Influences of yellow and green lights on the visual response of western flower thrips and field verification

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Abstract: This study aimed to determine the effects of spectral light characteristics on the visual response of the western flower thrips, the strengthening mechanism of thrips response behavior regulated by light, and thrips response characteristics to contrast light. Light with combined and single wavelength were tested by using a self-made behavior response device for thrips. Light sources for trapping thrips were made to verify the trapping effect on thrips in a greenhouse, and the reasons for changes in thrips behavior were analyzed to characterize the mechanism of their phototactic response. The results showed that the light mode (single, contrast, combined light) affected the thrips visual response and approach response, whereas in contrast light, the effects were optimal. Combination light inhibited the thrips visual response, and when the illumination increased, the thrips visual response to single and combination light intensified, and the thrips approach sensitivity to green light increased in contrast and combination light. However, the light mode did not affect the thrips visual response and sensitivity to spectral light characteristics. The degree of thrips visual response to yellow light was stronger than that to green light, while the degree of thrips visual response to green light was stronger than that to yellow light, indicating that the photo-induced mechanism of the thrips visual response differed from that of the thrips approach response. Moreover, in the greenhouse, the trapping effect of different light sources on thrips was positively correlated with temperature. The trapping effect of green light was optimal, followed by a yellow light source, while the difference of light intensity (illumination, illumination energy) and its photo-thermal intensity between yellow and green light was the reason for the differences in the degree of visual trends and the trapping effects of thrips. However, the sensitivity of thrips responding to different light depended on the difference in the heterogeneous stimulation intensity of different spectral light. Thus, light brightness and photo-thermal effects were the causes of thrips visual responses, while bio-photoelectric reaction effects caused thrips to produce a visual response and affected the degree of the thrips visual response. The results reveal the underlying causes of pest control by light, and provide a theoretical basis for the research and development of pest induction equipment and light arrangements.

Keywords: pest control, western flower thrips, yellow and green light, visual response, field verification, light mode

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1 Introduction

Western flower thrips (*Frankliniella occidentalis*) are one of the most serious pests affecting vegetables, flowers, and other crops worldwide[1]. Chemical methods are mainly used to control thrips, but the “3R (resistance, resurgence, residue)” problem caused by the long-term use of chemical pesticides has shifted attention to other means for thrips prevention and control[2]. In recent years, the biological response characteristics of insects to chromatographic illumination, and the light perception, color vision, and light intensity vision mechanisms of thrips have been reported[3-5]. Color light induction management technology for controlling thrips has been suggested; however, the lack of research on the mechanism of thrips visual taxis restricts the efficacy of this technology. Therefore, the study of the spectral illumination characteristics of thrips visual sensitivity and phototactic manipulation factors can help to reveal the phototactic mechanism and visual behavior inducement of thrips, and may provide a basis for photo-induced manipulation of thrips biological habits, for better lighting prevention and control technology.

The thrips phototactic sensitivity spectrum has been studied previously. Research on the color vision mechanism and biological characteristics of thrips has shown that thrips have the strongest response in the wavelength range of 500-600 nm, while sunlight intensity, the shape and size of the chromatogram, the background color of the host, and the hanging height all affect the trapping effect of sticky plates[6-9]. Matteson et al.[10] found that the peak value of the retinal potential of *F. occidentalis* was 545 nm, while the trapping peak value was 524 nm, and therefore presented the irritability of color tropism within a short distance[11,12]. Thus, the sensitive spectrum of thrips visual reaction is not consistent with that of the thrips visual response. Fan et al.[13,14] found that the highest reaction of *F. occidentalis* to color light wavelengths was 524 and 560-590 nm, and that

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illumination affected the thrips phototactic sensitivity; however, the photoinduced effect of light intensity on the change of thrips visual sensitivity was not explained. Yang et al.[15,16] further reported that the phototactic response of *F. occidentalis* to yellow light (560 nm) was the highest, followed by green light (520 nm). These results indicate that yellow and green light can effectively induce the visual response of *F. occidentalis*, and the yellow and green spectrum can avoid the trap diversity of the broad-spectrum trap lamp and any influence on crop photosynthesis[17,18]. To our knowledge, however, there have been no reports on the regulation of yellow and green light on the phototactic adaptability of thrips, the influence reinforcement effect of light factors on thrips visual taxis, and the stimulus of photo-induced changes of thrips visual sensitivity. Moreover, studies on the phototactic induction applications of thrips are still in the initial stages, and there are many problems, such as the influencing mechanism of the thrips biological regulation induced by light, thrips habitat dependence, and the influence of environmental factors, which may restrict the successful use of yellow and green light to trap thrips in the field.

In this study, yellow and green LED lights were used to investigate the degree of visual taxis and the degree of visual responses (the visual response effect) of western flower thrips, to determine the induction of visual taxis response changes, to clarify the illumination characteristics of thrips visual sensitivity, and to identify the reinforcement mechanism of photo-regulation behavior. A population of *F. occidentalis* was exposed in a greenhouse to yellow and green LED lights, to verify the induction effectiveness of these light sources, and to characterize the thrips phototactic response mechanisms for pest control strategies.

2 Materials and methods

2.1 Experiment 1 - Visual response of *Frankliniella occidentalis* to yellow and green light

2.1.1 Insects

Western flower thrips samples were obtained from the vegetable and flower demonstration base of Henan Academy of Agricultural Sciences. The thrips were robust female adults of multiple generations, harvested 1-2 d after eclosion. Using thrips collected on the same day, 60 thrips per group were prepared and used as test insects after dark adaptation for 30 min before the experiments, and each group was replicated 3 times..

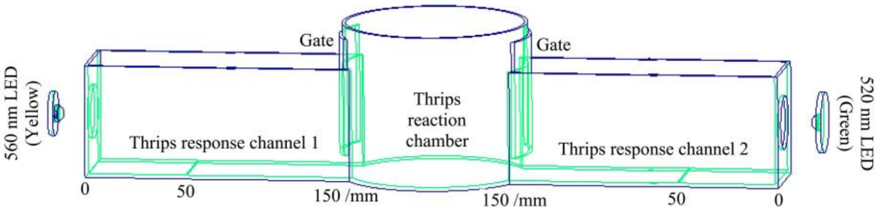
2.1.2 Light radiation and light measurements

The peak wavelengths spectra of the 3 W light-emitting diode (LED; Hongtai Electronics, Yueqing City, Zhejiang, China) lights were yellow (560 nm) and green (520 nm). The experimental illumination was calibrated using an illuminance meter (Model: TES-1335; resolving power: 0.01 lx; Taiwan Taishi, Macao, Taiwan) and was set to 6000 lx and 12 000 lx, respectively.

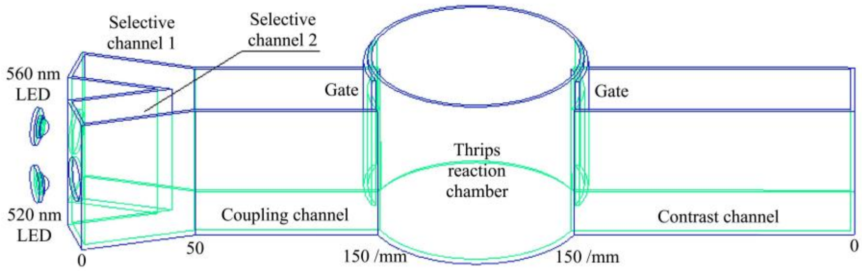
2.1.3 Experimental device

To determine the effects of yellow and green contrast light on thrips visual sensitivity, the visual responses were tested using device 1 (Figure 1a). Device 1 was composed of a thrips reaction chamber (Φ100 mm×80 mm), and thrips response channel 1, and channel 2 (length×width×height: 150 mm×40 mm×60 mm), which were separated by gates. The yellow and green LED light sources were placed at the front of channel 1 and channel 2, respectively, and the yellow and green light sources were introduced into the channel through the central hole.

To determine the regulatory effects of yellow and green light on thrips approach sensitivity, the thrips visual response and visual selection sensitivity induced by the combined yellow and green lights were tested by using device 2 (Figure 1b). With this device, the coupling channel (length×width×height: 100 mm×40 mm×60 mm) and contrast channel (length×width×height: 150 mm×40 mm×60 mm) were connected to the reaction chamber (Φ100 mm×80 mm), separated by a gate. The front end of the coupling channel was extended by two arms (the angle between selective channel 1 and selective channel 2 was 30°, length×width×height: 50 mm×40 mm×60 mm), and the yellow and green LED light sources were respectively placed at the front end of the two arms, while the light was introduced through the central hole. To determine the illumination characteristics of thrips visual sensitivity by using device 1, the yellow and green LED light sources were placed at the front end of one channel. The section shown in Figure 1 was used to analyze the changes of thrips visual taxis induced by the yellow and green lights.



a. Device 1 for the thrips visual behavior response



b. Device 2 for the thrips visual selection response

Figure 1 Devices used for investigating the visual response of thrips

2.1.4 Experimental methods

The experiments were conducted from 20:00 to 22:00 at (27±1)℃ and (65±5)% relative humidity in darkness.

Using the same illumination (6000 lx, 12 000 lx) of yellow light and green light in device 1 and device 2, three groups (60 thrips per group) of dark adapted thrips were used to determine the visual response to different light patterns (contrast light, combined light, and single light). Before every experiment, according to the light pattern of every device, the light source was arranged to calibrate the illumination, and the test insects were introduced into the reaction chamber with a brush. During testing, the light sources and gates were opened to test the visual response of each group of test insects to the corresponding light conditions, so that three groups of test insects were used in each test. After every determination, the light source and gates were closed, and the indoor light source was opened to allow counting of the number of thrips distributed at 0-50 mm and 0-150 mm in each channel.

2.1.5 Data computation

The percentage of the mean values of thrips in three experiments distributed at 0-150 mm and 0-50 mm in every channel for 60 thrips was calculated. In device 1, n_{11} and n_{12}, n_{13} and n_{14} are the mean values of thrips distributed at 0-150 mm, 0-50 mm of thrips response in channel 1 and 2, respectively. In device 2, n_{21}, n_{22} are the mean values of thrips distributed at 0-50 mm of selective channel 1, selective channel 2, respectively, and n_{23} is the sum of thrips distributed at 0-50 mm of selective channel 1, selective channel 2, and 50-150 mm of coupling channel.

Thrips visual response rate (n_{11}/60, n_{12}/60, n_{23}/60) was the thrips visual response degree to single yellow or green light in device 1, to combination light in device 2, and thrips total response rate (n_{11}+n_{12})/60 was used to determine the sum of the thrips visual responses to single yellow and green light. Thrips approach rate (n_{13}/60, n_{14}/60, n_{21}/60, n_{22}/60) reflected the degree of thrips visual taxis to yellow and green light in device 1 and device 2, and thrips approach contrast rates (n_{11}-n_{12})/60, (n_{21}-n_{22})/60 were used to determine the D-value of the thrips approach to yellow and green light, to determine the difference of the thrips approach sensitivity. Thrips total approach rate (n_{21}+n_{22})/60 was used to determine the sum of the thrips approach to the combined yellow and green lights. Moreover, according to the visual response, and the thrips approach to single light (yellow light or green light) and the combined light (yellow light and green light), the influences of light patterns on the thrips visual response were analyzed to determine the illumination characteristics of the thrips visual response and approach sensitivity.

2.2 Experiment 2 – Field test verification

Based on the laboratory test results, to determine the trapping effects of yellow and green light on western flower thrips in the field, the thrips induction experiments were conducted in a vegetable greenhouse (length×width×height = 120 m×11 m×4 m) at the Zhengzhou suburb of Henan Province on June 20-26, 2019. The mixed plants of pepper, tomato, and cucumber grew well in the greenhouse, and the growth of each plant was similar, with each plant in the peak fruiting stage. *F. occidentalis* had been bred for many generations in the same area.

2.2.1 Experimental light sources

The light sources used for trapping and counting the *F. occidentalis* are shown in Figure 2.

a. Schematic diagram of light source b. Yellow light source c. Green light source d. Yellow-green (1:1) light source

1. Upper box (build-in a light rain control system) 2. Support rod 3. White sticky board 4. LED emitter 5. Light body support frame 6. Lower box 7. Collecting container 8. Clamping device 9. Air suction device.

Figure 2 The experimental light sources

The light source used air suction and a white sticky board. The air suction device is shown in Figure 2(9), and was located between the sliding device and lower box Figure 2(6) and collecting container. A white sticky board Figure 2(3) was used to catch the thrips flying around the lights at night and was clamped on the support rod by a clamping device. A support rod Figure 2(2) was connected with the upper box and the lower box. The light source and fan control systems were built into the upper box and the lower box contained an inverted funnel, which facilitated trapping the thrips in the collecting container. LED emitter lights were placed on the support frames of the upper and lower boxes. The two spectrums were yellow (560 nm) and green (520 nm) used in various combinations. The power of every light source was 20 W, and the illumination of the light source was 12 000 lx, which decayed to 0.1 lx at the irradiation distance of 20 m.

2.2.2 Light source arrangement

Three light sources were suspended in the middle position of the 120 m length of the greenhouse. The upper edge of the lower box was flat with the top of the plant. To avoid light interference, the layout interval between the two light sources was 40 m. The layout mode is shown in Figure 3.

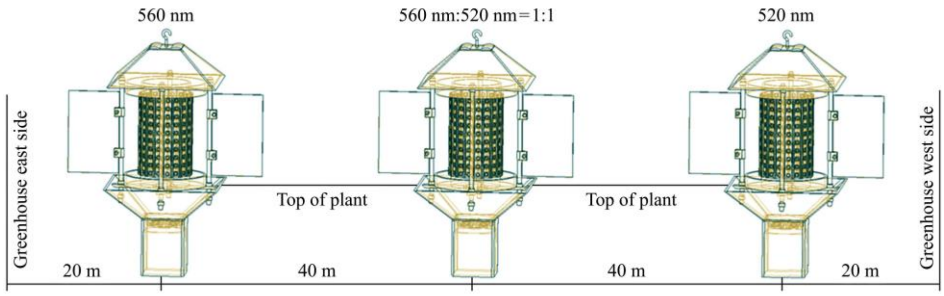


Figure 3 Layout mode of light sources in the greenhouse

2.2.3 Experimental methods

Three light sources were turned on at 19:00 every day and were turned off at 05:00 of the next day. At 21:30, 24:00, 02:30, and 05:00, the white sticky plate and collecting device were replaced to count thrips numbers. Test times per night were divided into four periods (19:30–21:30, 21:30–0:00, 0:00–02:30, and 02:30–05:00), and the average number of thrips trapped by every light source during the four time periods of six nights was calculated. The average temperature at the four time periods of every night for six nights was recorded to determine the influence of temperature on the phototactic trapping effect of thrips. The relative humidity in the shed was constant, and was (65.0±2.5)%.

2.2.4 Data analysis

For experiments 1 and 2, a general linear model analysis was used to compare the thrips mean percentage induced by different light patterns. For multiple comparisons, LSD tests at p=0.05 were used. The Student's t-test was used to determine the difference between two different light intensities in experiment 1 and two different light sources in experiment 2. SPSS statistical software for Windows (SPSS, Chicago, IL, USA), version 16.0 and Excel Software for Windows (Microsoft, Redmond, WA, USA) were used for all statistical analyses. The results are expressed as the mean±standard error (SE).

3 Results and discussion

3.1 Visual response of western flower thrips to yellow and green light

The results of the thrips visual response and visual taxis to yellow and green light under different light patterns, are shown in Tables 1 and 2, and Figure 4.

The effects on the thrips visual response were significantly different between light patterns (F_{6000}=197.07, p<0.001; F_{12000}=8.01, p<0.01), but there was no significant difference for yellow single light (560 nm), green single light (520 nm), and combined light (p>0.05); all were significantly lower than that using contrast light. At 6000 and 12 000 lx, the effects of the thrips visual response to contrast light were 77.70% and 71.05%, respectively, while under 6000 lx, green light was the worst, followed by yellow light, and under 12 000 lx, the combined light was the worst, followed by yellow light (Table 1). The effect of the thrips visual response to yellow single light, green single light, and combined light stimulated by 12 000 lx was significantly better (F_{560}=121.0, p<0.001; F_{520}=96.00, p<0.001), and was better than ($F_{520+560}$ = 96.00, p<0.05) that stimulated by 6000 lx. Contrast light stimulated by 12 000 lx, presenting the inhibition effect, was lower than ($F_{520\ \mathrm{vs}\ 560}$=2.573, p<0.05) that stimulated by 6000 lx.

Table 1 Effects of the thrips visual response to single, combination, and contrast light

		Thrips visual response rate /%			Total response rate/%		
		Single light		Combined light	Contrast light	F value	p value
		560 nm	520 nm	520 nm + 560 nm	520 vs 560	df=3	
Illumination/lx	6000	50.10±0.96a**	48.76±0.96a**	53.44±0.96a**	77.70±1.11b**	197.07	<0.001
	12000	62.35±0.56a	60.12±1.11a*	57.34±0.56a$^{\#}$	71.05±2.22b$^{*\ \#}$	8.01	<0.01
F value	df=1	121.0	96.00	12.25	2.573		
p value		<0.001	<0.001	<0.05	<0.05		

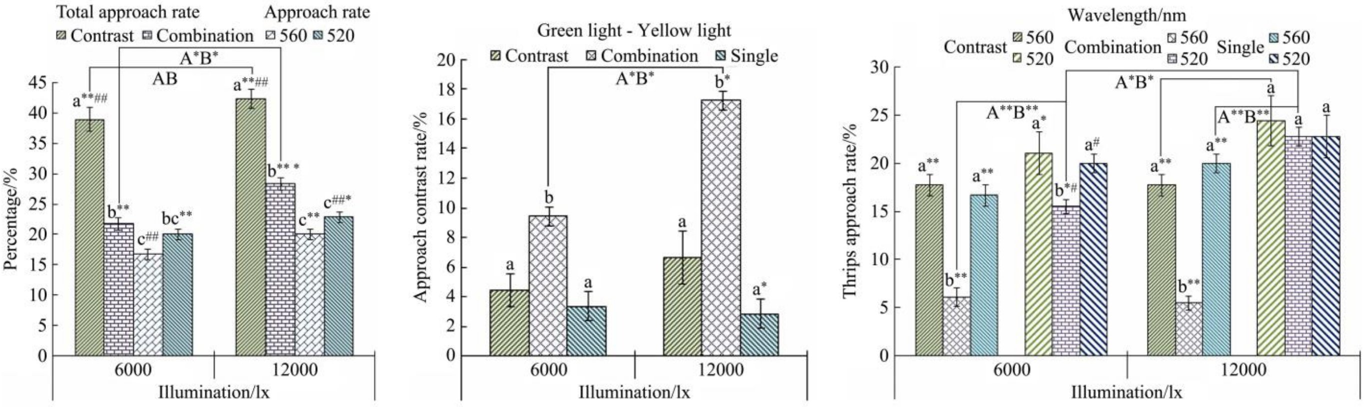
Note: On the same line, different lower-case letters indicate significant differences (p<0.05), and different letters with the same single superscript and with the same double superscript indicate very significant differences (p<0.01) and extremely significant differences (p<0.001), respectively. The same for Table 2.

Table 2 The thrips visual response to yellow and green light in single contrast light

		Thrips visual response rate /%					
		Single light		Contrast light		F value	p value
		560 nm	520 nm	560 nm	520 nm	df=3	
Illumination/lx	6000	50.10±0.96a$^{*\ **}$	48.76±0.96a$^{\#\#}$	42.18±1.11b*	35.52±1.11c$^{**\ \#\#}$	36.165	<0.001
	12000	62.35±0.56a**	60.12±0.96a**	41.07±2.22b**	29.98±1.98c**	98.25	<0.001
F value	df=1	121.0	96.00	0.199	6.252		
p value		<0.001	<0.001	>0.05	>0.05		

The light patterns were different while the illumination was the same, and the thrips total response to contrast light was optimal (Table 1). However, when comparing single light with contrast light, the difference of the thrips visual response to yellow and green light was significant (F_{6000}=36.165, p<0.001; F_{12000}=98.25, p<0.001) (Table 2), while in single light, the difference between yellow and green light was not significant (p>0.05). In contrast light, the thrips visual response to yellow light was better than that to green light (p<0.05), and the thrips visual response to yellow and green light in single light was better than that to yellow light in contrast light. Under different illuminations, using single light, the thrips visual response was stimulated by 12 000 lx yellow light, and green light was better than 6000 lx (p<0.001), while in contrast light, stimulated 12 000 lx yellow and green light were slightly better than that of 6000 lx, respectively. The results showed that contrast light inhibited the thrips visual response, and the thrips visual response to green light was lower than that to yellow light.

The differences of the thrips visual taxis response among different light patterns were significant (F_{6000}=50.85, p<0.001; F_{12000} = 113.85, p<0.001), and when compared to combined light and single light with contrast light, the difference was significant (p<0.001). The thrips visual taxis effect induced by contrast light was better, and that caused by yellow light was the worst (Figure 4a). Among different illuminations, the differences of the thrips total approach to contrast light and combined light were significant (p<0.05), while compared to yellow light, green light was not significant, but compared with the 6000 lx and 12 000 lx enhanced thrips visual taxis effects, the enhancement caused by combined light was the strongest (6.68%). At less than 12 000 lx, the thrips visual taxis effect caused by contrast light was optimal (42.19%), followed by combined light (28.39%), and yellow light (20.04%) (Figure 4a). The thrips visual approach sensitivity to green light was superior to yellow light, but the light pattern significantly affected the thrips approach sensitivities to green and yellow single light (F_{6000}=12.935, p<0.01; F_{12000}=32.03, p<0.01). When comparing contrast light and single light, the influence of combined light was the most significant (p<0.01); furthermore, between different illuminations, the difference caused by combined light was the most significant (F=98.00, p<0.01), and at less than 12 000 lx, the approach contrast was the highest (17.26%), followed by at 6000 lx (9.46%) (Figure 4b).



a. Thrips visual taxis effect b. Thrips approach contrast rate c. Thrips visual taxis degree

Note: Different lower-case letters marked with the same single superscript and with the same double superscript denote very significant differences (p<0.01) and extremely significant differences (p<0.001), respectively. AB, A^*B^*, $AA^{**}B^{**}$ indicate significant differences (p<0.05), very significant differences (p<0.01), extremely significant differences (p<0.001), respectively, and cases with no significant differences are left unmarked. The same notation was used in Figure 6.

Figure 4 Results of the thrips approach responses to different yellow and green light. Different lower-case letters indicate significant differences (p<0.05, multiple comparisons; LSD)

Among different light patterns of yellow light, the differences of the thrips approach were significant (F_{6000}=55.456, p<0.001; F_{12000}=67.029, p<0.001), and the thrips approach caused by combined light was the worst (approximately 6%). Using the same light pattern, between 6000 and 12 000 lx, the difference of the thrips approach was not significant (p<0.05), and at less than 12 000 lx, the thrips approach caused by single light was the highest (20.04%) (Figure 4c). Among different light patterns of green light, the illumination affected the thrips approach (F_{6000}=9.466, p<0.05; F_{12000}=1.571, p>0.05), and at less than 6,000 lx, the thrips approach caused by combined light was the worst (15.59%), while when comparing with 6000 lx, 12 000 lx enhanced the degree of the thrips visual taxis, and the enhancement effect caused by combined light was the strongest (7.24%) (F=84.88, p<0.01). However, the thrips approach caused by 12 000 lx contrast light was the highest (24.24%) (Figure 4c).

The results shown in Figure 4 indicate that the thrips visual taxis effect caused by contrast light was the best, and the combined light affected the degree of the thrips visual taxis. However, the degree of the thrips visual taxis to green light was higher than that to yellow light, and the intensity of illumination enhanced the thrips visual approach sensitivity to green light, in contrast light and combined light, while it weakened the difference of the approach sensitivity to yellow and green light using single light, and the enhancement effect caused by combined light was the strongest (7.24%).

3.2 Thrips trapping effects induced by different light sources in the field

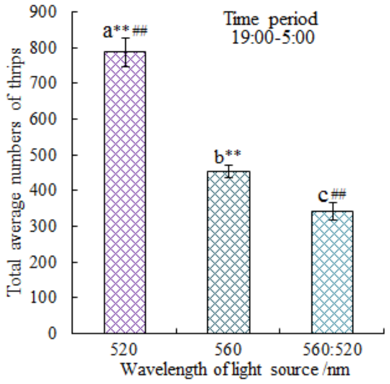
The trapping effects of western flower thrips induced by different light sources at different periods of night are shown in Table 3.

Table 3 Capture effects of different light sources on thrips at different time periods

		Thrips average numbers trapped by light source /head					
Time period		19:00-21:30	21:30-12:00	0:00-2:30	2:30-5:00	F value	p value
Average temperature/ ℃		27±0.5	25±0.5	23±0.2	21.5±0.2	df=3	
Wavelength /nm	520	$376.33±8.76A^{**}a^{**\ \#\#}$	$193.33±26.67A^{*}b^{**\ *}$	$123.33±9.28A^{*}c^{\#\#}$	$98.33±4.41A^{*}c^{\#\#\ *}$	70.637	<0.001
	560	$190.00±20.21B^{**}a^{*\ **}$	$101.67±6.01B^{*}b^{*}$	$85.00±5.00Bc^{*}$	$70.00±10.41Bc^{**}$	18.981	<0.01
	560:520=1:1	$136.67±19.65B^{**}a^{*\ **}$	$96.67±3.33B^{*}b$	$61.67±6.01B^{*}c^{*}$	$46.67±4.41B^{*}c^{**}$	14.19	<0.01
F value	df=2	54.524	11.718	19.415	13.642		
p value		<0.001	<0.01	<0.01	<0.01		

Note: In the same column, different capital letters indicate significant differences (p<0.05). *, and ** indicate very significant differences (p<0.01) and extremely significant differences (p<0.001), respectively. In the same line, different lower-case letters indicate significant differences (p<0.05) and different lower-case letters with the same single superscript and with the same double superscript indicate very significant differences (p<0.01) and extremely significant differences (p<0.001), respectively.

At the same time period of night, the difference of the thrips trapping effects induced by different light sources was significant (p<0.01), and the difference from 19:00–21:30 was the most significant (F=54.524, p<0.001). The difference between the yellow light source and light source at yellow: green = 1:1 was not significant, and both were lower than that of green light, while that of yellow: green = 1:1 was the worst (Table 3). At different time periods of night, the difference of the thrips trapping effect induced by the same light source was significant (F_{520}=70.637, p<0.001; F_{560}=18.981, p<0.01; $F_{560:520}$ = 14.19, p<0.01), and with an increase of night time, the trapping effect decreased, while from 19:00–21:30, the trapping effect was the best, but between 0:00–02:30 and 02:30–05:00, 21:30–12:00, and 0:00–02:30, the difference of the trapping effect was not significant (Table 3).



Note: Different lower-case letters marked with the same double superscript denote extremely significant differences (p<0.001), respectively.

Figure 5 Thrips trapping effect induced by light source

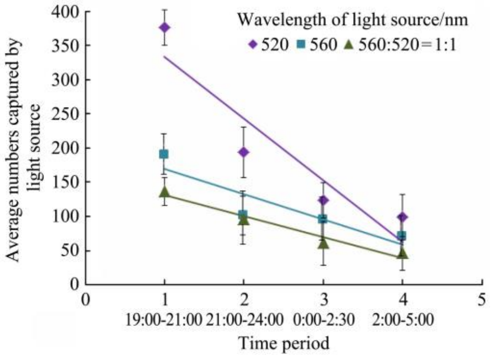


Figure 6 Thrips trapping effects in the night time period

Overall, within 10 h at night, the thrips trapping effect (791.33 heads/night) induced by green light was significantly better than that by yellow light. The source of yellow: green = 1:1 was followed by the yellow light source (456.67 heads/night), while that of light source of yellow: green = 1:1 was the worst (341.67 heads/night) (Figure 5). Correlation analyses showed that there was a significant linear correlation between the trapping effect induced by different light sources and night time periods (Figure 6). There was a negative correlation between the thrips average numbers trapped by different light sources and different time periods (R_{520}=–0.929, R_{560}=–0.904, $R_{560:520}$=–0.982, p=0.05). The relative humidity in the shed was constant, but the temperature decreased with the increase of night time period (Table 3). Thrips average numbers trapped by different light sources were therefore positively correlated with night temperature (R_{520}=0.929, R_{560}= 0.904, $R_{560:520}$=0.982, p=0.05); that is, the higher biological activity of thrips caused by higher temperatures enhanced the trapping effect induced by light.

3.3 Discussion

The natural phenomenon of "flying moth darts into the fire" is the bases of the night moth trapping lamp design. The western flower thrips is a small invasive pest, and based on its sensitivity to chromatography, color sticky plate technology[19] is used to attract thrips to its sensitive color light. At present, the lack of research on insect phototactic response mechanisms and insect visual sensitivity factors have restricted the development of a phototactic induction device for thrips pests. The results of the present study showed that the effects of different light patterns on the thrips visual response were different, and the thrips visual response to contrast light was the best. Among them, combined light weakened while contrast light enhanced the effect of the thrips visual response, and the intensity of illumination strengthened in single light and combined light, and the enhancement effect was the strongest in single light (an increase of approximately 11.5%), while in contrast light, the thrips visual response was inhibited. Studies have shown that the insect visual system absorbs photon energy and this induces visual potential response sensitivity, and generates a visual physiology response through the transmission of different neurons. The intensity of illumination and the adaptive function of insect bodies is caused by the antagonism of the visual spectrum affecting the degree of visual response[20-22]. The thrips visual response was affected by the bio-photoelectric effect induced by spectral light characteristics, and the degree of the thrips visual response to yellow light was superior to green light. The results further showed that light intensity enhanced the thrips visual taxis effect, which was further reinforced by combined light and contrast light. However, the degree of the thrips visual taxis to green light was superior to yellow light. The spectral light of the thrips visual response sensitivity was significantly different from that of the approach sensitivity, and spectral light could induce thrips to produce a good visual response (Table 2), but it was not able to make thrips produce good visual taxis (Figures 4-5). This indicated that the photo-induced mechanisms of the visual response of insects are not different from that of the insect visual taxis, which is of great significance in revealing the underlying causes of the insect phototactic induction mechanism, and could provide a theoretical basis for the development of pest phototactic induction control techniques.

To clarify the differences of photo-induced influence mechanisms between the thrips visual response and visual taxis, different light parameters were used, as listed in Table 4.

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

Optical parameters of light source		Illumination/lx	6000		12000	
		Wavelength/nm	560	520	560	520
		Power/W	0.815	0.85	0.856	0.884
		Light energy/mW cm^{-2}	2.54	3.98	12.3	13.76
Position/mm	50	Illumination/lx	230	301	0.05	0.06
		Light energy/mW cm^{-2}	660	1506	0.18	0.24
	150	Illumination/lx	29.4	24.8	0.006	0.005
		Light energy/mW cm^{-2}	87.6	62.5	0.023	0.019

It can be seen from Table 4 that at 150 mm, the intensity of illumination and light energy of yellow light were stronger than that of green light, so the coupling stimulation intensity of yellow light brightness and its light energy preferentially induced the thrips visual sensitivity response, and then produced the visual behavioral response. The heterogeneity of spectral light intensities was therefore the reason for the difference of the thrips sensitive responses to yellow vs. green light. In the "Y" type combination arrangement of yellow-green light sources, the coupling intensity at 150 mm was stronger than that of green light, but weaker than yellow light, while in the contrast arrangement of yellow and green light sources at 150 mm, the intensity was superposed for enhancement. The irradiation intensity was then responsible for differences of the thrips visual responses to different light patterns. Furthermore, with the increase in the intensity of illumination, contrast light inhibited the effect of the thrips visual response, originating from the different internal demands of individual insects for light intensity, and the effect of light interference on the output of the physiological regulation reaction of thrips visual sensitivity[23-25]. Thus, the increment of light intensity determined the synergistic effect of single light and combined light on the thrips visual response.

Under the same illumination, the difference between the thrips total approach in combined light (38.85% induced by 6000 lx, 42.19% induced by 12 000 lx) and the sum of the thrips approach to yellow and green light in single light (36.74% induced by 6000 lx, 42.86% induced by 12 000 lx) was not significant (Figure 4a), showing that contrast light did not affect the degree of the thrips visual taxis. Table 4 shows that the illumination intensity and light energy of green light were all stronger than that of yellow light, thus, the thrips visual approach sensitivity to green light was superior to yellow light (Figure 4c). This was because the stimulation intensity of green light was stronger than that of yellow light, and the stimulation intensity of yellow and green light dominated the thrips visual taxis effect and determined the degree of visual taxis of thrips. In combined light, the superposition strength of yellow light and green light at 50 mm was stronger than green light alone, which enhanced the effect of the thrips visual taxis. The visual effect of the thrips identification selectivity to yellow and green light in combined light correspondingly inhibited the degree of thrips visual taxis (Figure 4a, Figure 5). With the increase of the illumination intensity, the increment of green light intensity was significantly stronger than that of yellow light (Table 4), which enhanced the degree of thrips visual taxis to green light (Figure 4).

Studies have shown that insect visual pigment absorbs photons when light stimulates the insect visual system, which leads to the transformation of insect vision from dark adaptation to light adaptation. During a 30 min mesopic vision state, the insect phototactic response is therefore more sensitive[26-29]. However, this study showed that the trapping effect of the light source on thrips in the light adaptation state was still significant (Table 3). By analyzing light parameters of a light source (Table 4), under the same illumination of 3W LED, the luminous power and the luminous energy of green light were all higher than that of yellow light; therefore, the photoelectric conversion effect of LED green light made LED scattering heat and light radiation heat all stronger than LED yellow light. That is, the illumination temperature of green light was higher than that of yellow light, and on the basis of the thrips visual sensitivity to yellow and green spectra, which was enhanced by the stimulation of light intensity on the multiple vision pigments, spectral light brightness induced thrips to generate the photoreceptive orientation response, and the thermal effect produced by LED luminous characteristics enhanced thrips receptive taxis, and the photo-thermal coupling effect induced thrips to generate the visual taxis effect. The photo-thermal effect caused the thrips to generate the visual taxis effect, while the difference of light intensity and heat intensity between yellow and green light was the reason for the difference of the thrips visual taxis effect. The perceptive inertia difference of thrips individuals to light and heat was inhibited by the degree of visual taxis of the thrips population. It has been found that light energy can be absorbed by specific organs and insect surfaces, resulting in energy accumulation, producing photodynamic bio-compensatory activity, and the effect of temperature on thrips phototactic physiology law was unclear[30,31]. Further studies of the gene regulation of insect phototactic physiology, and thrips phototactic physiology law are needed. Likewise, the different mechanisms increasing the light stimulation intensity on insect responses should be further studied.

4 Conclusions

This study showed that the effects of the visual response and the visual taxis of western flower thrips to the contrast light of yellow light and green light were optimal, and that combined yellow and green light weakened the effect of the thrips visual response, while it enhanced the effect on the thrips visual taxis. An increase of illumination increased the thrips visual response to the single light (yellow, green) and combined light, and intensified the thrips approach sensitivity to green light, in contrast to combined light, showing that the light pattern and light intensity affected the thrips visual response. The contrast light and the combined light inhibited the degree of thrips visual response, and the degree of visual taxis to yellow and green single light, but the degree of thrips visual response to yellow light was higher than that to green light. The degree of thrips visual taxis to green light was superior to yellow light, indicating that the light spectra of the thrips visual response sensitivity was significantly different from that of approach sensitivity. The trapping effect of the light source on *F. occidentalis* was positively correlated with temperature, and was stimulated best by a green light source, followed by a yellow light source, resulting from the difference of light intensity and thermal intensity of light energy between yellow and green light. This also accounted for the difference of the thrips visual trapping effect caused by a yellow and green light source. Moreover, the sensitivity difference of the thrips visual response to light, originating from the difference of stimulus intensities of spectral light, and the photo-thermal effect were the reasons why thrips generated visual taxis. Thus, the bio-photoelectric effect induced by light was the reason that thrips generated a visual response.

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