Photo-induced visual response of western flower thrips attracted and repulsed by their phobotaxis spectrum light

Qihang Liu[1], Yuqing Wu[2], Mingfu Zhao[1*]

(1. *Henan Institute of Science and Technology, Xinxiang 453003, Henan, China*;
2. *Institute of Plant Protection, Henan Academy of Agricultural Sciences, Zhengzhou 450002, China*)

Abstract: This study aimed to clarify the synergistic phototactic attraction-repulsion effect formed by the photo-induced approach-avoidance behavior of thrips, construct phototactic attraction-repulsion light control technologies. The phototactic push-pull effects of red light and UV (365 nm), violet (405 nm), green (520 nm), and yellow (560 nm) single light, as well as their pairwise combined light on the behavior of western flower thrips were investigated using an apparatus that measured thrips response. The study also analyzed the influence of light properties on the phototactic attraction-repulsion effects of thrips and the synergistic effects of red light, and the attraction-repulsion regulation mode. The influence factors on the photo-induced attraction-repulsion effect of thrips were also discussed. The results showed that the red light, presenting the push effect, drove thrips to respond to the sensitive light. The synergistic attraction-repulsion effect of red light and single light, as well as that of red light and combined light was related to the light intensity. However, the attraction-repulsion synergism did not reflect thrips response effect and approach effect pulled and pushed by red light and single light, red light and combined light. Thrips preference for green-yellow light, and their behavior depended on the degree of UV light, making the attraction-repulsion synergy of red and green light the strongest. When the light intensity increased, the attraction-repulsion synergy of red and yellow light was the strongest. The attraction-repulsion response to red light and single light was related to the spectral attribute of the single light, with that of red light and UV light being better. The attraction-repulsion response to red light and combined light was related to light intensity. The intensity of combined light made the attraction-repulsion response to red light and the combined UV and violet light be the best, and the brightness of long-short spectrum light rendered red light and the combined UV and yellow light the best. All such light and combinations were remarkably better than that of red light and UV light. Relative to red light and UV light, the use of red light and combined light provided limited enhancement to the approach effect of thrips; however, under red light and combined light, violet light intensified the approach of thrips to UV light, with yellow light strengthening the approach to green light. Those results provided a scientific basis for the development of light trapping equipment and the adjustment of light control strategies for thrips.

Keywords: Western flower thrips, photo-induced visual response effect, attraction-repulsion effect, phobotaxis spectrum light, light intensity

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1 Introduction

Western flower thrips (*Frankliniella occidentalis*) are among the most serious pests to vegetables, flowers and other crops worldwide, and have become a major threat to crops in China[1]. Currently, chemical, physical, and biological control measures have been used to combat thrips[2,3]. As a physical control method, color traps have been popularized and used; however, the host, chromatographic shape, size, background color, and color plate height affect the trapping effect[4,5]. Thus, using the phototactic nature of thrips' color vision[6], lamplight control technologies are a prospective application for their control. Therefore, studying the influence of light on the visual responses of western flower thrips, not only helps to understand their phototactic sensitivities and photo-behavioral regulation mechanisms, but also provides a theoretical basis for lamplight control technologies.

Thrips are diurnal pests with apposition compound eyes that are significantly different from the visually photosensitive mechanisms and photo-biological behaviors of nocturnal pests that use superposition compound eyes[7,8]. Thus, thrips are difficult to control using the same light control technologies of nocturnal pests. Studies[9-13] have shown that thrips exhibit photo-activities from UV to far-infrared spectrum light, and visual push-pull strategy. And the preference reaction of green light sensitive receptors in retinal cells, UV sensitivity and chromatographic antagonism function, make thrips visual trend sensitivity to green light be stronger than that to yellow light, thrips approach sensitivity to 365 nm light be the strongest. While thrips show the visual sensitively repellent behavior to red light, and red light drove thrips to select the optical target with visual trend and approach sensitivity, and light intensity is also an influence factor. Thus, the reasonable arrangement of red light and spectral light can regulate thrips photo-biological activity form the phobotaxis behavior, and provide a phototactic attraction-repulsion control strategy for these

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Biographies: Qihang Liu, PhD, Associate Professor, research interests: locust capturing technology of optical-mechanical-electrical integration, Email: bjliuqihang@163.com; **Yuqing Wu**, PhD, Professor, research interests: phototaxis trapping control of agriculture pests, Email: yuqingwu36@hotmail.com.

***Corresponding author: Mingfu Zhao**, MSE, Professor, research interests: modern wisdom agriculture, signal processing and control, Email: 985316013@qq.com. Henan Institute of Science and Technology, Xinxiang 453003, China. Tel: +86-373-3040396, Email: mingfuzhao@sina.com.

pests. Some studies also found that light intensity attributes (illumination, light energy) changed thrips visual response sensitivity from 560 nm light to 365 nm light. The coupling of long (520, 560 nm) and short (365, 405 nm) spectrum light on thrips phototactic effect caused them to exert preference behaviors for long wavelength light and bio-activity behaviors for short wavelength light, while thrips sensitive light attributes decided on thrips phototactic effect[14-16]. Thus, the combination of hetero-spectral light could regulate thrips phototactic sensitivity, which the addition of red light could enhance. However, the photo-induced effect of the phobotaxis properties and the attraction-repulsion effect on the phototactic behaviors of thrips remain unclear. Then, the attraction-repulsion synergism effects of thrips phobotaxis spectrum light characteristics on thrips phototactic effect are needed to be further studied.

In this study, the phototactic effect of western flower thrips to the single light of UV, violet, green, and yellow light, and their pairwise combined light under red light and no red light was investigated using a device for measuring the visual response of thrips. This study also analyzed the regulatory differences of different light attributes (illumination, light energy) on the approach-avoidance behavior of thrips, and detailed the phobotaxis attraction-repulsion configuration of thrips. We also determined the synergy of phototactic attraction-repulsion regulation measures. And under red light, the phototactic selection of western flower thrips to the single light in pairwise combined light was investigated to determine the attraction-repulsion effect of combined light and red light, and discuss the phototactic attraction-repulsion manipulation mode of phobotaxis spectrum light. This study will assist in constructing phototactic attraction-repulsion control technologies for thrips, and provide technical support for the development of light trapping apparatuses and the adjustment of control strategies for pests.

2 Materials and methods

2.1 Insects

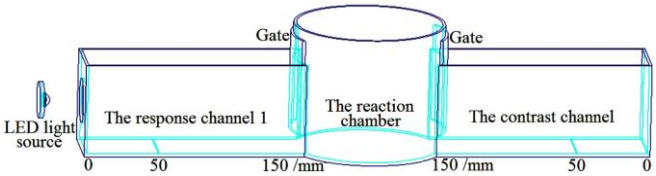
Western flower thrips were obtained from the vegetable and flower demonstration base of the Henan Academy of Agricultural Sciences. Thrips were robust female adults from multiple generations, harvested 1-2 d after eclosion. Using thrips collected on the same day, 30 thrips per group were prepared and placed on the leaves of *Phaseolus vulgaris* L. in a feeding room (*Φ*3.5× 3.5 cm). These thrips were used as the test insects after dark adaptation for 30 min prior to experimentation.

2.2 Light sources and light measurements

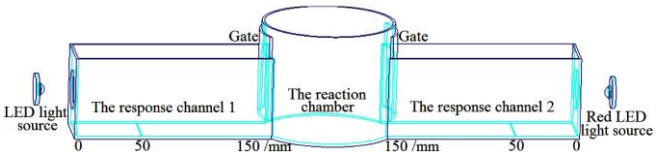
Three W light-emitting diodes (LED, Hongtai Electronics, Yueqing City, China) were used as the test light source. The test wavelengths were 365 nm (UV), 405 nm (violet), 520 nm (green), 560 nm (yellow), and 650 nm (red) nm. The illumination of the light source was calibrated using an illuminance meter (Model: TES-1335; resolving power: 0.01 lx; Taiwan Taishi, Macao, Taiwan) and was set to 6000 lx and 12 000 lx. The light energy of the light source was calibrated using a radiation meter (Model: FZ-A, resolving power: ±5%; Beijing Instrument, Beijing, China) and set to 60 mW/cm^2 and 120 mW/cm^2, to analyze the influence of light on the visual phobotaxis sensitivity of thrips. As thrips exhibited a visual sensitivity threshold restricting visual responses to light intensities exceeding 12 000 lx and 70 mW/cm^2, other light intensities were not analyzed in this study.

2.3 Experimental devices

To clarify the attraction-repulsion effect of red light with UV, violet, green, and yellow light on the visual response of thrips, as well as the visual response and approach response to single light (Figure 1a), red light and single light (Figure 1b) were tested separately by using device 1 (Figure 1). The reaction chamber (Φ100 ×80 mm) was connected to thrips response channel 1 and the contrast channel (Figure 1a), or the response channel 1 and the response channel 2 [Figure 1b (length ×width ×height: 150 ×40 × 60 mm)]. All channels were separated by gates. The single spectral LED light source (UV, violet, green, yellow) was placed at the front of channel 1 (Figure 1a), while the single spectral LED light source (UV, violet, green, yellow) and red LED light source were placed at the front of channels 1 and 2, respectively. The channels were marked as shown in Figure 1 to analyze the specific regulatory effects of different light attributes on the visual response of thrips to the single light under contrasting red light.



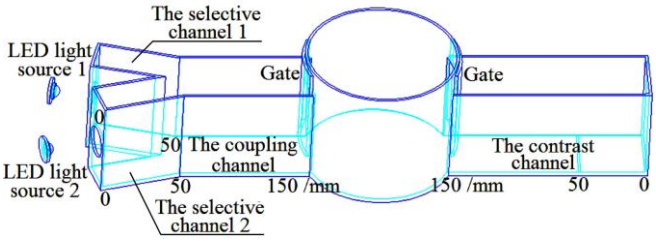
a. Single spectrum light



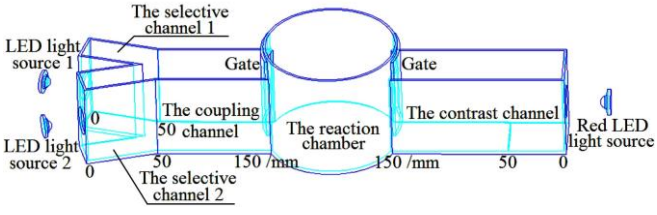
b. Red light and single spectrum light

Figure 1 Device 1 for investigating the visual response effect of thrips

To clarify the influence of red light on thrips approach selection to single wavelength light in combined light, and their changes in photo-sensitive responses caused by different light attributes, the visual response and approach response of western flower thrips to combined light (Figure 2a), and red light and combined light (Figure 2b) were tested using device 2 (Figure 2). The combined light spectrum was green + yellow, violet + yellow, UV + yellow, violet + green, UV + green, and UV + violet, which were obtained using two LED light sources.



a. Combined light



b. Red light and combined light

Figure 2 Device 2 for investigating the visual response effect of thrips

In device 2, the coupling channel (length ×width ×height: 100 mm ×40 mm ×60 mm) and the 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 (length×width×height: 50 mm×40 mm×60 mm, respectively), two LED light sources with different spectra were placed at the front end of the two arms, and the red LED light source was placed at the front of the contrast channel, as shown in Figure 2b. The channels were marked as shown in Figure 2 to analyze the influence of different light attributes on the approach selection of thrips to single wavelength light in combined light, and the action effect of red light on the visual response of thrips to combined light.

2.4 Experimental methods

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

Using devices 1 and 2 at 6000 lx, 12 000 lx, 35 mW/cm^2, and 70 mW/cm^2 for each single spectrum light (Figure 1a), red light combined with each single spectrum light (UV, violet, green, yellow; Figure 1b), each combined spectrum light (Figure 2a), and red light with each combined spectrum light (Figure 2b), three groups (30 thrips per group) of dark-adapted thrips were used to carry out the experiments.

Prior to each experiment, and according to the light intensity of each device, the light source was arranged to calibrate the illumination and light energy, and the test thrips were added to the reaction chamber using a brush. During testing, the light sources and gates were opened to test each group of thrips to the corresponding light intensity, so that three groups of test insects were completed sequentially in each test. After each test, the light source and gates were closed, and the indoor light source was opened to facilitate counting of the number of thrips distributed at 0-50 mm and 0-150 mm in each channel.

2.5 Data computation and analysis

The approach rate (R_3, %), and the visual response rate (R_4, %) were calculated to reflect the approach sensitivity and the visual response sensitivity to single light caused by red light, and analyze the attraction-repulsion effect of red light and single spectrum light: $R_3=(n_{21}/30)\times100\%$, $R_4=(n_{22}/30)\times100\%$;

D-values of the approach rates, and the visual response rates with and without red light (R_1, %; R_2, %) were calculated to reflect the photo-induced attraction-repulsion effect of red light on thrips under the same light conditions: $R_1=((n_{21}-n_{12})/30)\times100\%$, $R_2=((n_{22}-n_{12})/30)\times100\%$;

The visual response rate (R_3, %) was calculated to reflect the visual response sensitivity of thrips to combined light under contrasting red light: $R_3=((n_{41}+n_{42}+n_{43})/30)\times100\%$;

D-values of the visual response rates(R_4, %) were calculated to analyze the attraction-repulsion effect of red light and combined light on the visual response sensitivity of thrips to combined light: $R_4=(((n_{41}+n_{42}+n_{43})-(n_{31}+n_{32}+n_{33}))/30)\times100\%$;

The approach selection rate (R_5, %; R_6, %) was calculated to indicate the approach selection sensitivity of thrips to heterogeneous spectrum light under contrasting red light: $R_5=(n_{41})/30\times100\%$, $R_6=(n_{42})/30\times100\%$;

D-value of the approach selection rate (R_7, %) was calculated to reflect the difference in approach selection sensitivity to the single light of combined light under contrasting red light: $R_7=(n_{41}-n_{42})/30\times100\%$;

The contrast D-value of the approach selection rate (R_8, %) with and without red light was calculated to reflect the influence of red light on the approach selection sensitivity of thrips to single light in combined light: $R_8=((n_{41}-n_{42})-(n_{31}-n_{32}))/30\times100\%$;

The total approach selection rate (R_9, %) was calculated to indicate the approach sensitivity of thrips to combined light under contrasting red light: $R_9=(n_{41}+n_{42})/30\times100\%$;

D-values of the total approach selection rates (R_{10}, %) were calculated to analyze the difference in approach sensitivity to combined light with and without red light: $R_{10}=((n_{41}+n_{42})-(n_{31}+n_{32}))/30\times100\%$;

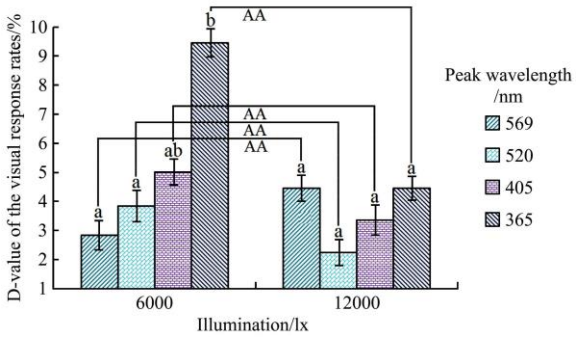
In the formulae: n_{11} and n_{21}, n_{12} and n_{22} (Figure 1a and 1b) were the mean values of thrips numbers distributed at 0-50 mm and 0-150 mm in response channel 1 of device 1, respectively. n_{31}, n_{32}, n_{33} (Figure 2a), and n_{41}, n_{42}, n_{43} (Figure 2b) were the mean values of thrips numbers distributed in the selective channel 1, the selective channel 2, and the coupling channel, respectively.

General linear model analyses were employed to compare the mean percentage of insects caused by single light, combined light, single light and red light, combined light and red light. For multiple comparisons, the LSD test at p = 0.05 was used. The Student's t-test was used to determine the differences between two different light intensities with the same spectrum (p = 0.05), and between two different spectra with the same light intensities (p = 0.05). SPSS 16.0 (SPSS Inc., Chicago, IL, USA) and Excel Software for Windows were used for all statistical analyses. The results are shown as the percentage ± standard error.

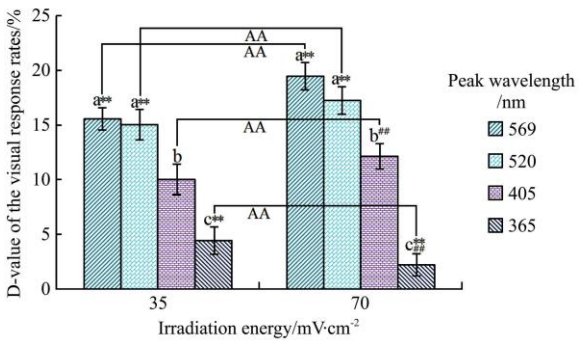
3 Results and discussion

3.1 The attraction-repulsion effect of red light and single light on the phototactic response of thrips

Under contrast red light, the phototactic response to single light was better than that without red light (Figure 3), and light energy significantly affected the effect of red light (Figure 3a: $F_{35\ mW/cm^2}$ = 17.383, p<0.01; $F_{70\ mW/cm^2}$ = 48.369, p<0.001). The phototactic response to yellow light was the strongest, while that to UV light was the weakest. However, the influence of illumination on the effect of red light was not significant (Figure 3b, p>0.05; $F_{6000\ lx}$ = 3.056; $F_{12000\ lx}$ = 2.441), while the phototactic response to UV light was the strongest and that to yellow light was the weakest.



a. Under illumination

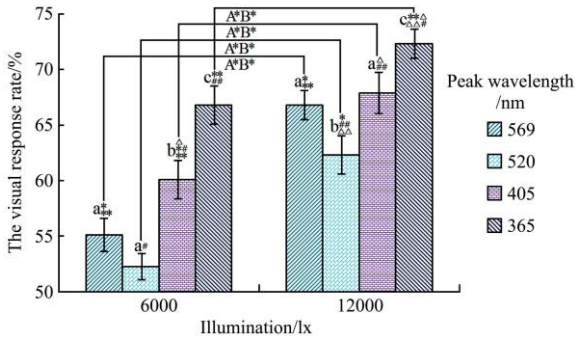


b. Under light energy

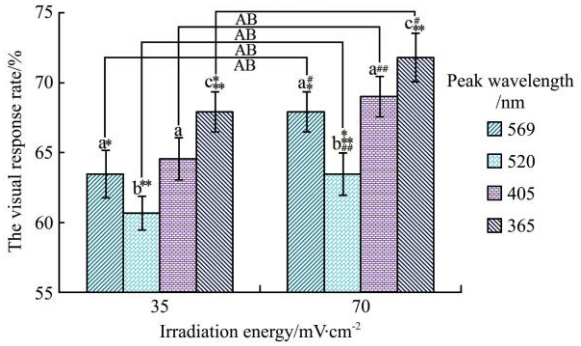
Figure 3 Attraction-repulsion effect of red light and single light on the visual sensitivity of thrips to single light

Under the same illumination and light energy, among different wavelengths: the same small letters indicate no significant difference (p>0.05); different small letters indicate significant differences (p<0.05); different small letters with the single identifier, double identifier indicate very significant differences (p<0.01), extremely significant differences (p<0.01), respectively. Under the same wavelength, between 6000-12 000 lx, 35 and 70 mW/cm^2, AA shows no significant difference (p>0.05), AB, A*B* respectively show significant differences (p<0.05), very significant differences (p<0.01).

When illumination increased, the effect of red light on the response of thrips to UV light was weakened (p<0.05), while that to other spectral light had no obvious effect (p>0.05), while when light energy increased, while that of the same spectral light had no significant change (p>0.05). These results showed that red light repulsed the visual response of thrips to single spectral light, presenting the repulsion synergism effect. Single spectrum light showed the attraction effect. Under illumination the attraction-repulsion synergism effect of red light and UV light at 6000 lx, while under light energy that of red light and yellow light at 70 mW/cm^2 was the strongest (9.46%, 19.48%), respectively. Moreover, with the increase of light intensity, the attraction-repulsion synergism effect of red light and UV light was inhibited while that of red light and yellow light was enhanced. Thus, the attraction-repulsion synergy of red light and single spectrum light was due to the photosensitivity induced by the intensity of the single spectrum light.



a. Under illumination



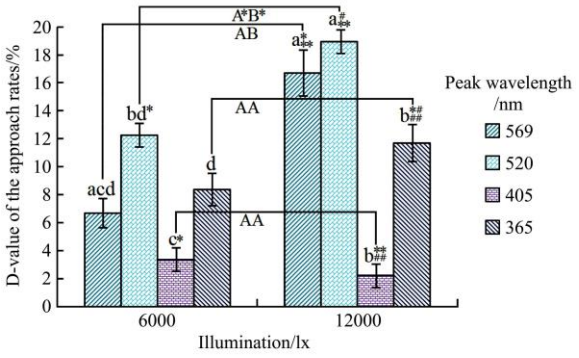
b. Under light energy

Figure 4 Visual response sensitivity of thrips to single light under contrasting by red light

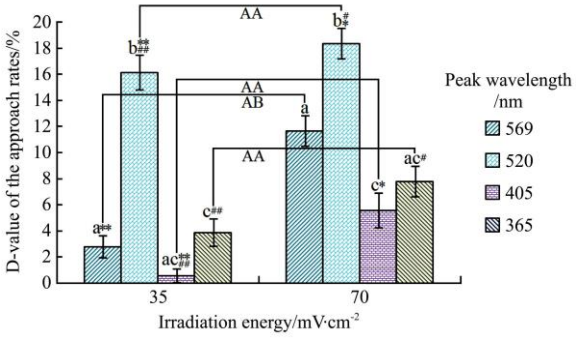
However, under the same light intensity, the visual response of thrips attracted and repulsed by red light and single spectrum light was due to the visual sensitivity induced by the spectral property (p<0.001: $F_{6000\ lx}$ = 40.283, $F_{12000\ lx}$ = 36.444; $F_{35\ mW/cm^2}$ = 12.852, p<0.01; $F_{70\ mW/cm^2}$ = 19.458, p<0.001) (Figure 4). Under red light, the visual response sensitivity to UV light was the best, followed by that to violet light. When light intensity increased, the attraction-repulsion effect of red light and the same single spectrum light was intensified. And the attraction-repulsion effect under illumination (p<0.01) intensified by red light and yellow light was the strongest, while that intensified by red light and UV light was the weakest, and the intensify effect under illumination were all stronger than that under light energy (p<0.05). But, when light intensities were 12 000 lx and 70 mW/cm^2, the attraction-repulsion response to red light and UV light was the best (72.00%), with that of red light and green light being the worst (63.00%).

3.2 Attraction-repulsion effect of red light and single light on thrips phototactic approach sensitivity

Under contrast red light, the phototactic approach sensitivity of thrips to single spectral light was better than that without red light (Figure 5). The effect of red light was significantly related to spectral light attribute (p<0.01, $F_{6000\ lx}$ = 9.316; p<0.001, $F_{12000\ lx}$ = 50.738; p<0.001, $F_{35\ mW/cm^2}$ = 39.583; p<0.01; $F_{70\ mW/cm^2}$ = 9.919) (Figure 5), and the synergistic effect of red light on the approach sensitivity to green light was the best.



a. Under illumination



b. Under light energy

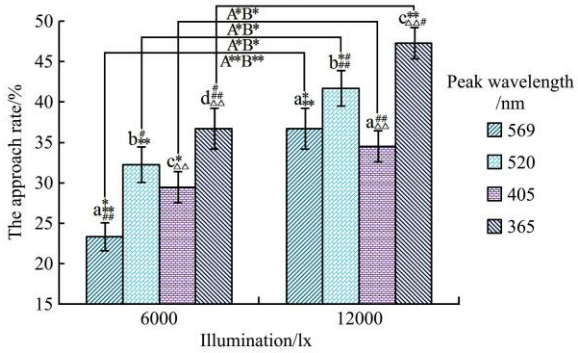
Figure 5 Attraction-repulsion effect of red light and single light on the approach sensitivity of thrips to single light

Under the same illumination and light energy, among different wavelengths: the same small letter indicate no significant difference (p>0.05); different small letters indicate significant differences (p<0.05); different small letters with the single identifier, double identifier indicate very significant differences (p<0.01), extremely significant differences (p<0.01), respectively. Under the same wavelength, between 6000 and 12 000 lx, 35 and 70 mW/cm^2, AA shows no significant difference (p>0.05), AB, A*B*, A**B** respectively show significant (p<0.05), very significant (p<0.01), extremely differences (p<0.01), extremely significant differences (p<0.001).

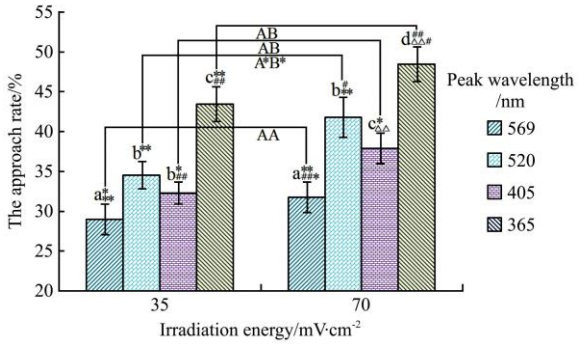
When illumination increased, the attraction-repulsion synergy of red light and green light was the strongest (p<0.01), followed by that of red light and yellow light (p<0.05). When light energy increased, the attraction-repulsion synergy of red light and yellow light was the strongest (p<0.05), while comparing with 35 mW/cm^2,

that of red light and other spectral light was enhanced by 70 mW/cm^2, but not significant (p>0.05). Thus, light intensity affected the attraction-repulsion synergy of red light and spectral light property, and the attraction-repulsion synergy of red light and green light at 12 000 lx and 70 mW/cm^2 was the strongest (18.50%), followed by red and yellow light with 12 000 lx.

Under the same light intensity, the phototactic attraction-repulsion effect of the visual approach sensitivity to red light and single spectrum light was related to the spectral light attribute (p<0.001: $F_{6000\ lx}$ = 50.458, $F_{12000\ lx}$ = 52.333, $F_{35\ mW/cm^2}$ = 82.444, $F_{70\ mW/cm^2}$ = 39.562) (Figure 6). The attraction-repulsion effect of red light and UV light was the best, followed by that of red light and green light. With increases in light intensity, the attraction-repulsion approach effect of red light and single light was significantly enhanced, with the enhancement caused by illumination being stronger than that by light energy, and that enhanced by red light and yellow light was the strongest (p<0.001). However, the attraction-repulsion approach effect of red light and UV light at 12 000 lx and 70 mW/cm^2 was optimal (47.50%), followed by that of red light and green light (41.75%).



a. Under illumination

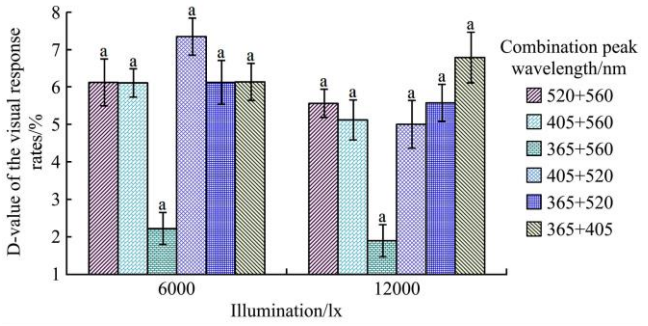


b. Under light energy

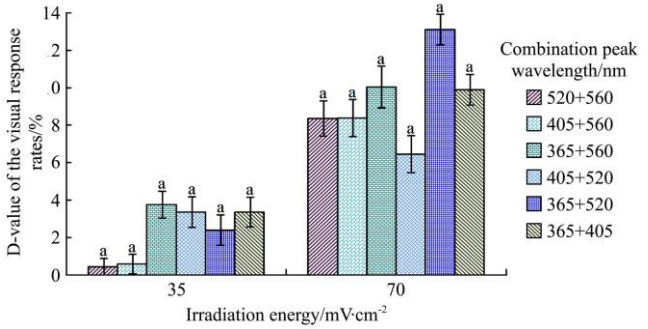
Figure 6 Approach sensitivity of thrips to single light under contrasting red light

3.3 Attraction-repulsion effect of red light and combined light on phototactic response

Under contrast red light, the phototactic response sensitivity of thrips to combined light was better than that without red light (Figure 7). Among the different combined lights, differences in the attraction-repulsion synergy of red light and combined light was not significant (p>0.05). Comparing 6000 lx with 35 mW/cm^2 in red light and yellow + green light, and red light and yellow + violet light, the attraction-repulsion synergy caused by 6000 lx was significantly better than that of 35 mW/cm^2 (p<0.05). However, in red light plus other combined light, the difference was not significant (p>0.05). Comparing 12 000 lx with 70 mW/cm^2, the attraction-repulsion synergy caused by 70 mW/cm^2 was the most significant in red light and yellow + UV light (p<0.01).



a. Under illumination



b. Under light energy

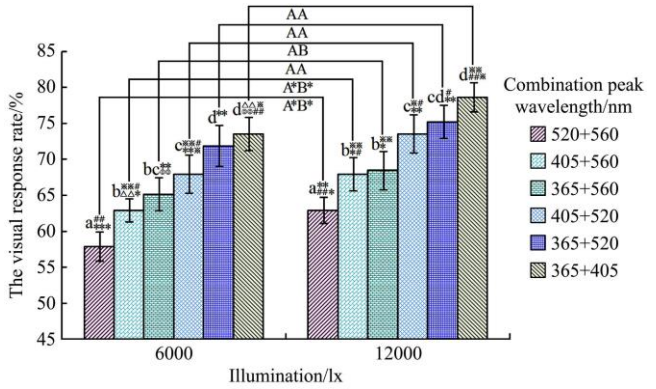
Figure 7 Attraction-repulsion effects of red light and combined light on the visual sensitivity of thrips to combined light

Under the same illumination and light energy, among different wavelengths: the same small letter indicate no significant difference (p>0.05); different small letters indicate significant differences (p<0.05); different small letters with the single identifier, double identifier indicate very significant differences (p<0.01), extremely significant differences (p<0.01), respectively. Under the same combined wavelength, between 6000 and 12 000 lx, 35 and 70 mW/cm^2, AA shows no significant difference (p>0.05), AB, A*B* respectively show significant (p<0.05), very significant (p<0.01), extremely differences (p<0.01) differences. And in Figure 7, under the same combined wavelength, there was no significant difference between 6000 and 12 000 lx, 35 and 70 mW/cm^2.

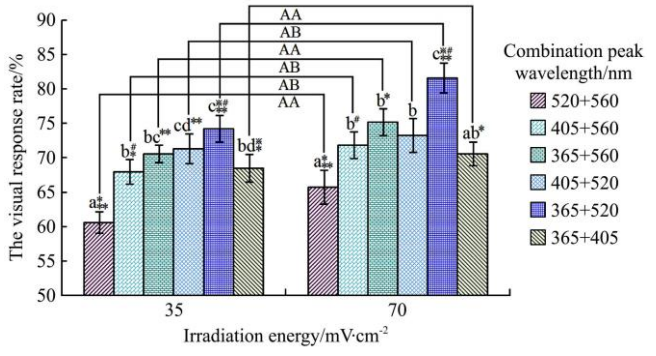
With increases in light intensity, under the same combined light, illumination inhibited the effect of red light; however, the difference was not significant (p>0.05). Additionally, light energy intensified the effect of red light, and in yellow + violet light, the effect of red light was not significant (p>0.05). Under other combined lights, the enhancement of the effect of red light caused by the increase of light intensity was significant, with that in yellow + UV light being the most significant (p<0.01). Thus, the coupling effect of spectral light property combined with light intensity affected the attraction-repulsion effect of red light and combined light. Under illumination, and under light energy, the synergy of red light on the phototactic response of thrips to green + violet light at 6000 lx, to green + UV light at 70 mW/cm^2 was the strongest (7.35%, 13.09%), respectively.

When the light intensity was the same, red light significantly affected the phototactic response to different combined spectral lights (p<0.001, $F_{6000\ lx}$ = 35.269, $F_{12000\ lx}$ = 24.765, $F_{35\ mW/cm^2}$ = 14.331; p<0.01, $F_{70\ mW/cm^2}$ = 8.704) (Figure 8), with the effect being related to combined light attribute. Under illumination, the attraction-repulsion response to red light and violet + UV light was optimal, followed by that of red light and green + violet light. Under light energy, the phototactic response of red light and green + UV light was the optimal, followed by that of red light and yellow +

UV light. And when the light intensity increased, the attraction-repulsion response to red light and the same combined wavelength light was enhanced. In contrast, under illumination at 12,000 lx, the attraction-repulsion response to red light and UV + violet light was the strongest (78.59%), followed by that to red light and violet + green light (75.15%). Under light energy of 70 mW/cm^2, the attraction-repulsion response to red light and UV + green light was the strongest (81.55%), followed by that to red light and UV + yellow light (75.15%).



a. Under illumination



b. Under light energy

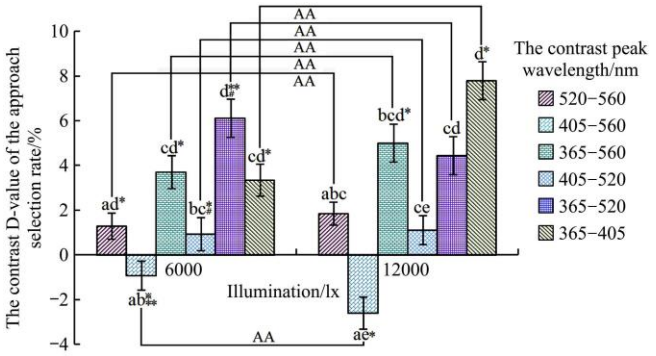
Figure 8 Visual response sensitivity of thrips to combined light under contrasting red light

3.4 Attraction-repulsion effect of red light and combined light on the approach selection to single spectral light

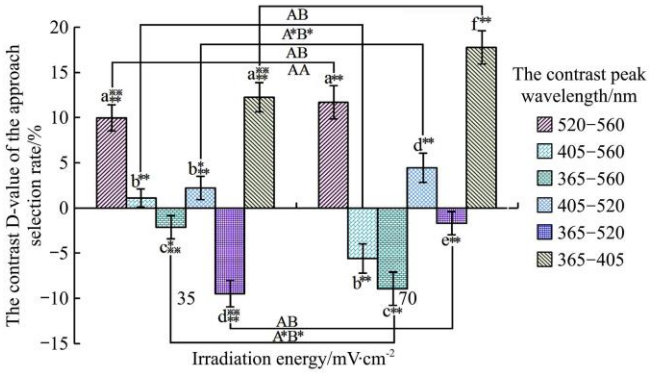
Under the same light intensity, red light significantly affected the approach selection to single spectral light in combined light (p<0.01, $F_{6000\ lx}$ = 6.612; p<0.05, $F_{12000\ lx}$ = 4.526; p<0.001, $F_{35\ mW/cm^2}$ = 71.273; p<0.001, $F_{70\ mW/cm^2}$ = 206.427) (Figure 9).

Under illumination, red light inhibited the approach selection sensitivity of thrips to violet light (in violet + yellow light; p<0.05), while under other combined lights, red light intensified the approach selection sensitivity to the corresponding single spectrum light (p<0.05). Under different light energies, in UV + yellow and UV + green light, red light inhibited the approach selection to UV light. In violet + yellow light, red light intensified the response at 35 mW/cm^2, while light energy of 70 mW/cm^2 inhibited the response to violet light. In green + yellow light and UV + violet light, red light significantly intensified the response to green and UV light, respectively.

Under the same illumination and light energy, among different wavelengths: the same small letter indicate no significant difference (p>0.05); different small letters indicate significant differences (p<0.05); different small letters with the single identifier, double identifier indicate very significant differences (p<0.01), extremely significant differences (p<0.01), respectively. Under the same wavelength, between 6000 and 12 000 lx, 35 and 70 mW/cm^2, AA shows no significant difference (p>0.05), AB, A*B* respectively show significant (p<0.05), very significant (p<0.01) differences.



a. Under illumination



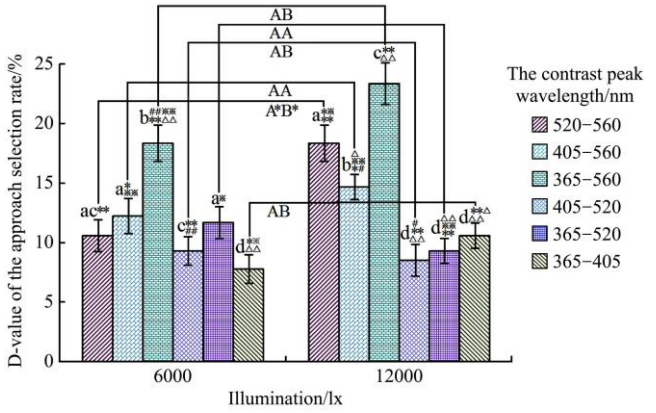
b. Under light energy

Figure 9 Contrast approach selection sensitivity of thrips to single light in combined light under red and no red light

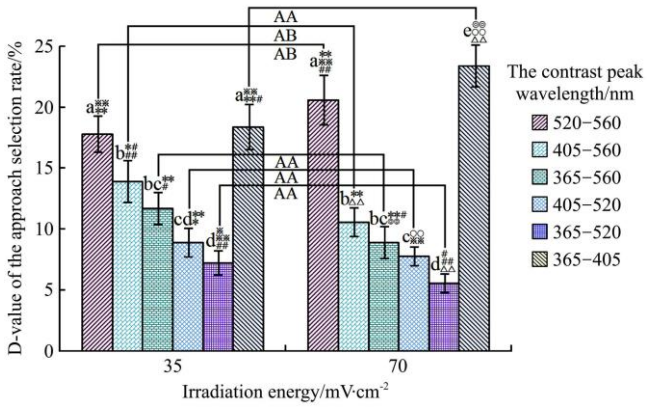
With increases in light intensity, the influence of illumination on the effect of red light was not significant (p>0.05). Similarly, in green + yellow light, and violet + green light, increases in light energy on the effect of red light were not significant, while in the other combined lights, the influence of light energy was significant, with violet + yellow light exhibiting the most significant effect (p<0.01). Thus, the action of red light on approach selection to the sensitive single wavelength light in combined light was related to light intensity. And under illumination at 12 000 lx, the intensity of the approach selection of thrips to UV + violet light intensified by red light, and to violet + yellow light inhibited by red light was the strongest (7.79%), and the weakest (–2.60%), respectively. While under light energy, that to UV + violet light intensified by red light at 70 mW/cm^2, and to violet + yellow light inhibited by red light at 35 mW/cm^2 was the strongest (17.81%), and the weakest (–9.47%), respectively.

Under the action of red light and the same light intensity, the combined spectral light attribute significantly affected the intensity and sensitivity of the approach selection to two single spectrum lights. When light attribute was the same, light intensity significantly affected the effect of red light (p<0.001: $F_{6000\ lx}$ = 26.606, $F_{12000\ lx}$ = 55.383, $F_{35\ mW/cm^2}$ = 25.924, $F_{70\ mW/cm^2}$ = 131.279) (Figure 10). Under illumination with 6000 lx and light energy with 35 mW/cm^2, red light respectively made the difference of thrips approach selection sensitivity to UV and yellow light, UV and violet light be the most significant, followed by green and yellow light. When light intensity increased, it increasingly affected the effect of red light. And under illumination with 12 000 lx, the difference of thrips approach selection sensitivity between violet light and green light, and between UV light and green light affected by red light was

not significant (p>0.05), while in the other combined lights, the difference of thrips approach selection sensitivity, significantly intensified by red light, between green light and yellow light was the most significant (p<0.01). Under light energy with 70 mW/cm^2, the difference of thrips approach selection sensitivity to green and yellow light, UV and violet light was significantly affected by red light(P<0.01), in the other combined light, the difference of thrips approach selection sensitivity, inhibited by red light, between violet light and yellow light was the most significant (p<0.05). The results showed that under red light, light intensity affected the comparative approach selection intensity for two spectral lights, while under illumination, the difference in comparative approach selection intensity to UV light and yellow light at 12 000 lx was the strongest (23.38%). Under light energy, the comparative approach selection intensity to UV light and violet light at 70 mW/cm^2 was the strongest (23.38%).



a. Under illumination



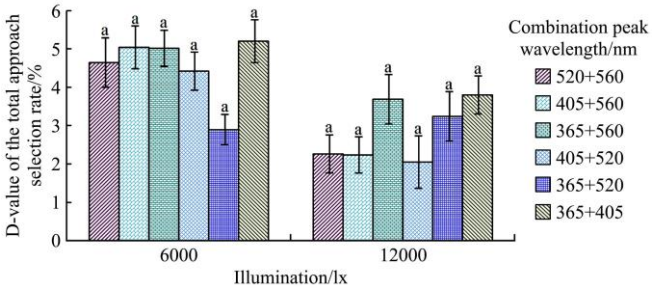
b. Under light energy

Figure 10 Approach selection sensitivity of thrips to single light in combined light under contrasting red light

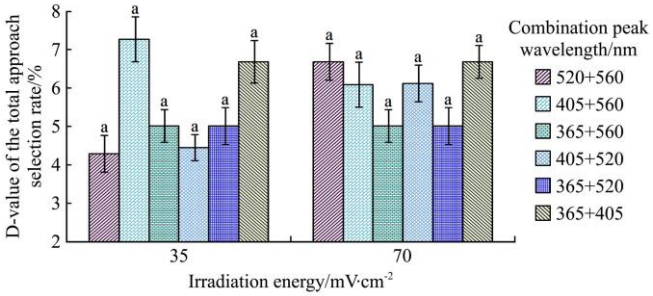
3.5 The attraction-repulsion effect of red light and combined light on the phototactic approach sensitivity

Under red light, the total approach sensitivity to combined light was better than that without red light (Figure 11), and among the different combined lights, the difference in attraction-repulsion synergy was not significant (p>0.05). When light intensity increased, the synergistic effect of red light was inhibited by the intensity of the illumination (p>0.05). The light energy intensity on the synergistic effect was not significant either.

In addition, the attraction-repulsion synergistic effect caused by red light and violet + yellow light under light energy was better than that of red light and violet + UV light under illumination. Therefore, the attraction-repulsion synergy of red light and combined light on the total approach sensitivity was related to the combined light attribute. Under illumination, the attraction-repulsion synergy of red light and violet + UV light at 6000 lx was the strongest (5.20%), while under light energy, the attraction-repulsion synergy of red light and violet + yellow light at 35 mW/cm^2 was the strongest (7.27%).



a. Under illumination

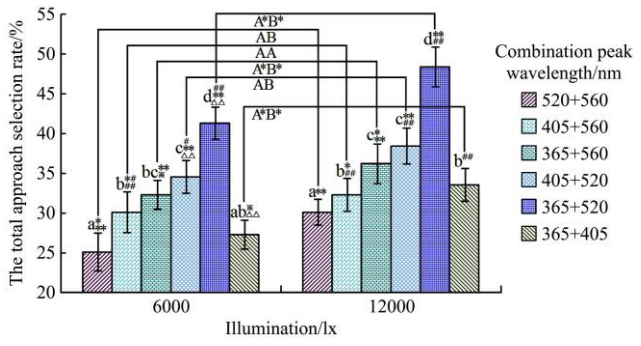


b. Under light energy

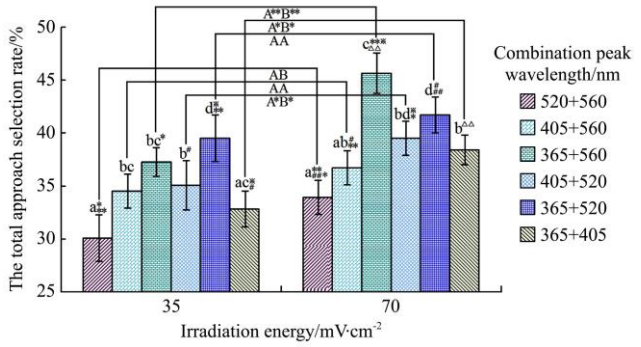
Figure 11 Attraction-repulsion effects of red light and combined light on approach sensitivity of thrips to combined light

Under the same illumination and light energy, among different wavelengths: the same small letters indicate no significant difference (p>0.05); different small letters indicate significant differences (p<0.05); different small letters with the single identifier, double identifier indicate very significant differences (p<0.01), extremely significant differences (p<0.01), respectively. Under the same combined wavelength, between 6000 and 12 000 lx, 35 and 70 mW/cm^2, AA shows no significant difference (p>0.05), AB, A*B* respectively show significant (p<0.05), very significant (p<0.01), extremely differences (p<0.01) differences. And in Figure 11, under the same combined wavelength, there was no significant difference between 6000 and 12 000 lx, 35 and 70 mW/cm^2.

Under the same light intensity, red light significantly affected the total approach sensitivity to combined light, which was related to the combined light attribute (p<0.001, $F_{6000\ lx}$ = 36.90; p<0.001, $F_{12000\ lx}$ = 59.386; p<0.01, $F_{35\ mW/cm^2}$ = 8.376; p<0.001, $F_{70\ mW/cm^2}$ = 15.162) (Figure 12), and illumination, light energy made thrips phototactic approach sensitivity to red light and UV + green light, to red light and UV + yellow light be the better, respectively. When light intensity increased, the phototactic approach sensitivity to red light and combined light was enhanced. Under illumination, the enhancement in UV + violet light was the most significant (p<0.01), while under light energy, the enhancement in UV + yellow light was the most significant (p<0.01). Thus, light intensity affected the attraction-repulsion approach of thrips. Under illumination at 12 000 lx and 6000 lx, the attraction-repulsion approaches caused by red light and UV + green light were the best and worst, respectively (48.33% vs. 41.30%). Under light energy at 70 mW/cm^2, the attraction-repulsion approaches caused by red light and UV + yellow light, and UV + green light were the best and worst, respectively (45.65% vs. 41.75%).



a. Under illumination



b. Under light energy

Figure 12 Approach sensitivity of thrips to combined light under contrasting red light

3.6 Discussion

Previous studies showed that light intensity affected the driving effect of red light on the visual sensitivity and selectivity of thrips to yellow, green, violet, and UV light, as well as that of their combinations[17,18]. In present study, we found that compared to no red light, red light enhanced the visual sensitivity of *Frankliniella occidentalis* to yellow, green, violet and UV light. The light intensity attribute affected the attraction-repulsion synergy, showing that illumination made the attraction-repulsion synergism effect of red light and UV light be stronger, and the increase of illumination inhibited its synergism effect. While light energy made that of red light and yellow light be stronger, and the enhancement of light energy intensified its synergism effect. These results were consistent with the influence degree of light intensity on thrips visual sensitivity relating to wavelength factors[19,20]. Light intensity did not affect the attraction-repulsion synergy of red light and single light on the phototactic approach sensitivity. Notably, the attraction-repulsion synergy of red light and green light was the strongest, and when light intensity increased, the synergy increased, suggesting that light intensity and wavelength affected the detection and selection of thrips to light targets. Those findings also provided a scientific basis for the development of trapping devices for thrips. Under combined light, the effect of red light on the approach sensitivity of thrips to two different spectrums was related to spectral attribute and light intensity, intensifying the action effect of red light, which caused the enhancement effect of red light on the approach sensitivity to UV + violet, green + yellow light at 70 mW/cm^2 was the strongest, and the second strongest, respectively, while at 35, 70 mW/cm^2, the inhibitory effect of red light on the approach sensitivity to UV + green light, UV + yellow light was the strongest, and the second strongest, respectively, maybe originating from the antagonistic mechanism of wavelength detection of thrips pests[21,22]. Therefore, red light enhanced the discrimination between lights of adjacent wavelengths, but inhibited the discrimination between short wavelengths vs. long wavelengths. Further measurements of illumination in Figure 2b showed that at 70 mW/cm^2, the illumination of violet light was 2-times that of UV light, and the illumination of yellow light was 1.25 and 5 times that of green, and UV light, respectively. At 35 mW/cm^2, the illumination of violet light was 10 times that of UV light, and the brightness of two hetero-spectral lights affected the effect of red light, thus, providing a theoretical basis for the changes in the specific behavior of thrips when selecting light targets.

The attraction-repulsion effect of red light and combined light enhanced the visual sensitivity response and approach sensitivity response of thrips to combined light; however, the influence of specific light intensity of two hetero-spectral lights, made the enhancement of illumination inhibited the attraction-repulsion synergism effect of red light and combined light on thrips visual response sensitivity. Meanwhile, increases in light intensity weakened the attraction-repulsion synergy of red light and combined light on the approach response sensitivity, showing that under the repulsion action of red light, UV spectrum band magnitude, spectral sensitivity and light intensity could cause thrips to exhibit dominant specificity behaviors, and enhance the attraction of the combined UV light and yellow light, and UV light and green light.

Relative to single light under the same illumination, UV + yellow light weakened the synergy of red light on the visual response sensitivity of thrips, while the other combined lights enhanced the synergistic effect relative to yellow, green, and violet light, however, the change was not significant. And the intensity of illumination did not affect the attraction-repulsion synergy effect of red light and combined light on thrips visual response sensitivity. Moreover, when light energy increased, relative to UV light, the combined light enhanced the synergistic effect of red light, however, relative to yellow, green light, the combined light significantly inhibited the synergistic effect. These results implied that when different spectral lights were perceived at the same time, the combined light reduced the visual sensitivity of thrips[23-25]. When light intensity increased, relative to red light and yellow light, red light and green light, the attraction-repulsion synergism effect of red light and combined light on the approach sensitivity significantly reduced, further showing that was related to the heterogeneous light intensity attributes of spectral light. And the specific behavior of thrips preference for green-yellow light determined the synergism effect of red light, while the intensity dependence of UV light behavior mode restricted the synergism effect.

The attraction-repulsion synergistic effect of red light and single light and red light and combined light, did not reflect the attraction-repulsion response and approach effect. Under red light and single light, increases in light intensity increased the attraction-repulsion effect. The spectral light attribute also determined the attraction-repulsion effect, with the attraction-repulsion effects under red light and UV light being optimal, while the specific regulatory effects of light intensity and wavelength characteristic[26], made the attraction-repulsion response effect caused by red light and violet light be the second, showing that the interaction of the specific behavior for wavelength and the enhancement characteristic of light intensity can change thrips behavior action spectrum. Under red light and combined light, increases in light intensity increased the attraction-repulsion effect. Under illumination, the intensity of the combined light energy determined the attraction-repulsion response, with that induced by red light and UV + violet light being the strongest. Under light energy, the coupling regulation effect of the long-short spectra and the brightness of light determined the attraction-repulsion response,

with that caused by red light and UV + yellow light being the strongest. Moreover, the attraction-repulsion effect caused by the strongest lighting mode (red light and UV + violet light under illumination, red light and UV + yellow light under light energy) and the second strongest lighting mode (red light and UV + green light) of red light and combined light were significantly better than that induced by red light and UV light of the same light intensity. When light intensity increased, the attraction-repulsion effect caused by red light and green + yellow light was lower than that by red light and yellow light. These results were not consistent with thrips sensitivity detection mechanism to light, and UV + green light did not increase the attractiveness intensity of thrips[27,28], which may be due to the effect of red light on thrips.

In red light and combined light, when the light intensity increased, the attraction-repulsion approach effect was enhanced, while under illumination, the optimal attraction-repulsion approach effect was observed under red light and UV + green light at 12 000 lx. Under light energy, the optima attraction-repulsion approach effect was induced by red light and UV + yellow light at 70 mW/cm^2. And compared to red light and UV light, the change of the attraction-repulsion approach effect was not significant. These results may originate from thrips antagonistic sensitivity detection mechanism and independent behaviors driven by different sensitive photoreceptors in motion output[29], which affected the attraction-repulsion approach effect of red light and combined light, and the enhancement of UV ray dosage in combined light did not effectively increase the approach effect. Thus, using the attraction-repulsion effect of red light and combined light to enhance the approach sensitivity of thrips has limitations. While in red light and combined light, under red light illumination, yellow light intensified the sensitive selectivity to UV light, and green light, while under red light energy, violet light, and yellow light intensified the sensitive selectivity to UV light, and green light, respectively.

4 Conclusions

Contrast red light enhanced the visual response sensitivity and approach sensitivity of western flower thrips to single spectrum light and combined light, and light intensity affected the attraction-repulsion synergy of red light and single light on the visual response sensitivity of thrips, while it did not affect the approach sensitivity. The preference for green-yellow light and the dependence on UV intensity affected the attraction-repulsion synergy of red light and combined light, which was due to the different light intensities of two heterogeneous spectra. Additionally, the brightness of light intensity affected the short-range contrast selectivity of thrips. Increases in light intensity increased the attraction-repulsion response and approach effect of red light and single light, and red light and combined light. The attraction-repulsion effect of red light and single light was due to the single spectrum light attribute, while that of red light and combined light was due to the light intensity of the combined light. Compared to red light and UV light, using the attraction-repulsion effect of red light and combined light to enhance the approach effect of thrips had limitations. However, it could be seen that under red light, violet light intensified the approach selection sensitivity of thrips to UV light, while yellow light strengthened the approach selection sensitivity to green light. These findings will contribute to the development of light traps for thrips control, as well as the adjustment of thrips control strategies.

Acknowledgements

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