Visual response effects of western flower thrips manipulated by different light spectra

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Abstract: To understand how spectral light wavelength affects thrips visual sensitivity, the selective response and the approach sensitivity of western flower thrips were examined. The results showed that light intensity affected thrips selective sensitivity to different spectra, with good visual sensitivity to blue, ultraviolet (UV), and green light changes to UV, violet, and yellow light when illumination increased from 120 lx to 6000 lx. Red light was the sensitive spectral light driving thrips to respond to sensitive light. Under illumination, the best sensitivity response to spectra was violet, while under light energy, this changed to UV when light energy was increased to 120 mW/cm^2. However, the photo-stimulus properties (illumination or light energy) did not affect the optimal approach sensitivity to UV light. Furthermore, when illumination or light energy stimulated thrips to select two different spectral lights, the total response sensitivity to 12000 lx of UV and violet light were the best (83.27%), while at 60 mW/cm^2 of UV and yellow light was the best (82.15%). But different photo-stimulus properties influenced on the total approach sensitivity to the stimulation of two different spectral lights when the intensity of light increased, showing that to 12000 lx of violet and green light was the best (53.18%), while for 120 mW/cm^2 of UV and green light was the best (47.74%). The thrips visual selection response effects stimulated by illumination were different from that induced by light energy, and originated from the thrips different bio-regulatory effects caused by the intensity of light energy of illumination and the intensity of illumination of light energy. Therefore, different photo-stimulus effects can manipulate thrips visual sensitivity to enhance the phototactic effect.

Keywords: western flower thrips, visual response effect, spectral light, illumination, light energy
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1 Introduction

Western flower thrips, *Frankliniella occidentalis* (Thysanoptera), is a serious worldwide pest found on vegetables, flowers, and other crops, but it has also spread rapidly in recent years, becoming seriously harmful as a main alien invasive pest in China[1]. Its individual size is small, the activity is often concealed, chemical pesticides have no efficacy when sprayed on thrips, and this can easily result in insecticide resistance[2]. At present, by using insect positive and negative affinity to specific light waves, color-light induction technology has become a green agricultural way to control thrips pests[3,4]. Therefore, a study of the visual selection response characteristics of thrips induced by light may reveal the sensitive light characteristics of thrips phototactic responses, thereby providing a theoretical investigation of thrips phototactic mechanisms and the photosensitization changes of thrips biological effects induced by light.

Previous researchers have studied sticky traps for thrips pests utilizing insect color discrimination. Moffitt et al.[5] reported that yellow, blue, or white sticky traps were currently recommended for monitoring and controlling thrips. It is also reported that varying color combinations could be more attractive to thrips. For example, a yellow trap on a black, violet, or blue background may catch greater numbers of *F. occidentalis*, but this is affected by the size and shape of the traps[6]. This may be because the colors simulate the natural background conditions with a suitable wavelength and a suitable color intensity[7-9]. Thus, a study of the selection mechanism of thrips color perception behavior could help to predict what could manipulate the thrips visual behavior response. Matteson *et al*. studied the phototactic behavior of *F. occidentalis* using a retinal potential technique to show the peak value at 540 nm, further speculating that the photoreceptor types of thrips adults may detect green light, blue light and ultraviolet light[10-12]. Fan *et al*. found that the light spectrum had a great impact on thrips phototactic behavior; the influencing effects of light intensity was greater than the wavelength[13-15], indicating that thrips compound eyes had a strong self-regulation and adaptation mechanism to light intensity, and could select different spectral light wavelengths. Murata et al. found that the visual sensitivity of *Thrips palmi* ranged from UV to red light[16]. However they did not determine which wavelength was a more sensitive spectral light for thrips visual selection, and did not

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determine a mechanism for why spectral light affected the generation of thrips visual responses and changes of thrips visual response behaviors.

To explore the visual selection mechanism of *F. occidentalis* for different light spectra, and the resulting effects on thrips biological behavior manipulated by light, the effects of different light spectra on the visual selection behavior of *F. occidentalis* adults were investigated for different behavior responses in the laboratory. We also analyzed the influence of light factors on thrips phototactic responses to explain the cause of thrips visual responses and to identify the optimal trap light for controlling thrips.

2 Materials and methods

2.1 Insects

Western flower thrips samples were obtained from flowers of different plants in the Zhengzhou area of Henan Province, China, and were used to establish a laboratory colony. The insects were reared on green bean pods (*Phaseolus vulgaris L.*) in rearing cages, at (25±1)°C with 70% ± 5% relative humidity under a light/dark cycle of 14 h:10 h photoperiod, respectively. Thirty thrips adults per group were kept 30min in plastic containers (40 mm×50 mm) before the experiments.

2.2 Light radiation and light measurements

The spectra of 3 W LED with peak wavelengths used in the experiments were: red (660 nm), orange (610 nm), yellow (560 nm), green (520 nm), blue (465 nm), violet (405 nm), UV (365 nm), and white (composite wavelength). The incident illumination calibrated by an illuminance meter (Model: TES-1335, Resolving power: 0.01 l×) was set to 6000 lx, and 12000 lx, respectively, and the radiating energy calibrated by a radiation meter (Model: FZ-A, resolving power: ±5%) was set to 60 mW/cm^2, and 120 mW/cm^2, respectively, to minimize the influencing effects of illumination and light energy on thrips visual selection response.

2.3 Experiment 1 (Thrips visual selection response induced by different light spectra)

To screen the thrips light sensitive spectra, we used device 1 (Figure 1) to test the thrips visual selection response.

The device used eight channels (length × width × height: 150 mm×30 mm×60 mm) and a circular reaction chamber (Φ100 mm×80 mm), placed on a circular platform. Each channel was connected to the reaction chamber and was separated by a gate. Channels 1-8 were divided into three sections, marked with 0 mm, 50 mm, 100 mm, and 150 mm to identify thrips visual selection responses. The LED with the spectrum of red, orange, yellow, green, blue, violet, UV, and white were placed at the front end of channels 1-8.

Thrips visual selection response effects were measured by using device 1 at (25±1)°C in darkness. Before the experiment, incident light was set to the same illumination of 6000 lx and 12000 lx, respectively, and the same radiating energy of 60 and 120 mW/cm^2, respectively. Corresponding to every illumination or energy, three groups of thrips received 30 min dark adaptation prior to experimentation. When testing, a group of thrips was introduced into the reaction chamber, and the gates were opened and LEDs turned on for 10 min. After that, the gates were closed and LEDs turned off, then the lamp in the laboratory was turned on to count and record thrips present in channels 1-8; the three groups were tested individually until the experiment was completed. Using the same method, the thrips visual selection response caused by every light mode was determined.

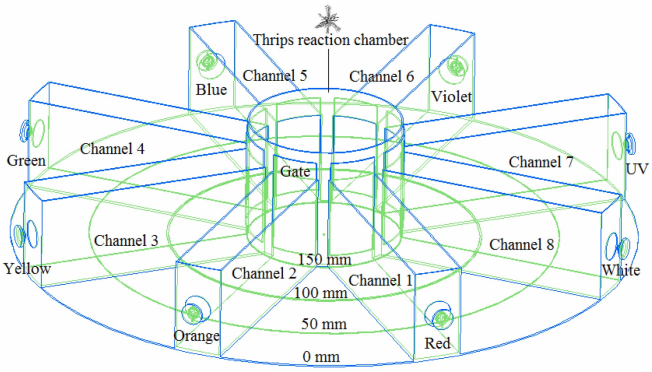


Figure 1 Device used in experiment 1 to investigate thrips visual selection response induced by different light spectra

2.4 Experiment 2 (The contrast selection effects of thrips responding to two different light spectra)

Based on the results from Experiment 1, LED light spectra were divided into classes: red, orange, white light, and yellow, green, violet, and UV light. Experimental device 2 (Figure 2) was used to investigate thrips sensitive selection effects of two different light spectra. The device had two channels (length × width × height: 150 mm× 30 mm× 60 mm) and a circular reaction chamber (Φ100 mm× 80 mm). A gate between them was used to avoid light interference. Section divisions of channels were marked with 0 mm, 50 mm, 100 mm, and 150 mm to analyze the thrips visual response effects. The two LEDs were placed at the front end of the two channels. The measured spectra vs. contrast spectra were red vs. orange, red vs. white, orange vs. white, yellow vs. green, yellow vs. violet, yellow vs. UV, green vs. violet, green vs. UV, and violet vs. UV.

The LED spectrum vs. contrast LED spectrum determination was done at the same illumination (6000 lx, 12000 lx) or light energy (60 mW/cm^2, 120 mW/cm^2), and three groups of thrips, after 30 min dark adaptation, were used to test the thrips contrast selection at (25±1)°C in darkness. When testing, a group was introduced into the bottom reaction chamber, using the same method as in Experiment 1. The three groups were each analyzed individually. After every investigation, the thrips distributed in the two channels were counted and recorded.

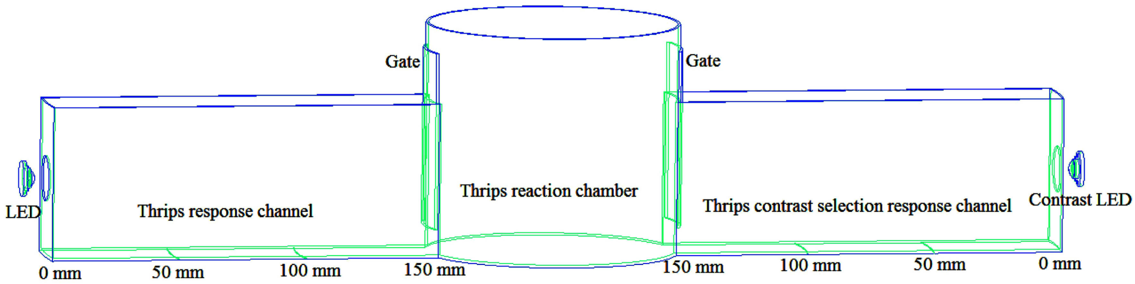


Figure 2 The device used in Experiment 2 to investigate thrips sensitive selection effects for two different light spectra

2.5 Data computation and analysis

The thrips numbers of every group were recorded at 0-50 mm and 0-150 mm in every channel. We calculated the percentage of the recorded thrips numbers for 30 thrips. Then the mean percentage of the three groups was calculated to analyze the thrips visual selection response effect (thrips selective sensitivity, thrips selective approach sensitivity). In Experiments 1 and 2, the selective response rate (the mean percentage at 0-150 mm, %) was used to reflect thrips selective sensitivity (thrips selective response degree) to every light spectra. To reflect thrips approach sensitivity (intensity, Experiment 1), and the approach rate (%) was used to compare the percentage of the mean percentage at 0-50 mm with that at 0-150 mm. The data from Experiment 2 directly reflected the mean percentage at 0-50 mm. In Experiment 2, the contrast approach rate (%), and the contrast response rate (%) were the mean percentage at one channel section (0-50 mm, 0-150 mm) subtracted from that at the same section of the other channel, and were separately calculated, reflecting the difference of thrips contrast selection effect between two spectral lights. The total approach rate and the total response rate was the sum of the mean percentages at 0-50 mm or 0-150 mm in all channels, respectively, reflecting the thrips total approach sensitivity, and thrips total response sensitivity (thrips total response degree).

General linear model analysis was employed to compare the mean percentage of insects induced by each LED, and for multiple comparisons: LSD, LSD tests at p=0.025 were used. The Student's t-test was used to determine the difference between two different light intensities with the same spectrum in Experiments 1 and 2 (p=0.025), and between two different spectrum with the same light intensity in Experiment 2 (p=0.025). SPSS, version 16.0 (SPSS Inc., Chicago, IL, USA) and Excel Software for windows were used for all statistical analyses. Results are shown as the mean ± standard error (SE).

3 Results and discussion

3.1 Thrips visual selection response effect induced by different light spectra

Thrips selective responses to every light spectra tested are shown in Table 1.

On the same horizontal line, the same small letter shows no significant difference (p>0.025), different letters with the same single superscript show significant differences (p<0.025), and the others show extremely significant differences (p<0.0001) with unmarked superscripts. Between 6000 lx and 12000 lx, or 60 mW/cm^2 and mW/cm^2, AA shows no significant difference (p>0.025); A*B* shows very significant differences (p<0.025) on the same vertical row.

The selective response rate differed significantly under the same intensity of light (6000 lx: F = 40.75, df = 7, p<0.0001; 12000 lx: F=73.487, df=7, p<0.0001; 60 mW/cm^2: F=65.635, df=7, p<0.0001; 120 mW/cm^2: F = 15.878, df = 7, p<0.0001) (Table 1). The thrips selective sensitivities to red, orange, and white light were the worst, while sensitivities to yellow, green, violet, and UV light were better. Therefore, thrips selective sensitivity was decided by the light spectrum.

Table 1 Selective response rate of thrips induced by spectral light illumination and energy at 0-150 mm /%

Spectrum		red	orange	yellow	green	blue	violet	U.V.	white
Illumination /lx	6000	1.11±1.11a*A	4.44±1.27a$^{\triangle}$A	16.65±1.92b$^{\#\bigstar}$g A	12.21±1.11c$^{\#}$hiA	9.99±1.11d$^{*\triangle}$hjA	22.20±1.11e$^{\bigstar}$A*	14.44±1.1fgijA	1.11±1.11aA
	12000	2.22±1.11aA	4.60±1.11aA	21.09±1.11bA	15.54±1.11cA	8.88±0.00 d$^{*\triangle}$A	14.44±1.11c*B*	15.54±0.54c$^{\triangle}$A	2.22±1.11aA
Light energy /mW·cm^{-2}	60	1.11±1.11aA	3.33±1.11aA	19.98±1.92b$^{*\triangle}$A	9.99±0.00c$^{\#※}$A	7.78±1.11cdA	25.46±1.08e*A	15.54±1.11f$^{\triangle\#}$A	4.44±1.11a$^{※}$dA
	120	2.22±1.11a*A	2.22±1.11a*A	16.67±1.92bcA	12.21±1.11b$^{*\triangle\#}$A	6.67±1.92a$^{\triangle}$A	19.99±1.92c$^{\#}$A	14.43±1.12bcA	3.33±2.22aA

Table 2 Approach rate of western flower thrips selecting yellow, green, violet, and U.V. light /%

Spectrum		yellow	green	violet	UV
Illuminatio/lx	6000	17.45±0.74a*A	0.00±0.00bA	44.8±2.26c$^{\triangle}$A	31.50±3.36d$^{*\Delta}$A
	12000	14.85±0.96a*A	0.00±0.00b*A	52.32±2.16c$^{\triangle}$A	35.52±3.78d$^{\Delta}$A
Light energy/mW·cm^{-2}	60	0.00±0.00a**A	0.00±0.00a**A	52.65±0.99b**A**	61.65±1.37c**A**
	120	0.00±0.00a**A	0.00±0.00a**A	23.72±0.64b**B**	33.28±1.46c**B**

On the same horizontal line, the same small letter shows no significant difference (p>0.025), different letters with the same single superscript show very significant differences (p<0.025), and the other different letters show extremely significant differences (p<0.0001) for the same illumination. For the same light energy, **show extremely significant differences (p<0.0001). Between 6000 lx and 12000 lx, or 60 mW/cm^2 and 120 mW/cm^2, AA shows no significant difference (p>0.025), and A**B** show extremely significant differences (p<0.025) on the same vertical row.

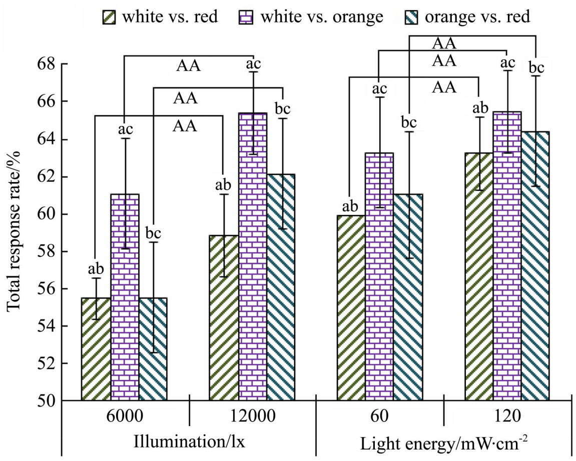
Because thrips showed no approach sensitivity to red, orange, blue, and white light, we only calculated the approach rates of thrips for yellow, green, violet, and UV light (Table 2). Thrips approach sensitivity to yellow, green, violet, and UV light showed extremely significant differences (df=3, p<0.0001, 6000 lx: F=86.90; 12000 lx: F=106.25; 60 mW/cm^2: F=321.43; 120 mW/cm^2: F=452.43). Under illumination, thrips approach sensitivity to violet light was the greatest. Under various tested light energies, thrips approach sensitivity to UV light was the greatest. These results indicated that the increasing illumination of thrips approach sensitivity to violet and UV light were enhanced, while that to yellow light was less. However, with increasing light energy, thrips approach sensitivity to violet and UV light was less. Therefore, photo-stimulus properties affect thrips approach sensitivity to spectral light.

3.2 Thrips contrast selection to two different light spectra

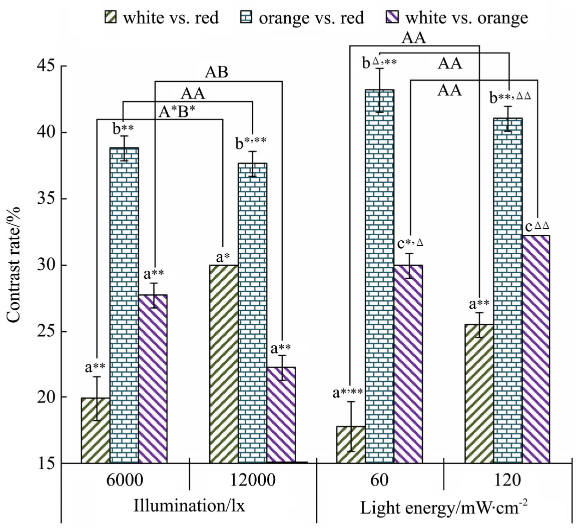
3.2.1 The contrast selection effect among different pairings of white, red, and orange light

Thrips total response degree showed no significant difference among different pairings (df=2, 6000 lx: F=1.657, p=0.267; 12000 lx: F=1.482, p=0.300; 60 mW/cm^2: F=0.439, p=0.664; 120 mW/cm^2: F=0.281, p=0.764) (Figure 3a), while the total response rate was enhanced by approximately 5% when light intensity increased.

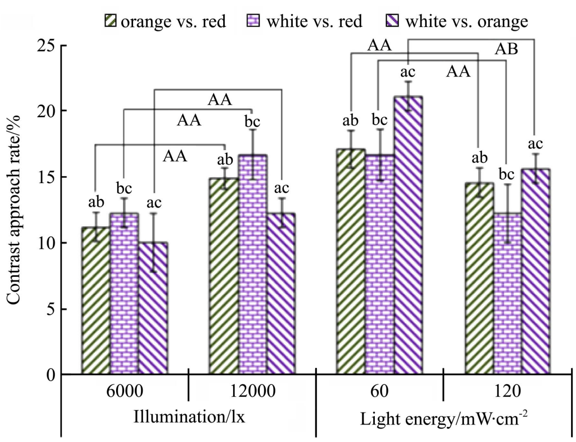
Thrips selective sensitivity to white light was the optimal, followed by orange light, red light (Figure 3b). Between 6000 lx and 12000 lx, the contrast response rate in white vs. red light (F=27.05, p=0.007), and white vs. orange light (F=12.50, p=0.024) showed significant differences, while it increased to 25.51% in white vs. red light, and to 32.20% in white vs. orange light, then decreased to 41.36% in orange vs. red light, when light energy increased from 60 to 120 mW/cm^2. These results indicated that the worst sensitivity spectrum was red, followed by orange.



a. Total response rate at 0-150 mm



b. Contrast response rate at 0-150 mm



c. Contrast approach rate at 0-50 mm

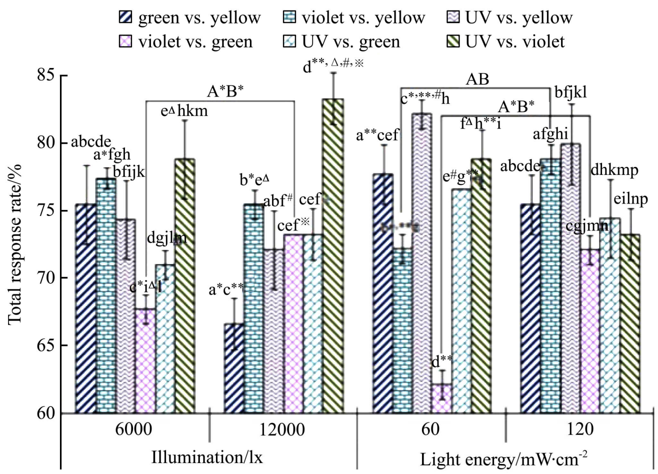
Note: The same small letter shows no significant difference (p>0.025), different letters show significant differences (p<0.025), different letters with * or Δ show very significant differences (p<0.025), and different letters with **, **, or ΔΔ show extremely significant differences (p<0.0001). Between 6000 and 12000 lx, or 60 and 120 mW/cm^2, AA shows no significant difference (p>0.025), AB, A*B*, and, respectively, show significant differences (p<0.025), very significant differences (p<0.025), and A**B** show extremely significant differences (p< 0.0001); the others show no significant differences (p>0.025). The same as below.

Figure 3 Thrips total response degree and contrast selection effect for spectral light and contrast spectral light at 0-150 mm

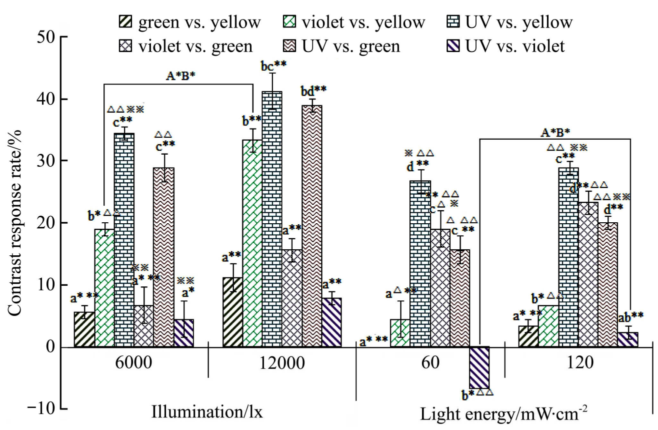
Furthermore, thrips approach sensitivity to white light was the best, followed by orange light, red light. While the contrast approach rate showed no significant difference among different pairings (df=2, 6000 lx: F=0.374, p=0.703; 12000 lx: F=2.561, p=0.157; 60 mW/cm^2: F=2.702, p=0.146; 120 mW/cm^2: F=1.18, p=0.37) (Figure 3c). The contrast approach rate in white vs. red light was the greatest (6000 lx: 12.21%; 12000 lx: 16.65%) under illumination, while when light energy stimulated thrips. The contrast approach rate in white vs. orange light was the greatest (60 mW/cm^2: 21.09%; 120 mW/cm^2: 15.54%). Illumination therefore made the thrips approach sensitivity to spectral light different from light energy. The worst total response rate, and the best contrast selective rate was white vs. red (6000 lx: 55.51%; 12000 lx: 58.84%), and orange vs. red light (6000 lx: 38.84%; 12000 lx: 37.73%), respectively, showing that red light drove thrips to select the sensitive spectral light, and was regulated by the enhanced light intensity.

3.2.2 The contrast selection effect of different pairings of yellow, green, violet, or UV light

There were significant differences of the total response sensitivity to different pairings (df=5, 6000 lx: F=3.516, p=0.035; 12000 lx: F=8.453, p=0.001; 60 mW/cm^2: F=22.019, p<0.0001; 120 mW/cm^2: F=1.863, p=0.175) (Figure 4a). The total response degree for UV vs. violet light (6000 lx: 78.81%; 12000 lx: 83.27%) under illumination, and for UV vs. yellow light (60 mW/cm^2: 82.15%; 120 mW/cm^2: 79.93%) under light energy, were the best, respectively.



a. Total selective response rate at 0-150 mm



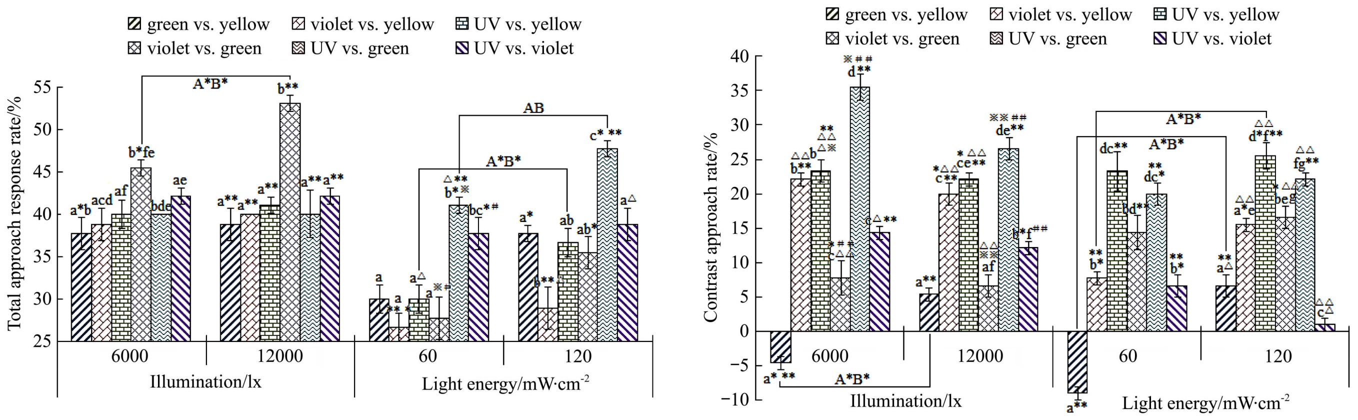
b. Contrast selective response rate at 0-150 mm

Figure 4 Total selective response rate and contrast selective response rate of western flower thrips adults for light spectra and contrast light spectra at 0-150 mm in two channels

Moreover, between 6000 lx and 12000 lx, at 60 and 120 mW/cm^2, respectively, there was a very significant sensitivity difference for violet vs. green light (F=24.894, p=0.008; F=40.405, p=0.003), and a significant difference for violet vs. yellow light (F=1.891, p=0.024; F=17.74, p=0.014). While 6000 lx showed that total response sensitivity to green vs. yellow (75.49%), violet vs. yellow (77.36%), and UV vs. yellow (74.37%) light were better at 12000 lx, 120 mW/cm^2 for violet vs. yellow (78.81%), and violet vs. green light (72.16%) were better than at 60 mW/cm^2.

Under the same illumination conditions, the contrast response rates showed that the selective sensitivity to UV light was better. Under light energy, the selective sensitivity to 60 mW/cm^2 of violet light was better, while that to 120 mW/cm^2 of UV light was better. Moreover, there were extremely significant differences of the contrast selective sensitivity among different pairings under the same light condition (df=5, p<0.0001, 6000 lx: F=53.78; 12000 lx: F=58.30; 60 mW/cm^2: F=38.72; 120 mW/cm^2: F=89.04) (Figure 4b). For the contrast response rate, UV vs. yellow light was the highest (6000 lx: 34.41%; 12000 lx: 41.08%; 60 mW/cm^2: 26.63%; 120 mW/cm^2: 28.86%), and the contrast response rate increased when light intensity increased (Figure 4b), indicating that thrips contrast selective response sensitivity was enhanced by the increasing intensity.

Thrips showed selectively different spectral light sensitivities, and the total approach rate and the contrast approach rate for different pairings differed from each other (Figures 5a and 5b).



a. Total selective approaching response rate at 0-50 mm

b. Contrast selective approaching response rate at 0-50 mm

Figure 5 Total approach response rate and contrast approach response rate of western flower thrips adults for light spectra and contrast light spectra at 0-50 mm in two channels

Under the same light conditions, there were significant differences of the total approach rate among different pairings (df=56 000 lx: F=2.894, p=0.061; 12000 lx: F=10.094, p=0.001; 60 mW/cm^2: F=7.892, p=0.002; 120 mW/cm^2: F=7.855, p=0.002) (Figure 5a). Under illumination, and light energy, respectively, the total approach rate for violet vs. green, and UV vs. green light were the best (6000 lx: 45.50%; 12000 lx: 53.18%; 60 mW/cm^2: 41.07%; 120 mW/cm^2: 47.74%); while green vs. yellow and violet vs. yellow light were the worst. When comparing 6000 lx with 12000 lx, and comparing 60 with 120 mW/cm^2, respectively, the total approach sensitivity to 12000 lx, and 120 mW/cm^2 was superior to 6000 lx, and 60 mW/cm^2, respectively.

Moreover, there were significant differences of the contrast approach rates among different pairings (df = 5, p<0.0001: 6000 lx: F=55.078; 12000 lx: F=30.60; 60 mW/cm^2: F=27.187; 120 mW/cm^2: F = 28.785) (Figure 5b). Under illumination and light energy, respectively, the contrast approach rate for UV vs. green (6000 lx: 35.54%; 12000 lx: 26.63%), and UV vs. yellow (60 mW/cm^2: 23.33%; 120 mW/cm^2: 25.54%) light were the highest. The approach sensitivity to yellow light was superior to that of green light under 6000 lx and 60 mW/cm^2, while sensitivity to green light was superior to that of yellow light under 12000 lx and 120 mW/cm^2. The approach sensitivity to UV light was the greatest, followed by violet light. There were significant differences for green vs. yellow light between 6000 lx vs. 12000 lx (F=30.188, p=0.005), 60 vs. 120 mW/cm^2 (F=72.573, p=0.001), and for violet vs. yellow light between 60 vs. 120 mW/cm^2 (F=24.595, p=0.005). In summary, the stimulating effect of light illumination differed from light energy, and green light illumination and yellow light energy increased thrips approach sensitivity to select UV light, inhibiting with increasing illumination, and intensifying with increasing light energy, respectively.

3.3 Discussion

Previous studies have speculated that the photoreceptor types of thrips adults may include green, blue, and ultraviolet photoreceptors[17], showing that these light spectra are recognized by insects, and can induce an optic nerve reaction, and may cause a phototactic response[18,19]. In this study, we found that under 120 lx, the spectral lights used in Experiment 1 all induced western flower thrips to show a selective visual response, and the response to blue light was the best, followed by UV, and green light (Table 3), indicating that only under the appropriate illumination, does the optic nerve sensitivity spectrum result in a better selective response.

Table 3 Selective response rate of western flower thrips adults induced by different spectral light at 0-150 mm/%

Illumination /lx	Spectrum							
	red	orange	yellow	green	blue	violet	U.V.	white
120	1.11±1.11ab$^{*\,**}$	2.22±1.11aed**	4.44±1.11befg**	12.21±1.11h$^{\triangle**}$	17.76±1.11i$^{\triangle}$i$^{**\,\triangle\triangle}$	6.66±1.11c*f$^{\triangle}$j$^{\triangle\triangle}$	14.44±1.1hi$^{**\,\triangle\triangle}$	5.56±1.11dg$^{\triangle}$j$^{\triangle\triangle}$

The labels are the same as shown in Table 2.

Previous studies has reported that tiny insects are more sensitive to green and yellow light[20], and less sensitive to red and orange light[21], and the attraction effects of UV light on many insects are better[22]. In our study, we found that under stronger photic conditions the stimulating effect of illumination or light energy made the selective sensitivity to UV, violet, and yellow light better, while red, orange, and white light sensitivity were worse (Table 1). Trichromophoric insects can use the opposing mechanism of color perception to select their favorite color light[23], and spectrum and light intensity affect thrips phototactic selection[24,25]. This may be a reason for the change of selective sensitivity to UV, violet, yellow, and green light under the same light conditions. The insect color and light perception provide a good visual guarantee for their behavior[26], which may have caused the thrips visual response to generate the approach behavior. The difference of a mesopic stress state from dark vision to photopic vision stimulated by different spectral lights could have caused the different approach sensitivity (Table 2).

When illumination and light energy increased, the change of the selective sensitivity, and the approach sensitivity to the same light spectra were different (Tables 1 and 2). To reveal the functional effects of illumination and light energy, we measured the illumination and light energy of UV, violet, green, and yellow light at 50 mm and 150 mm (Table 4).

Table 1 and Table 4 show that under the same illumination, the stronger illumination at 150 mm induced a superior selective response degree (6000 lx: violet, 31.3 lx, 22.20%; 12000 lx: yellow, 87.6 lx, 21.09%). Under the same light energy, the stronger light energy at 150 mm caused the superior selective response degree (60 mW/cm^2: violet, 0.10 mW/cm^2, 25.46%; 120 mW/cm^2: violet, 0.18 mW/cm^2, 19.99%). These results indicated that thrips relied on the stronger visual stimulation information to respond to the sensitive light target as shown in Experiment 1. When illumination increased from 6000 lx to 12000 lx, at 50 mm, light energy of violet and UV light was enhanced by 0.23 mW/cm^2 and 0.1 mW/cm^2, making the selective response degree increase by 7.52% and 4.02%, respectively. When light energy increased from 60 to 120 mW/cm^2, illumination of violet, UV light was enhanced by 1868, and 1450 lx, respectively, making the selective response degree decrease by 28.93%, and 28.37%, respectively (Table 2). Under illumination, spectral light quality therefore determined the approach sensitivity, intensified by light energy intensity when illumination increased, and under light energy, spectral light energy determined the approach sensitivity, and was inhibited by the intensity of illumination when light energy was increased.

Table 4 Measured illumination and light energy at 50 and 150 mm

		Position /mm	Illumination/lx				Light energy/mW·cm^{-2}			
			yellow	green	violet	UV	yellow	green	violet	UV
Illumination/lx	6000	150	29.4	24.8	31.3	21.2	0.006	0.005	0.04	0.028
	12000	150	87.6	62.5	39.6	36.5	0.023	0.019	0.042	0.054
Light energy/mW·cm^{-2}	60	150	322	289	134	123	0.09	0.058	0.10	0.06
	120	150	522	458	342	262	0.16	0.11	0.18	0.17
Illumination/lx	6000	50	230	301	330	398	0.05	0.05	0.11	0.22
	12000	50	660	1506	450	539	0.18	0.24	0.34	0.32
Light energy/mW·cm^{-2}	60	50	2700	2492	1332	1110	0.613	0.482	0.822	0.92
	120	50	4860	4760	3200	2560	1.32	0.952	1.36	1.54

In Experiment 2, under illumination, the stronger light energy was UV vs. violet light (Table 4), corresponding to the best total response degree (Figure 4a), intensifying by 4.46% when illumination increased from 6000 lx to 12000 lx, and thus indicating that light energy intensity of illumination decided the selective sensitivity. Under light energy, the total response degree for UV vs. yellow light was the best, corresponding to the maximum difference of illumination (UV vs. yellow), and indicating that illumination of spectral light energy affected the selective sensitivity, by a 2.22% decrease when light energy increased from 60 mW/cm^2 to 120 mW/cm^2. The contrast selective sensitivity to UV vs. yellow light was the greatest, and UV vs. violet light was the worst (Figure 4b), originating from the difference of visual sensitivity, regulated by the intensity of light. Thus, spectral light illumination and energy changed thrips visual selection response, affecting the approach behavior. These may originate from the difference of thrips bio-sensitivity to different photoelectric conversion intensity of LED spectral light illumination and energy, causing photo-thermal effects of LED photoelectric output, and finally affecting the thrips sensitivity selection response.

A study has reported that many tiny insects, such as thrips, whitefly, and aphids, can sensitively perceive blue and yellow color in background light, and when daylight illumination was 4000 lx, the attraction effect was the best[27]. While not all spectral light backgrounds induced the selective responses of the thrips, as shown in Table 1 and Figure 3, thrips selective sensitivity to red light was the worst, causing the selection of other spectral light types, similar to the results reported in Mika et al.[28]. Some studies have also found that photoreceptors in compound eyes of thrips and whiteflies are very sensitive to the UV spectrum (200-400 nm)[29], and our results showed that the selective sensitivity to 365 nm light was the best, followed by violet, and yellow light (Figures 4 and 5); and yellow and green light intensity regulated the approach sensitivity to select UV light. These results could indicate synergetic effects of photo pigments, screening pigments, and sensitizing pigments in insect compound eyes[30-33].

4 Conclusions

The present study showed that the sensitive selection response effect of western flower thrips to spectral light changed by enhancing the illumination and energy, presenting an intensifying or inhibiting effect to alter their approach sensitivity. The stimulating effect of UV vs. violet light energy, and the co-regulatory effects of UV vs. violet light caused a better response sensitivity under the same illumination conditions, and light energy, respectively. Moreover, yellow and green light enhanced the approach sensitivity to UV and violet light and red light drove thrips to select other light spectra. These results indicated that the driving effect of red light enhanced thrips visual selection response effect for UV and violet light coupled with yellow or green light. However, our results are still insufficient to explain the influencing effect of different light spectral characteristics on the selective approach behavior, such as the photo-thermal effects of light on the insect approach sensitivity. Further experiments are required to obtain a physiological understanding of insect visual responses to light spectra.

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