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Evaluation of light attraction for the stored-product psocid, *Liposcelis bostrychophila*

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Abstract The psocid, *Liposcelis bostrychophila* Badonnel (Psocoptera: Liposcelididae), is the most widespread psocid pest of stored products. Because *L. bostrychophila* has developed resistance to several chemical insecticides, it is important to investigate other integrated pest management (IPM) approaches, and a critical part of IPM programs is an effective monitoring program. Monitoring tools for psocids are limited, and few studies have been conducted on monitoring of psocids, with none on the attraction of lights for psocids. Therefore, we studied the response of *L. bostrychophila* adults to eight wavelengths of light-emitting diodes (LED) in paired-choice pitfall test. Among the LEDs evaluated, the strongest response by *L. bostrychophila* adults was to 351 nm UV. When LEDs were tested against brewer's yeast (the most preferred attractant for *L. bostrychophila* among more than 20 potential attractants found in previous studies), the 351 nm

UV wavelength was the only light that attracted more psocids than brewer's yeast. These results suggest that the use of LEDs might be useful in psocid-monitoring programs for *L. bostrychophila* and other psocid species.

Keywords *Liposcelis bostrychophila* · Psocoptera: Liposcelididae · Stored products · Grains · Monitoring · Light preferences · Behavior

Key message

- Psocids are stored-product pests of increasing concern worldwide, and monitoring tools are limited. For the first time, the use of Light-Emitting Diodes (LED) for attraction of the main psocid species, *Liposcelis bostrychophila*, was explored.
- Eight LEDs in combination with brewer's yeast (attractant highly preferred by *L. bostrychophila*) and/or blank controls were tested in choice tests.
- The LED emitting 351 nm UV light elicited the strongest response by *L. bostrychophila* adults. This response was even stronger than for brewer's yeast.

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Introduction

Psocids are stored-product pests of increasing economic importance, and *Liposcelis bostrychophila* Badonnel (Psocoptera: Liposcelididae) is one of the most commonly found species (Mills et al. 1992; Turner 1994). This psocid has been reported in Australia (Rees and Walker 1990; Rees 1994), Asia (Leong and Ho 1994; Rajendran 1994; Rees 1994; Wang et al. 1999, 2000b), Africa (Lienhard and

Smithers 2002), South America, (Lienhard and Smithers 2002), Europe (Turner 1994, 1998), Canada (Mills et al. 1992), and the U.S. (Throne 2010; Phillips and Throne 2010). Psocids can cause significant damage and reductions in grain weight of stored products such as rice, *Oryza sativa* L. (McFarlane 1982; Rees and Walker 1990) and wheat, *Triticum aestivum* L. (Gautam et al. 2013; Kučerová 2002), and contamination of food commodities (Turner 1994; Athanassiou et al. 2010b). Additionally, several psocids have been documented to be resistant to the fumigant phosphine (Ho and Winks 1995; Nayak et al. 1998; 2003; Nayak and Collins 2008; Nayak et al. 2014), contact insecticides such as carbamates (Nayak et al. 1998), pyrethroids (Nayak et al. 1998, 2002; Opit et al. 2012), organophosphates (Ding et al. 2002; Dou et al. 2006), pyrethrins (Athanassiou et al. 2009), spinosad (Nayak et al. 2005; Athanassiou et al. 2009), and the insect growth regulator methoprene (Athanassiou et al. 2010a).

Psocids associated with stored products move in and out of the food material and have been shown to respond to environmental conditions such as temperature and moisture or relative humidity. Opit et al. (2009) observed that populations of psocids in steel bins were more abundant at the center of the bin during the fall where temperature and grain moisture content were higher than in other parts of the bin. In laboratory tests, *L. bostrychophila* responded to temperature gradients (Throne and Flinn 2013) and moisture gradients (Diaz-Montano et al. 2014a), with a preference for the warmest and highest moisture regions. However, how stored-product psocids respond to light conditions has not been investigated. Environments where stored-product insects are found have highly variable light conditions, from dark inside bulk grain to light on grain surface, outside bins, and packaged food materials. *Liposcelis bostrychophila* has seven ommatidia, two oval and five round, with normal smooth surfaces (Yang et al. 2015) and thus the potential to respond to light; however, it is not certain if this response is reduced in stored-product species since they are often found in dark habitats.

Monitoring tools are essential components of integrated pest management (IPM) programs, but few studies have been conducted to address how to most effectively monitor stored-product psocids. Brewer's yeast-baited traps have been used to monitor psocids in domestic household surveys in the U.K. (Turner and Maude-Roxby 1989; Turner and Bishop 1998). Opit et al. (2009) observed that commercially available pitfall-type traps and corrugated cardboard refuges were effective methods to sample psocids [*Liposcelis entomophila* (Enderlein) and *L. decolor* (Pearman)]. However, different attractants or combinations of attractants might increase psocid captures in traps. *Liposcelis bostrychophila* preferred substrates with fungal extracts over control substrates (Green 2008), and preferred

yellow millet over other grains, with addition of brewer's yeast to yellow millet increasing response (Green and Turner 2005). Diaz-Montano et al. (2014b, 2015) performed a systematic evaluation of different available potential volatile chemical attractants for seven psocid species, including *L. bostrychophila*, and found that they strongly responded to volatile odors coming from brewer's yeast, wheat germ, and/or wheat germ oil.

The attraction of many insects to light has been documented, but we are not aware of any studies addressing this topic with psocids. There have been some studies on the attraction of other stored-product pests to different wavelengths of light. Kirkpatrick et al. (1970) tested attraction to green and ultraviolet (UV) light by several stored-product pest insects using suction light traps under simulated warehouse conditions, and they observed that a significant number of cigarette beetles, *Lasioderma serricornis* (Fabricius), flat grain beetles, *Cryptolestes pusillus* (Schönherr), and lesser grain borers, *Rhyzopertha dominica* (Fabricius) preferred the UV light, whereas higher numbers of almond moth, *Cadra cautella* (Walker), and the Indian meal moth, *Plodia interpunctella* (Hübner), selected the green light. Highest numbers of red flour beetles, *Tribolium castaneum* (Herbst), and rice weevils, *Sitophilus oryzae* (L.), were observed on traps with a combination of green and UV lights. In similar studies in laboratory rooms and peanut warehouses, Soderstrom (1970) observed greater numbers of Indian meal moth and Mediterranean flour moth, *Ephestia kuehniella* Zeller, responding to green lights, while the cigarette beetle, merchant grain beetle, *Oryzaephilus mercator* (Fauvel), rice weevil, red flour beetle, and lesser grain borer responded to UV lights. Sheribha et al. (2010) evaluated the light preference of red flour beetle using a multicolor device system and found that adults preferred clear, blue, and green lights and avoided red light. Duehl et al. (2011) tested light attraction of red flour beetle in a cloverleaf shape arena with four Light-Emitting Diodes (LEDs), and they found that significantly more adults were attracted to 390 nm UV compared to 360 and 380 nm UV and 410 nm blue light. Park et al. (2015) studied the response of the maize weevil, *Sitophilus zeamais* (Motshulsky), to five LEDs using a Y-maze chamber and observed that these beetles were more attracted to red (625 nm) followed by yellow (590 nm) and infrared (730 nm). In similar experiments, Jeon et al. (2012) found that the rice weevil were more attracted to blue (450 nm) followed by green (520 nm), red (660 nm), UV (365 nm), and infrared (730 nm). Sambaraju and Phillips (2008) studied the response of the Indian meal moth when given a choice between dark areas or areas with UV (395 nm), green (525 nm), or white (450–700 nm) lights; insects preferred the illuminated areas and UV elicited the strongest response. Cowan and Gries (2009)

studied the attraction of Indian meal moths to lights in a wind tunnel with two and four-choice experiments and found that UV (350 nm) and blue (405 nm) attracted more males and mated and virgin females. The identification of specific light wavelengths that attract psocids could be an important factor to enhance the monitoring of psocids. Therefore, the objective of this study was to evaluate attraction of the most important psocid pest *L. bostrychophila* to different specific wavelengths of light.

Materials and methods

Insect culture

The *L. bostrychophila* population (voucher specimen No. 202, Kansas State University Museum of Entomological and Prairie Arthropod Research) used in this study was from cultures that were started in 2006 with psocids collected from a grain elevator in Manhattan, KS. Psocids were reared on a diet of 95 % cracked hard red winter wheat (*Triticum aestivum* L. ‘Santa Fe’), 2 % wheat germ (Natural Raw Wheat Germ, Bob’s Red Mill Natural Foods Inc., Milwaukie, OR), 2 % brewer’s yeast (MP Biomedicals, Solon, OH), and 1 % crisped rice cereal (Rice Krispies, Kellogg’s Company, Battle Creek, MI) at 30 °C, 65 % RH, and a photoperiod of 16:8 L:D h. Mixed-age adults [between 0 and 90 days; adult longevity is 89.4 days at 30 °C (Wang et al. 2000a)] from a 3–6 month old culture of *L. bostrychophila* were evaluated in the experiments.

Experimental bioassay

The response of *L. bostrychophila* to LED colors was evaluated in paired-choice tests in a Petri dish with openings on opposite sides through which lights and/or chemical cues contained in vials entered the arena, and psocids that responded were captured in the vials (Fig. 1). The arena consisted of a polystyrene Petri dish (14 cm in diameter by 1.4 cm in height). The walls of this Petri dish had two holes opposite each other (5.0 mm in diameter and 14 cm apart along the diameter mid-line of the dish) and level with the bottom of the Petri dish. An acrylic tube (5.0 mm in outer-diameter, 3.0 mm in inner-diameter, 1.7 cm in length) was inserted in each hole of the Petri dish. The other end of the acrylic tube was connected to an acrylic vial (2.5 cm diameter by 5.4 cm height) through a hole (5.0 mm in diameter) located on the upper part of the vial (1.0 cm from the top). The acrylic vial had a second hole directly opposite (5.0 mm diameter), where the LED light was inserted. The acrylic vials were covered with black tape to block light escaping. The interior walls of the Petri dish and the acrylic vials were coated with

Fig. 1 Paired-choice pitfall arena

polytetrafluoroethylene (60 wt % dispersion in water, Sigma-Aldrich Co., St. Louis, MO) to prevent psocid climbing and capture psocids in the vials. The LEDs were powered by a rechargeable sealed lead acid battery (SP6-20, 6V 20AH/NB, SigmasTek, New York, NY) through a potentiometer (RV4NAYSD152A, 2 W Power Rating, 1.5 kOhm Resistance Value, Honeywell International Inc., Morristown, NJ).

There were six experiments in which paired-choice tests were conducted using acrylic vials that contained different treatments (Table 1). These treatments included LEDs (eight different wavelengths) alone or in combination with brewer’s yeast, paired with a blank vial as control, or a vial with brewer’s yeast only. Brewer’s yeast (1 g) was included for evaluation because it elicited the strongest response for several psocid species in previous experiments (Diaz-Montano et al. 2014b, 2015). Eight LEDs with different wavelengths were evaluated: four ultraviolet (UV) lights: 351 nm (L5-1-U5TH15-1, LEDSupply, Randolph, VT), 380 nm (RL5-UV0230-380, Super Bright LEDs Inc. St. Louis, MO), 390 nm (LED-5U8PK20, Lightobject, Sacramento, CA), and 400 nm (RL5-UV0430-400, Super Bright LEDs Inc. St. Louis, MO); violet: 420 nm (RL5-V1015, Super Bright LEDs Inc. St. Louis, MO), blue: 470 nm (RL5-B2430, Super Bright LEDs Inc. St. Louis, MO),

Table 1 List of paired-choice experiments in this study

Experiment	Vial 1	Vial 2
I	Light	Blank
II	Light	Brewer’s yeast
III	Light + Brewer’s yeast	Blank
IV	Light + Brewer’s yeast	Brewer’s yeast
V	Light + Brewer’s yeast	Light
VI	Brewer’s yeast	Blank

green: 527 nm (RL5-G7032, Super Bright LEDs Inc. St. Louis, MO), and red: 660 nm (RL5-R1330, Super Bright LEDs Inc. St. Louis, MO). Another experiment was conducted to confirm the earlier findings by Diaz-Montano et al. (2014b) that *L. bostrychophila* responds strongly to brewer's yeast. This earlier study used a different bioassay, so it was important to confirm that this species responds to brewer's yeast when presented as described here. A choice test was conducted comparing choice between a vial with brewer's yeast and a blank control vial.

Because the white light is a mixture of the colors of the visible spectrum, additional experiments were performed to observe the response of *L. bostrychophila* to clear white LED (IL151, Microtivity, Hong Kong). Paired tests were conducted to compare the choice between a vial with a clear white LED and a blank control vial, as well as the choice between a vial with a clear white LED and a vial with brewer's yeast.

Fifteen psocid adults were collected and placed in a small polystyrene Petri dish (3.5 cm in diameter). Food was withheld from the psocids for 24 h prior to adding to the arenas. The Petri dish was turned over carefully at the center of the arena, and the lights from the room were turned off. After a 10-min acclimation period, the small Petri dish was removed, and psocids were allowed to move freely in the large dish arena. After 4 h, the number of psocids outside (in the arena) and inside each acrylic vial was counted. The experiments were conducted in a walk-in growth chamber under dark conditions at 25 °C and 65 % RH.

Experimental design and analysis

The experiments were performed in the order presented in Table 1. The treatments within each experiment were performed randomly until 10 replications per each LED light were completed, in a randomized complete block design. Analysis of variance (ANOVA) was conducted to compare the numbers of *L. bostrychophila* adults captured in the vials in the treatments (vial 1 or vial 2). Post hoc multiple comparisons were conducted using Tukey's studentized range test (SAS Institute 2008). Pairwise comparisons were analyzed separately to compare the number of psocids captured between the two vials.

Results

Experiment I: Light versus blank

Across the different light treatments, more *L. bostrychophila* adults responded to the 351 nm UV light vial compared to vials with blue, violet, and red light

($F = 10.7$; $df = 7, 9$; $P < 0.001$) (Table 2). The pairwise comparisons showed that significantly more psocids preferred the LED lights compared to the blank control, except for the red light treatment ($F = 4.1$; $df = 1, 9$; $P = 0.0738$) (Table 2).

Experiment II: Light versus Brewer's yeast

The strongest response by psocid adults across the vials with different light wavelengths was to 351 nm UV ($F = 21.3$; $df = 7, 9$; $P < 0.001$), with double the capture compared to the other light wavelengths (Table 3). Psocids significantly preferred brewer's yeast ($F = 8.1$; $df = 7, 9$; $P < 0.001$) over all the LED wavelengths, except for the 351 nm UV treatment (Table 3). The pairwise comparisons showed that significantly more psocids preferred the vials with brewer's yeast compared to the different wavelength lights evaluated, except for 351 nm UV, where there was preference for the vial with light over brewer's yeast ($F = 23.0$; $df = 1, 9$; $P < 0.001$) (Table 3).

Experiment II: Light + Brewer's yeast versus blank

There were no significant differences in the number of psocids captured among the different vials with light + brewer's yeast treatments ($F = 0.9$; $df = 7, 9$; $P = 0.5105$), nor among captures in the blank control among treatments ($F = 0.93$; $df = 7, 9$; $P = 0.4863$) (Table 4). For all treatments, the pairwise comparison showed that significantly more psocids responded to the light + brewer's yeast compared to the blank control (Table 4).

Table 2 Number (mean $\pm$ SE) out of 15 individuals of *L. bostrychophila* mixed-age adults that in a paired-choice test selected the treatment vial when given a choice between a specific wavelength LED light and a blank control

LED Light	Vial 1 (Light)	Vial 2 (Blank)
UV—351 nm	10.1 $\pm$ 0.3 aA	2.9 $\pm$ 0.4 aB
UV—390 nm	8.7 $\pm$ 0.6 abA	3.2 $\pm$ 0.3 aB
UV—400 nm	8.7 $\pm$ 0.4 abA	3.3 $\pm$ 0.4 aB
Green—527 nm	8.3 $\pm$ 0.5 abA	3.1 $\pm$ 0.4 aB
UV—380 nm	8.1 $\pm$ 0.3 abcA	2.9 $\pm$ 0.5 aB
Blue—470 nm	7.5 $\pm$ 0.6 bcdA	3.4 $\pm$ 0.6 aB
Violet—420 nm	6.1 $\pm$ 0.5 cdA	4.2 $\pm$ 0.4 aB
Red—660 nm	5.5 $\pm$ 0.3 dA	4.5 $\pm$ 0.4 aA

Average of 10 replicates

Means followed by different lowercase letters within a column or different capital letters within a row are significantly different ($P < 0.05$, Tukey's test)

Table 3 Number (mean $\pm$ SE) out of 15 individuals of *L. bostrychophila* mixed-age adults that in a paired-choice test selected the treatment vial when given a choice between a specific wavelength LED light and brewer's yeast

LED Light	Vial 1 (Light)	Vial 2 (Brewer's Yeast)
UV—351 nm	8.1 $\pm$ 0.3 aA	5.2 $\pm$ 0.4 bB
UV—380 nm	4.2 $\pm$ 0.4 bB	8.3 $\pm$ 0.7 aA
UV—390 nm	3.6 $\pm$ 0.8 bcB	8.6 $\pm$ 0.7 aA
UV—400 nm	3.0 $\pm$ 0.3 bcdB	8.7 $\pm$ 0.8 aA
Violet—420 nm	2.4 $\pm$ 0.5 bcdB	9.6 $\pm$ 0.7 aA
Green—527 nm	2.2 $\pm$ 0.8 bcdB	10.5 $\pm$ 0.8 aA
Blue—470 nm	1.8 $\pm$ 0.4 cdB	10.3 $\pm$ 0.6 aA
Red—660 nm	1.3 $\pm$ 0.4 dB	11.2 $\pm$ 0.8 aA

Average of 10 replicates

Means followed by different lowercase letters within a column or different capital letters within a row are significantly different ($P < 0.05$, Tukey's test)**Table 4** Number (mean $\pm$ SE) out of 15 individuals of *L. bostrychophila* mixed-age adults that in a paired-choice test selected the treatment vial when given a choice between a specific wavelength LED light + brewer's yeast and a blank control

LED Light	Vial 1 (Light + Brewer's Yeast)	Vial 2 (Blank)
UV—380 nm	10.7 $\pm$ 0.7 aA	1.9 $\pm$ 0.4 aB
UV—351 nm	10.3 $\pm$ 0.4 aA	3.2 $\pm$ 0.5 aB
Red—660 nm	9.8 $\pm$ 0.3 aA	3.0 $\pm$ 0.3 aB
UV—390 nm	9.7 $\pm$ 0.8 aA	2.9 $\pm$ 0.7 aB
Violet—420 nm	9.6 $\pm$ 0.3 aA	2.9 $\pm$ 0.4 aB
Green—527 nm	9.5 $\pm$ 0.3 aA	3.1 $\pm$ 0.4 aB
UV—400 nm	9.5 $\pm$ 0.5 aA	3.4 $\pm$ 0.6 aB
Blue—470 nm	9.3 $\pm$ 0.4 aA	3.4 $\pm$ 0.6 aB

Average of 10 replicates

Means followed by different lowercase letters within a column or different capital letters within a row are significantly different ($P < 0.05$, Tukey's test)

Experiment IV: Light + Brewer's yeast versus Brewer's yeast

In the treatment light + brewer's yeast vials across the different treatments, significantly ($F = 4.4$; $df = 7, 9$; $P < 0.001$) more psocid adults responded to the 351 nm UV light vial compared to vials with red, 380 and 390 nm UV, and blue light combined with brewer's yeast (Table 5). Psocid response to the other vial (brewer's yeast alone) was not significantly different ($F = 0.9$; $df = 7, 9$; $P = 0.5366$) among the treatments (Table 5). The pairwise comparisons showed that only for the 351 nm UV + brewer's yeast treatment were significantly ($F = 27.9$; $df = 1, 9$; $P < 0.001$) more psocids found in the light and brewer's yeast vials compared to the brewer's yeast treatment (Table 5).

Experiment V: Light + Brewer's yeast versus light

There were no significant differences in the number of psocids responding to vials with light and brewer's yeast across the different treatments (except for response to 351 nm UV being significantly less than response to red light) ($F = 2.9$; $df = 7, 9$; $P < 0.001$) (Table 6). There were no significant ($F = 1.3$; $df = 7, 9$; $P = 0.2552$) differences in response to the light only vial across the different treatments (Table 6). The pairwise comparisons showed that significantly more psocids responded to the light + brewer's yeast treatment compared to the light alone treatment, regardless of the light wavelength (Table 6).

Experiment VI: Brewer's yeast versus blank

In this experiment to confirm an earlier study, significantly ($F = 227.8$; $df = 1, 9$; $P < 0.001$) more *L. bostrychophila* adults were found in the vial with brewer's yeast (11.2 ± 0.3) compared to the blank control (2.2 ± 0.4). The percentage of adults that responded to brewer's yeast was 75 %, and this was similar to the percentage observed in Diaz-Montano et al. (2014b).

Experiment VII: Response of *L. bostrychophila* to clear white LED

Significantly ($F = 29.27$; $df = 1, 9$; $P < 0.001$) more *L. bostrychophila* adults were found in the blank control vial (4.6 ± 0.9) compared to the vial containing the clear white LED (0.9 ± 0.4). More psocids also were found in the vial with brewer's yeast (10.5 ± 0.3) compared to the vial with the white light (1.7 ± 0.3) ($F = 396.0$; $df = 1, 9$; $P < 0.001$).

Discussion

Liposcelis bostrychophila adults responded strongly to lights in the UV spectrum, with the strongest response to 351 nm UV LED. When given a choice between responding to light or food odor (brewer's yeast), this psocid species preferred the food, except when presented with the 351 nm UV wavelength light which attracted more psocids than brewer's yeast alone. In a previous study, Diaz-Montano et al. (2014b) evaluated the response of *L. bostrychophila* to more than 20 potential attractants, and it was observed that brewer's yeast elicited the most consistent strong response from this psocid species. These results indicate that 351 nm UV light triggers a very strong phototaxis response from *L. bostrychophila* adults even when competing with brewer's yeast volatiles, and may be

Table 5 Number (mean $\pm$ SE) out of 15 individuals of *L. bostrychophila* mixed-age adults that in a paired-choice test selected the treatment vial when given a choice between a specific wavelength LED light + brewer's yeast and brewer's yeast

LED Light	Vial 1 (Light + Brewer's Yeast)	Vial 2 (Brewer's Yeast)
UV–351 nm	8.8 $\pm$ 0.4 aA	5.1 $\pm$ 0.3 aB
UV–400 nm	7.3 $\pm$ 0.5 abA	5.7 $\pm$ 0.5 aA
Violet–420 nm	7.3 $\pm$ 0.7 abA	6.2 $\pm$ 0.6 aA
Green–527 nm	6.2 $\pm$ 0.7 abA	6.2 $\pm$ 0.7 aA
Red–660 nm	5.8 $\pm$ 0.5 bA	6.5 $\pm$ 0.5 aA
UV–390 nm	5.7 $\pm$ 0.8 bA	6.5 $\pm$ 0.5 aA
UV–380 nm	5.5 $\pm$ 0.7 bA	6.7 $\pm$ 0.9 aA
Blue–470 nm	4.7 $\pm$ 0.8 bA	6.4 $\pm$ 0.7 aA

Average of 10 replicates

Means followed by different lowercase letters within a column or different capital letters within a row are significantly different ($P < 0.05$, Tukey's test)

Table 6 Number (mean $\pm$ SE) out of 15 individuals of *L. bostrychophila* mixed-age adults that in a paired-choice test selected the treatment vial when given a choice between a specific wavelength LED light + brewer's yeast and a specific wavelength LED light

LED Light	Vial 1 (Light + Brewer's Yeast)	Vial 2 (Light)
Red–660 nm	9.9 $\pm$ 0.3 aA	2.2 $\pm$ 0.3aB
UV–390 nm	8.7 $\pm$ 0.5 abA	2.8 $\pm$ 0.3 aB
UV–400 nm	8.6 $\pm$ 0.6 abA	3.4 $\pm$ 0.8 aB
Blue–470 nm	8.2 $\pm$ 0.8 abA	1.7 $\pm$ 0.3 aB
UV–380 nm	8.2 $\pm$ 0.9 abA	2.4 $\pm$ 0.5 aB
Violet–420 nm	8.2 $\pm$ 0.9 abA	2.0 $\pm$ 0.5 aB
Green–527 nm	7.1 $\pm$ 0.9 abA	2.6 $\pm$ 0.7 aB
UV–351 nm	5.7 $\pm$ 0.7 bA	1.8 $\pm$ 0.6 aB

Average of 10 replicates

Means followed by different lowercase letters within a column or different capital letters within a row are significantly different ($P < 0.05$, Tukey's test)

a potential attractant for monitoring where background food odors are present such as in a food facility. It is also possible that *L. bostrychophila* response to food baited traps may be reduced if used outside in the presence of sunlight, although we did not find a response to the full spectrum white light so this may be less of an issue. Further tests of food attractants alone should consider the interaction of response with light.

The combination of light and brewer's yeast appears to be a good synergistic attractant. When the eight light wavelengths were combined with brewer's yeast and tested against brewer's yeast, only the 351 nm UV + brewer's yeast attracted more psocids compared to the other combinations, and for all other treatments, similar numbers were captured in both vials regardless of the presence of LED lights. When lights + brewer's yeast were tested against lights alone, psocids were more attracted to the treatment with lights and brewer's yeast than to the

treatments with lights only. In the 351 nm UV treatment, the lowest recorded number of psocids made a choice, as most of the insects stayed on the arena and did not enter either vial. This observation again shows the strong preference of *L. bostrychophila* adults for 351 nm UV over brewer's yeast, because psocids preferred to stay on top of the arena than make a choice.

When psocids were given the choice of the LED lights versus the blank controls, they selected the treatment vial with lights, with the exception of treatment with red light and blank control, where the number of psocids found on both sides was similar. The highest percentages of *L. bostrychophila* adults that responded to the lights were observed on 351, 390, and 400 nm UV, green and 380 nm UV (67, 58, 58, 55, and 54 %, respectively). In the experiment where brewer's yeast was compared against the blank control, the percentage of *L. bostrychophila* adults that responded to brewer's yeast was 75 %. These results confirm the strong response by *L. bostrychophila* to the brewer's yeast and some of the LEDs tested, in particular the 351 nm UV light.

Most insects possess UV, blue and green photoreceptors that have maximum sensitivity at ~ 350 nm, ~ 440 nm, and ~ 530 nm, respectively (Briscoe and Chittka 2001). This is generally the case for stored-product pest beetles, such as *L. serricornis*, *C. pusillus*, *O. mercator*, *T. castaneum*, *R. dominica*, and *S. oryzae*, and pest moths such as *C. cautella*, *E. kuehniella*, and *P. interpunctella* (Kirkpatrick et al. 1970; Soderstrom 1970; Sambaraju and Phillips 2008; Cowan and Gries 2009; Sheribha et al. 2010; Duehl et al. 2011). *Sitophilus zeamais* may be an exception, since it also responded to red (625 nm), yellow (590 nm), and infrared (730 nm) light (Park et al. 2015), although the preference of yellow and infrared light was not significantly different from the preference for blue (470 nm) and green (520 nm) light. *Liposcelis bostrychophila* appears to be sensitive to a wide range of wavelengths, since when given a choice of light versus blank, there was a significant

and positive response to all wavelengths except for 660 nm red light (neutral response) and clear white LED (negative response). However, the strongest response of *L. bostrychophila* was to light in the UV range, with strongest response to the shortest wavelength tested (351 nm).

In this study, we determined the strong response by *L. bostrychophila* to LEDs producing 351 nm wavelengths. The strong response suggests that this might be a useful attractant for monitoring devices, especially given the strong response even in the presence of a food attractant. Future research should evaluate the attraction to this wavelength of light by other psocid species in order to determine if the same LED (351 nm UV) can attract multiple psocid species. Ultimately the use of traps with UV light LEDs alone or in combination with food attractants such as brewer's yeast needs to be evaluated to determine effectiveness under more realistic conditions found inside and outside food facilities where environmental conditions such as temperature and moisture content and dark/illuminated areas may influence psocid movement patterns.

Author contribution

JC, JD, JT, LC, and TP conceived the study. JD designed the study, performed the experiments, analyzed the data, and wrote the manuscript. JC, JT, LC, and TP revised and improved the manuscript.

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