, and shelf 2; and percentage of corrected total mortality was significantly greater for open shelves on the floor, and on shelves 1–4 (Fig. 3).

One-way ANOVA for shelf levels by shelving type and presence or absence of packages showed a significant difference in distribution of parasitism among the treatments (Tables 2 and 4). On open shelving units, no significant differences were found among shelves for percentage of parasitism or percentage of disks attacked, either with or without packages (Table 2). However, percentage of corrected egg mortality was significantly greater on shelf 3 compared with the floor and shelf 1 for open shelves without packages ($F = 3.72$; $df = 5, 80$; $P = 0.01$) (Table 2). On open shelves with packages, egg mortality was significantly greater on shelf 3 than on shelf 1 ($F = 2.64$; $df = 5, 80$; $P = 0.05$) (Table 2).

In contrast, on gondola shelving without packages, percentage of parasitism, percentage of disks attacked,

Table 3. Effect of packages and release point on parasitism of *P. interpunctella* by *T. deion* on gondola-type shelving

	% parasitism	% egg disks attacked	% total corrected mortality
Treatment 1: without packages, release on shelf 3			
Floor	12.81 ± 3.26b	21.25 ± 5.80c	8.60 ± 2.56b
Shelf 1	38.44 ± 5.20a	67.50 ± 6.37b	35.40 ± 6.09a
Shelf 2	40.31 ± 6.62a	70.00 ± 3.64ab	40.17 ± 8.31a
Shelf 3	51.88 ± 5.33a	92.50 ± 2.34a	64.58 ± 9.13a
Shelf 4	49.69 ± 3.22a	82.50 ± 5.38ab	52.66 ± 6.30a
Shelf 5	52.50 ± 8.92a	82.50 ± 5.38ab	53.87 ± 9.03a
Treatment 2: with packages, release on shelf 3			
Floor	25.94 ± 6.20c	46.25 ± 8.97c	28.70 ± 7.56b
Shelf 1	24.69 ± 2.00c	46.25 ± 2.50c	29.18 ± 3.73b
Shelf 2	30.00 ± 4.03bc	55.00 ± 6.06c	34.65 ± 5.13ab
Shelf 3	54.06 ± 6.86a	85.00 ± 5.08ab	57.93 ± 6.53a
Shelf 4	37.81 ± 4.59ab	63.75 ± 6.06bc	38.50 ± 4.36ab
Shelf 5	49.69 ± 3.18ab	88.75 ± 4.15a	51.34 ± 2.77ab
Treatment 3: without packages, release on shelf 1			
Floor	48.75 ± 5.98a	86.25 ± 4.59ab	70.23 ± 6.38ab
Shelf 1	55.63 ± 6.26a	88.75 ± 4.59a	89.93 ± 3.83a
Shelf 2	38.13 ± 6.68ab	55.00 ± 8.71c	51.21 ± 8.42bc
Shelf 3	23.13 ± 2.06b	45.00 ± 3.64c	31.52 ± 3.11c
Shelf 4	22.50 ± 6.14b	38.75 ± 9.14c	28.27 ± 8.75c
Shelf 5	33.13 ± 4.57ab	58.75 ± 5.80bc	47.90 ± 3.39bc

Values (mean ± SEM) within the same column and treatment followed by a different letter are significantly different (LSD with Tukey-Kramer adjustment [$P < 0.05$]).

and percentage of total corrected egg mortality all differed significantly among shelves ($F = 7.73$, $df = 5, 80$, $P = 0.01$; $F = 14.46$, $df = 5, 80$, $P < 0.01$; and $F = 8.45$, $df = 5, 80$, $P = 0.01$, respectively). Rates of parasitism on the floor were significantly lower than those on the five shelves. In addition, the percentage of disks attacked on shelf 1 was significantly lower than on shelf 3 (Table 3). For gondola shelves with packages, percentage of parasitism, percentage of disks attacked, and percentage of total corrected egg mortality were also significantly different among shelves ($F = 6.68$, $df = 5, 80$, $P = 0.01$; $F = 9.28$, $df = 5, 80$, $P < 0.01$; and $F = 4.95$, $df = 5, 80$, $P = 0.01$, respectively), with rates on the floor lower than those on the upper three shelves (Table 3).

The distribution of parasitism across shelf units for open shelves without packages was significantly different from a uniform distribution ($\chi^2 = 30.995$, $df = 5$, $P < 0.01$). This was also true for gondola shelves without packages ($\chi^2 = 88.12$, $df = 5$, $P < 0.01$), and gondola shelves with packages ($\chi^2 = 67.02$, $df = 5$, $P < 0.01$). However, the distribution of parasitism on open shelves with packages was not significantly different from a uniform distribution ($\chi^2 = 7.62$, $df = 5$, $P = 0.18$).

Release Height. Two-way ANOVA comparing release points on gondola shelves showed that shelf level, and the interaction between shelf level and height of parasitoid release, significantly affected percentage of parasitism, percentage of disks attacked, and percentage of corrected egg mortality (Table 4). When parasitoids were released on shelf 1, percentage of parasitism was significantly greater on the floor, and significantly lower on shelves 3 and 4, than when

Table 4. Mixed model ANOVA results for percentages of parasitism, egg disks attacked, and total mortality on gondola shelves between release points.

Effect	df	% parasitism		% egg disks parasitized		% total corrected mortality	
		F	P	F	P	F	P
Release point	1, 8	0.48	0.51	2.57	0.15	4.46	0.07
Shelf level	5, 40	3.73	0.01	3.95	0.01	5.43	0.01
Release point × shelf level	5, 40	17.86	0.01	24.35	0.01	23.37	0.01

parasitoids were released on shelf 3 (Fig. 4). In addition, a significantly greater percentage of disks was attacked on the floor and on shelf 1, and a significantly lower percentage of disks was attacked on shelves 3–5 when *Trichogramma* were released on shelf 1 (Fig. 4). When parasitoids were released on shelf 1, percentage of corrected total egg mortality was significantly greater on the floor and on shelf 1, and significantly lower on shelf 3, compared with mortality on the same shelves when parasitoids were released on shelf 3 (Fig. 4).

Significant differences were found among shelves for both release heights, indicating different patterns of parasitism between the two treatments. For shelf 1 releases, percentage of parasitism was greater on the

floor and on shelf 1 than on shelves 3 and 4 ($F = 5.93$; $df = 5, 80$; $P < 0.01$). Percentage of egg disks attacked was greater on the floor and on shelf 1 than on shelves 2–4 ($F = 10.88$; $df = 5, 80$; $P < 0.01$). The percentage of corrected total mortality was greater on shelf 1 than on shelves 2–4; and greater on the floor than on shelves 3 and 4 ($F = 15.21$; $df = 5, 80$; $P < 0.01$) (Table 3). In contrast, for shelf 3 releases, percentage of parasitism and percentage of corrected total mortality were lower on the floor than on the five shelves ($F = 7.73$, $df = 5, 80$, $P < 0.01$; and $F = 8.45$, $df = 5, 80$, $P < 0.01$, respectively), and percentage of egg disks attacked was lower on the floor than on the shelves, and lower on shelf 1 than on shelf 3 ($F = 14.46$; $df = 5, 80$; $P < 0.01$) (Table 3).

For both parasitoid release points, the pattern of parasitism among gondola shelves did not fit a uniform distribution ($\chi^2 = 78.43$, $df = 5$, $P < 0.01$; and $\chi^2 = 88.12$, $df = 5$, $P < 0.01$, respectively).

Discussion

Shelving and Packaging. The reduced levels of parasitism and *T. deion*-mediated mortality of *P. interpunctella* eggs on gondola shelves compared with open shelves could be due to a variety of structural differences between the two shelving types. Perhaps the most important difference is the pegboard divider present in gondola shelves. The pegboard divider extends from the top of the first shelf to the bottom of the fifth shelf and in addition to adding to the overall surface area of the shelving unit, might reduce spatial continuity between the two sides of a shelving tier. That parasitism on the top tier did not differ significantly between the two shelving types suggests that the central partition may interfere with foraging (Fig. 3).

Additional differences between gondola and open shelves are apparent in shelf continuity and construction. Gondola shelves are less continuous than open shelves as only the two shelf ends are in contact with the central partition, leaving a 0.5-cm gap running the length of the shelf. Although *T. deion* is capable of flight, this gap may limit shelf-to-shelf movement.

A final major structural difference between the two shelving styles is the presence of kickplates on gondola shelves (Fig. 2), which extend from the bottom of the lowest shelves to the floor. Percentage of eggs parasitized, percentage of egg disks attacked, and percentage of egg mortality on the lowest shelf did not differ significantly between the two shelving types, which suggests that few *T. deion* foraged underneath the

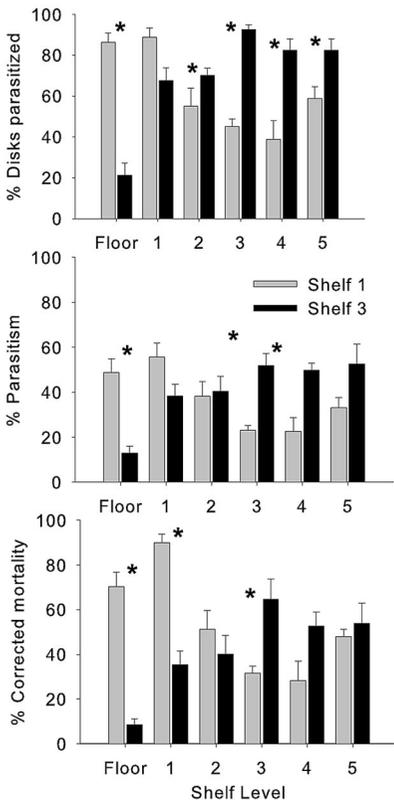


Fig. 4. Mean ± SEM percentage of parasitism, percentage of egg disks parasitized, and percentage of corrected total mortality of *P. interpunctella* eggs for either a first or third shelf release of *T. deion* on gondola shelves. Asterisk (*) indicates significant difference between treatments at that shelf level (t -test: $df = 8$, $P < 0.05$).

kickplates. When the release point was shifted from shelf 3 to the lowest gondola shelf, significantly more eggs were parasitized or had increased mortality. However, spillage typically accumulates on floors underneath shelving (Roesli et al. 2003, Nansen et al. 2004), and other studies have demonstrated the negative influence of increased microhabitat complexity on *Trichogramma* foraging ability (Schöller et al. 1996, Grieshop 2005). Thus, host eggs located in spillage beneath shelves are likely to escape parasitism due to increased microhabitat complexity.

A central release point would probably provide the best overall coverage of products located on both open and gondola shelving. However, to achieve adequate control of *P. interpunctella*, managers should make sanitation under shelves a priority. Where sanitation is not feasible, releases of the late larval parasitoid *Habrobracon hebetor* (Say) (Hymenoptera: Braconidae) might be used in conjunction with *T. deion* to manage *P. interpunctella* populations located in spillage under shelving (Grieshop 2005).

In contrast to shelving type, the presence or absence of packages seemed to have a limited effect on the percentage of egg parasitism, percentage of egg disks attacked, and egg mortality. An experiment on the effects of millet and flour on the host-foraging success of three species of *Trichogramma* species showed that increases in small-scale habitat complexity had a negative effect on *Trichogramma* egg foraging (Grieshop 2005). Differences in the distribution of percentage of parasitism, percentage of egg disks parasitized, and egg mortality between gondola shelves with and without packages (Table 3) suggests that gondola shelves may pose a significant problem for successful *T. deion* host foraging.

Release Height. Parasitism and mortality of sentinel egg disks on gondola shelves were greatest on the shelf where *T. deion* was released. However, there were differences in the vertical distribution of these rates depending on the height of the release shelf. For example, when parasitoids were released on shelf 3, there was a more even distribution of parasitism and mortality on shelves than when releases were made on shelf 1 (lowest). However, when released on shelf 3, *T. deion* was not very effective in killing host eggs on the floor. In contrast, parasitism and host egg mortality were high on the floor when parasitoids were released on shelf 1 (Fig. 4). Furthermore, in the shelf 1 releases, whereas the percentage of egg disks attacked and percentage of host mortality seem similar for the lower shelves and the floor, a greater percentage of parasitized egg disks was found on the upper level shelves than eggs parasitized or killed (Fig. 4). This may be due to the early exploitation of eggs closest to the release point followed by a lowered level of parasitism and/or successful larval development on older eggs located farther from the release point. Various studies have shown that host eggs become less attractive and/or suitable for parasitism by *Trichogramma* species over time as the caterpillar embryo develops (Marston and Ertle 1969, Monje et al. 1999). Because a single insect within an infested product results in the

loss of that product, a release pattern that results in a more complete exploitation of host patches is of critical importance to successful pest management. Thus, a central release point will likely provide better control than releases made on the first shelf.

Interestingly, within gondola shelves where *T. deion* was released on shelf 1, although percentage of parasitism, percentage of egg disks attacked, and corrected mortality decreased progressively on most of the shelves above the first level, a slight increase was observed on the uppermost (fifth) shelf (Fig. 4). Allen and Gonzalez (1974) described a horizontal bimodal dispersion of parasitism for *T. pretiosum* in cotton, *Gossypium hirsutum* L., fields, which they explained as either wind drift or other environmental factors, or the result of "parasitoid saturation," where parasitoids have had adequate time to forage over the entire study area. We are unsure why *T. deion* parasitized eggs at a slightly higher rate on shelf 5 compared with shelf 4. This effect only occurred when releases were made on the first shelf. The fact remains that releases made on shelf 3 were superior for overall coverage of the shelves compared with releases made on shelf 1.

Other studies that have examined vertical dispersion of *Trichogramma* species have shown a bias for either the upper or lower strata of plants in field and greenhouse conditions. Thorpe and Dively (1985) found that *T. pretiosum* foraged primarily at the bottom of laboratory arenas. Smith (1988) showed a differential bias in vertical dispersion of *Choristoneura fumiferana* (Clemens) (Lepidoptera: Tortricidae) eggs parasitized by *Trichogramma minutum* Riley, with greater rates of parasitism at the tops of trees when the parasitoid was released at 0.25 m, and greater rates of parasitism on eggs located on lower branches when parasitoids were released at ground level. In contrast, Wang et al. (1997) found that *T. ostriniae* Pang and Chen was more likely to parasitize sentinel egg clusters on the lower two-thirds of sweet corn plants in the field when released at a height of 1 m.

The most important finding from this study for stored product managers is that gondola shelves presented a less favorable foraging environment for *T. deion* than open shelves. One potential solution to this problem would be to use release points at two heights, or to release greater numbers of parasitoids on gondola shelving. We also found that the presence of packages on shelves does not seem to affect the ability of *T. deion* to locate hosts on open shelves, but it may hinder host foraging on gondola shelves. Finally, the vertical location of the release point greatly influenced the distribution of parasitism. We found that releasing *T. deion* on shelf three provided the most even coverage of shelves 1–5.

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