Locust visual response effect induced by the coupling light characteristics of linear detection polarization violet light and different spectrum lights

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Abstract: This study investigated the effects of polarized and spectral light interactions on locust polarotaxic behavior and elucidated the regulatory mechanisms of polarized and spectral lights. Locust visual response effect was investigated using a combined light source system comprising linear detection polarization violet light with various spectrum lights and a response device to explore the interaction mechanism of polarized and spectral lights on locust visual sensitivity characteristics and the specific sensitivity of locust phototaxis and polartaxis. Results indicated that the polarized vector sensitivity of locusts was related to combined light intensity, showing high visual response sensitivity at 0° and 180° under 1000 lx, whereas under rated illumination (150 mW/cm^2), the coupled spectrum attributes induced changes in the locusts' sensitive vectors. UV, violet, and blue lights enhanced the sensitivity at 90° and 270°, and green and orange lights did so at 0° and 180°. Moreover, UV and violet lights enhanced the aggregation and trend sensitivity at 210° and 30°, blue, green and orange lights induced high sensitivity at 0° and 180°. Under increasing illumination, the enhanced effect of light intensity on aggregation sensitivity under blue, green, and orange spectra and on trend sensitivity under orange spectra at 90° and 270° were highly pronounced because of the interaction between heterogeneous spectrum illumination and linear detection polarization vector illumination. Meanwhile, the spectral attribute determined the locust visual response effect, which was affected by the linear detection polarization vector. When illumination increased to rated illumination, coupled light intensity induced a specific vector sensitivity related to optical distance, showing the strongest response sensitivity to 180° under orange spectra and the strongest aggregation and trend sensitivity to 210° under violet spectra due to the interplay of polarization degree, coupling light intensity, and specific vision sensitivity caused by partially polarized light. Then, the locust visual response effect was improved by utilizing the enhancement effect of polarized violet light coupled with violet light at a close range and the inductive effect of polarized violet light coupled with orange light at a long distance, which provide theoretical support for understanding locust polarotactic orientation mechanisms, facilitate the development of polarization induced light sources for attracting locusts.

Keywords: *Locusta migratoria manilensis*, coupling light characteristics, linear detection polarization violet light, different spectrum lights, visual response effect
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1 Introduction

Locust plagues are characterized by locusts' suddenness, migratory behavior, and destructive effects on agriculture[1]. The conventional method of controlling locusts through heavy pesticide use hinders the sustainable development of modern agriculture[2]. Photophysical pest control has emerged as a primary environmentally friendly method. However, the effectiveness of photophysical control is constrained by locusts' visual tolerance and photophysiological induction response threshold[3-5]. Recent studies[6,7] on locusts' polarization-sensitive neuron structures and the interactions of two compasses in locusts' central complex have broadened our understanding of the factors regulating locust phototactic physiology and photobiological responses and offer insights into novel light stimulation modes. Therefore, studies on the photoinduction mechanisms of locusts' phototaxis and polarotaxis with specific vision sensitivity effects are theoretically important for comprehending locusts' visual response behavior mechanism and have practical value for locust polarization induction application.

Studies[8,9] have reported that locusts' visual response to unpolarized light depends on the stimulated region of the compound eye and light wavelength, and the response to polarized light relies on the photosensitive characteristics of the dorsal rim area (DRA)

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photoreceptor. Meanwhile, locusts' phototaxic sensitivity is related to photostimulation attributes, and their polartactic response effect is influenced by the polarization vector induced by polarized spectrum light that changes the sensitive vector. The interaction between polarized and spectral light fields generates a synergistic tuning stimulation effect and induces a phototactic-polartactic coupling response effect in locusts, thus providing a foundation for constructing coupled light field induction modes for locusts inspired by polarized and spectral lights.

Furthermore, the visual response effect of locusts depends not only on visual sensitivity to light but also on the visual physiological and biochemical transformation state induced by light changes; violet light stimulates locusts to generate enhanced phototactic activity, and orange light enhances locusts' visual sensitivity to violet light[10-13]. Studies on locusts' polarization-sensitive nerve mechanism have revealed the polarization perception mode for polarized spectrum vector light in locusts' photoreceptor and central complex. This mode presents a tuning response characteristic with alternating excitation and inhibition change at 90° intervals in the E-vector direction. The polarized spectrum attribute determines the perception sensitivity of locusts' polarization vision, and locusts' polartactic selectivity enhanced by polarized violet light intensity is strong[14-16]. Thus, light spectra influence the visual sensitivity of locust phototactic vision, and polarization vectors enhance the directionality of locust polartactic vision[17,18]. The use of locusts' specific sensitivity and preference selectivity to spectral and polarized violet lights can enhance the locust visual response effect. However, the function effect of the coupled light of linear polarization detection violet light and various spectrum lights on the locust visual response effect has not been explored. Therefore, studying locust visual response characteristics under these coupled light conditions can optimize the coupling function mode of polarized and spectral lights and elucidate the specific sensitivity of locust phototactic and polartactic vision.

In this study, the regulation enhancement and interaction modes of coupled light in locusts' visual response effects were investigated using a combined light source system with linear polarization detection violet light and different spectrum lights. The aim was to understand the specific action and influence of spectral and polarized lights on locusts' visual response behavior, obtain the technical characteristics of coupled light fields for locusts' phototaxis and polarotaxis, explore the changing visual sensitivity effect induced by spectral and polarized lights, and discuss the specific sensitivity response mechanism of locusts' phototactic and polartactic vision. This research provides a fundamental basis for understanding locusts' polarotaxic orientation response mechanism and constructing coupled light field induction mechanisms for locusts inspired by polarized light and stimulated by spectral light.

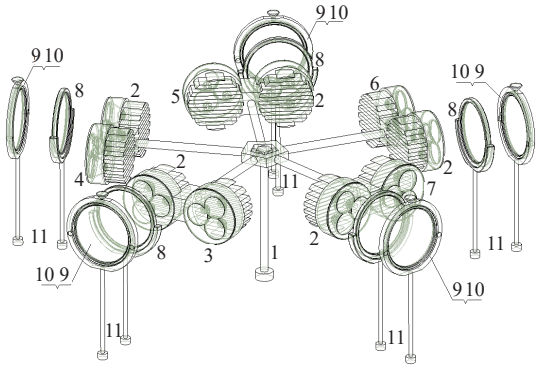
2 Materials and methods

2.1 Test insects

Locusts (*Locusta migratoria manilensis*) were obtained from an artificial breeding facility in Handan, Hebei, China, and reared under crowded conditions in a 12/12 h light/dark cycle. Only sexually mature male and female animals at least 1 week after final molt were used for the experiments. All experiments were conducted between 20:00 and 24:00 at room temperature (27°C-30°C) because of the high biological activity of the locusts.

2.2 Experiment light conditions

Three light-emitting diodes (3 W/pc, Hongtai Electronics, Yueqing, China) were made into UV, violet, blue, green, and orange light sources with wavelength peaks of 365, 400, 465, 520, and 610 nm, respectively (Figure 1). Each of the violet light sources, fixed with a spectral light source, was equipped with a linear polarizer with a 0° vector (light transmittance rate: 50%; polarization rate: 95%; PL-CIR HOYA, Japan; diameter: 55 mm) and a polarization detector with an adjustable vector (light transmittance rate: 50%; polarization rate: 95%; PL-CIR HOYA, Japan; diameter: 65 mm) to generate linear detection polarization violet light. Linear detection polarization violet light and different spectral lights were coupled to obtain experiment light. Relative to the 0° vector, vectors at 30° intervals from 0° to 360° were obtained by a polarization detector for the experiments. The illumination of light sources with and without linear polarizers was calibrated to 2000 and 1000 lx, respectively, by using an illuminometer (SPIC-300BW-H, Shenzhen Eurasia Precision Instrument Co., Ltd., Shenzhen, China). The rated illumination of light sources, powered by a 12 V power supply, was calibrated (UV, 10 000 lx; violet, 30 000 lx; blue, 150 000 lx; green, 200 000 lx; orange, 300 000 lx) to determine the stimulation effect of linear detection polarization violet and spectral lights with the same light energy (150 mW/cm^2), which was calibrated by using a radiation meter (Model: FZ-A, resolving power: ±5%; Beijing Instrument, Beijing, China) to unify the stimulus intensity.

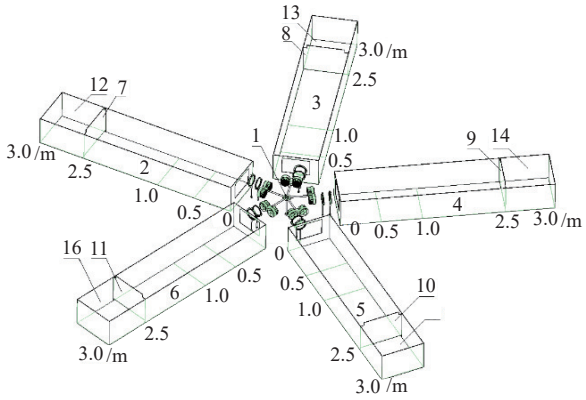


1. Support frame 1; 2. Violet light source; 3-7. UV, violet, blue, green, orange light source; 8. Linear polarizer; 9. Polarization detector; 10. Vector indexing frame; 11. support frame 2.

Figure 1 Combined light source system of linear polarization detection violet light and different spectrum lights

2.3 Experimental device

An experimental device (Figure 2) was designed to test the locust visual response effect. It had a combined light source system of linear detection polarization violet light and different spectrum lights and was placed in front of five locust visual response behavior channels (labeled 1-5) arranged at 72° intervals. The coupled light of linear detection polarization violet light and spectral light was projected into each response channel. The combined light source system was adjusted circumferentially to form a coupled light of linear detection polarization violet light with the same vector and different spectral lights or a coupled light of linear detection polarization violet light with different vectors and the same spectral light in the corresponding response channel. The locust polartactic response behavior channels (1-5) and the corresponding locust reaction chambers (1-5) were arranged to form a straight channel (3.0 m×0.5 m×0.4 m) separated at 2.5 m by channel gates 1-5. The channel division section is shown in Figure 2, which presents the visual response sensitivity to the coupling light.



1.Combined light source system of linear polarization detection violet light and different spectrum lights; 2-6.Locust visual response channel 1-5; 7-11. Channel gate 1-5; 12-16.Locust reaction chamber 1-5.

Figure 2 Device for testing locusts' visual response effect induced by the coupling light of linear polarization detection violet light and spectral light

2.4 Experimental methods

Five groups of test insects (30 locusts per group) were prepared to provide each vector the same illumination (1000 lx) and to have the same light energy of the light sources (rated illumination). Before each test, the light sources and polarizers were adjusted to achieve the desired conditions. The five groups of test insects were placed in corresponding reaction chambers (1–5) for 30 min of dark adaptation. During testing, the light sources and gates were opened to test the locust visual response effect with 30 min, and each group was tested three times with a 20 min interval between tests. The arrangement of the five combined light sources was rotated in turn by 72° for each group under the same violet vector coupled with different spectral lights. This method was repeated to complete the tests. The tests were completed in sequence by using the same method for each polarization detection violet vector coupled with the five spectral lights. After the tests, the numbers of insects distributed in each section of the five channels were counted.

2.5 Data computation and analysis

With the test data under the coupled light of each polarized detection vector and five spectral lights and with the mean number of insects from the 15 experiments distributed over 0.0-0.5, 0.0-1.0, and 0.0-2.5 m (n_1, n_2, and n_3) in the five channels, the locust visual trend intensity (%), visual aggregation degree (%), and visual response degree (%) were calculated as $n_1/30\times100\%$, $n_2/30\times100\%$, and $n_3/30\times100\%$, respectively, to reveal the functional effect of the coupled light of spectral light and linearly polarized detection violet vector light on the locust visual trend, visual aggregation, and visual response sensitivity (locust visual response effect).

One-way ANOVA of the general linear model was performed to analyze the sensitivity of the locust visual response effect induced by the same light spectrum with different vectors and by different light spectra with the same vector. For multiple comparisons, the least significant difference (LSD) test at p=0.05 was used. Student's t-test was applied to analyze the significance of different illuminations under the same coupling light. SPSS 16.0 (SPSS Inc., Chicago, IL, the USA) and Excel for Windows were used for all statistical analyses. All further analyses were performed with custom functions written in MATLAB (version 2021a, MathWorks, Natick, MA, the USA). The results are shown as the mean ± standard error.

3 Results and discussion

3.1 Locusts visual response sensitivity to coupled light of spectral light and linearly polarized detection violet vector light

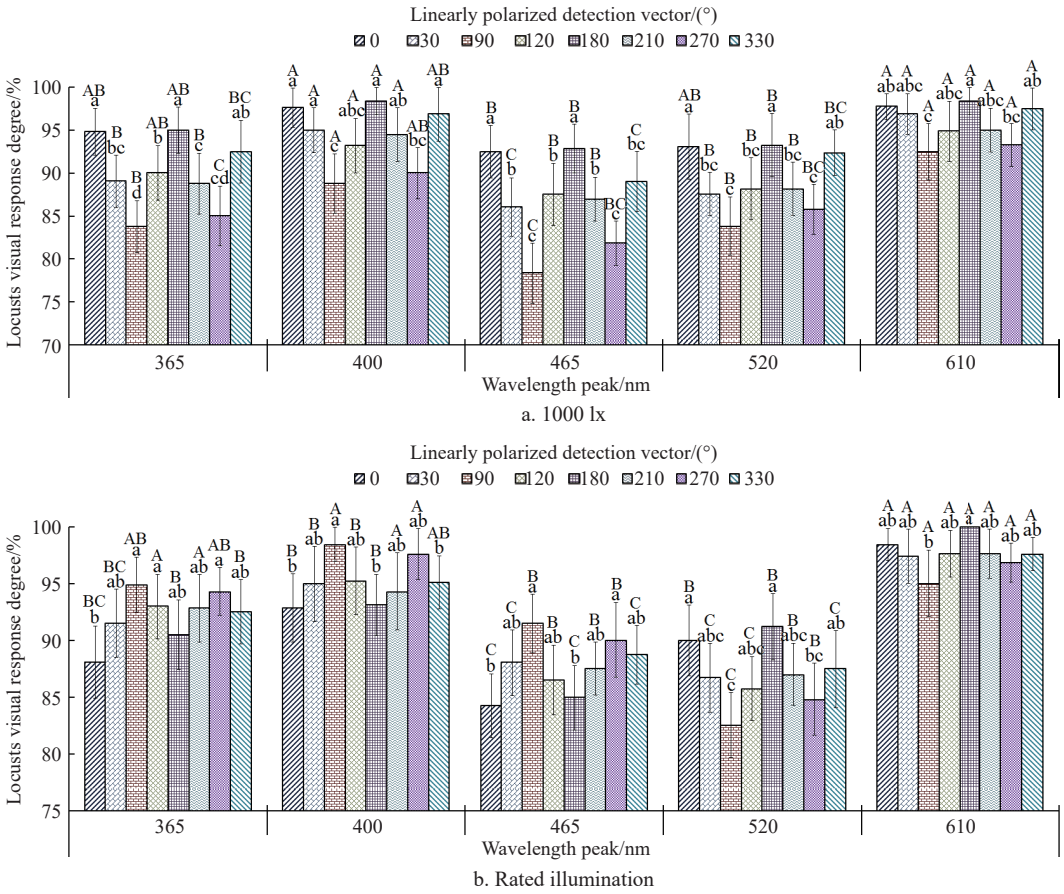
When the spectra coupled with the linearly polarized detection violet vector light were the same, under 1000 lx, the difference in the locust visual response sensitivity affected by the different polarized detection vectors was significant (Figure 3a: $F_{365\ nm}$=5.147, p=0.003; $F_{400\ nm}$=4.441, p=0.006; $F_{465\ nm}$=7.146, p=0.001; $F_{520\ nm}$=3.276, p=0.023; $F_{610\ nm}$=2.184, p=0.093), whereas under rated illumination, the difference was not significant (Figure 3b: $F_{365\ nm}$=1.363, P=0.860; $F_{400\ nm}$=1.337, p=0.296; $F_{465\ nm}$=1.990, p=0.121; $F_{520\ nm}$=1.920, p=0.132; $F_{610\ nm}$=1.187, p=0.364). However, under 1000 lx, the locusts showed strong response sensitivity at 180°, followed by 0°, and weak sensitivity at 90°, followed by 270°. Under rated illumination, the locusts presented varying response sensitivities depending on the coupled spectra; they showed strong response sensitivity at 90°, followed by 270°, and weak sensitivity at 0°, followed by 180° when UV, violet, and blue spectra were combined. Conversely, they presented strong response sensitivity at 0°, followed by 180°, and weak sensitivity at 90°, followed by 270°, when green and orange spectra were coupled. The differences between 90° and 270° and between 0° and 180° were not statistically significant (p>0.05).

Under 1000 lx, the locusts presented the highest response sensitivity to 180° coupling with orange and violet spectra, followed by 0°, and the weakest response sensitivity to 90° coupling with the blue spectrum, followed by 270°. Under rated illumination, the locusts had the strongest response sensitivity to 180° coupling with the orange spectrum, followed by 0° coupling with orange and 90° coupling with violet spectra; they showed the weakest response sensitivity to 90° coupling with the green spectrum, followed by 270°. When the illumination increased from 1000 lx to rated illumination, the interaction of linear detection polarization violet vector light and different spectral light affected the action effect of coupled light intensity on response sensitivity. Under UV, violet, and blue spectra, the inhibitory effect at the 0° and 180° vectors and the enhancement effect at the 90° and 270° vectors were remarkable (p<0.05), whereas that at the other vectors was not remarkable (p>0.05). Under green and orange spectra, the inhibition and reinforcement effects were related to the linear detection polarization vector, respectively, but the effect was not remarkable (*p>0.05*), and light intensity did not change the locust visual sensitivity to linear detection polarization violet light.

By comparison, under rated illumination, the response sensitivity to the 180° vector's coupling with the orange spectrum was the strongest, followed by the 0° vector's coupling with the orange spectrum and the 90° vector's coupling with the violet spectrum.

3.2 Locusts' visual aggregation sensitivity to the coupling light of spectral light and linearly polarized detection violet vector light

The locusts' visual aggregation sensitivity was significantly affected by the same spectra coupling with different polarized detection violet vector lights (Figure 4a: at 1000 lx, $F_{365\ nm}$=24.241, p=0.000; $F_{400\ nm}$=19.322, p=0.000; $F_{465\ nm}$=23.098, p=0.000; $F_{520\ nm}$=24.401, p=0.000; $F_{610\ nm}$=29.654, p=0.000; Figure 4b: at rated illumination, $F_{365\ nm}$=13.231, p=0.000; $F_{400\ nm}$=9.594, p=0.000; $F_{465\ nm}$=8.487, p=0.000; $F_{520\ nm}$=8.997, p=0.000; $F_{610\ nm}$=7.034, p=0.000). However, under 1000 lx, the locusts showed strong



Notes: Under 1000 lx and rated illumination, when the coupled spectra were the same and the linear detection polarization vector of the violet spectrum was different, the same lowercase letters indicate that the difference in locust visual response sensitivity was not significant (p>0.05, LSD), whereas the different lowercase letters indicate significant differences (p<0.05, LSD). Under 1000 lx and rated illumination, when the coupled spectra were different and the linear detection polarization vector of the violet spectrum was the same, the same capital letters indicate that the difference in locust visual response sensitivity was not significant (p>0.05, Student's t), whereas the different capital letters indicate significant differences (p<0.05, Student's t). The same as below.

Figure 3 Locusts' visual response sensitivity to linear detection polarization violet light coupled with spectral light

aggregation sensitivity at 0°, followed by 180°, and weak sensitivity at 270°, followed by 90°. Between 90° and 270° and 0° and 180°, the differences were not significant (p>0.05). Under rated illumination, the influence of the polarized detection vector on visual aggregation sensitivity varied depending on the coupled spectra. Specifically, when coupled with UV and violet spectra, the sensitivity at 210° was strong, followed by that at 30°; when coupled with blue, green, and orange spectra, the sensitivity at 180° was strong, followed by that at 0°. However, the sensitivity at 270° coupled with different spectra was poor, followed by that at 90°.

When the linear polarization detection vector of the violet spectrum was the same, the coupled spectrum attribute considerably affected the locusts' visual aggregation sensitivity (Figure 4). Under 1000 lx (Figure 4a), the influence at the 30° vector was the most significant (F=14.611, p=0.000), followed by that at 90° (F=13.929, p=0.000), whereas the influence was the least significant at the 120° vector (F=3.509, p=0.049), followed by that at 330° (F=7.886, p=0.004). Under rated illumination (Figure 4b), the influence at 30° was the most significant (F=51.066, p=0.000), followed by that at 210° (F=43.043, p=0.000), whereas the influence was the least significant at the 180° vector (F=14.062, p=0.000), followed by the 330° vector (F=16.011, p=0.000). However, when the vector was the same, the locusts showed strong aggregation sensitivity when coupled with violet spectra, followed by orange spectra, and weak sensitivity when coupled with green spectra, followed by UV spectra.

Under 1000 lx, the locusts presented the strongest aggregation sensitivity to 0° coupling with violet spectra, followed by 0° coupling with orange spectra, but no significant difference existed between them. Under rated illumination, the locusts had the strongest aggregation sensitivity to 210° coupling with violet spectra, followed by 30°, and no significant difference was found between them. However, under 1000 lx and rated illumination, the locusts had the weakest aggregation sensitivity to 270° coupling with green spectra, followed by 90°, showing no significant difference between them.

When illumination increased from 1000 lx to rated illumination, the interaction of linear polarization detection violet vector light and different spectral lights affected the action effect of coupled light intensity on aggregation sensitivity. Under UV and violet spectra, coupled light intensity enhanced aggregation sensitivity and strengthened the sensitivity vectors from 0° and 180° to 210° and 30°, respectively, and the enhancement effect of the 90° and 270° vectors was remarkable (p<0.05). Under blue, green, and orange spectra, the regulatory effect of coupled light intensity was related to the linear polarization detection vector, and aggregation sensitivity was related to the coupled spectra. At 0° and 180°, the inhibition effect was the least significant (p>0.05), and the aggregation sensitivity to the orange spectrum was strong. At 90° and 270°, the enhancement effect was the most significant, indicating the heterogeneous interference effect of spectral illumination and linear polarization detection vector illumination.

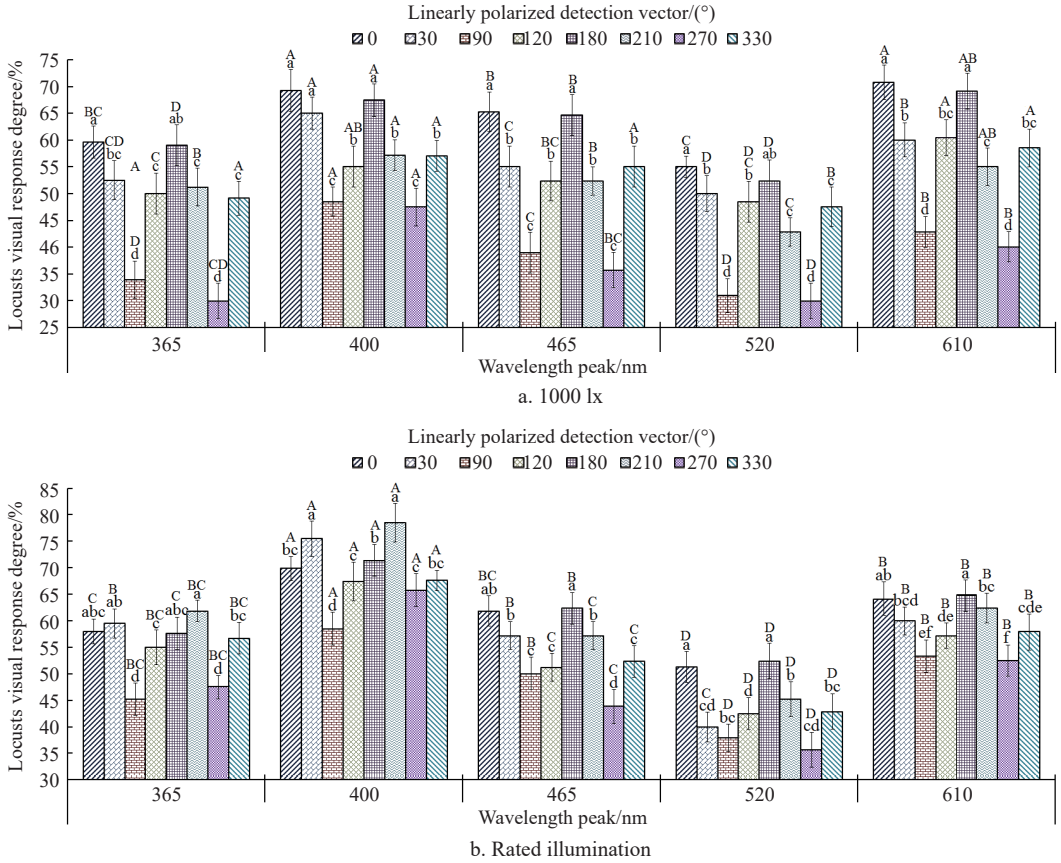


Figure 4 Locusts' visual aggregation sensitivity to linear polarization detection violet light coupled with spectral light

By comparison, under rated illumination, the aggregation sensitivity to the 210° vector coupling with the violet spectrum was the strongest, followed by the 30° vector.

3.3 Locusts' visual trend sensitivity to the coupling light of spectral light and linearly polarized detection violet vector light

The locusts' visual trend sensitivity was significantly affected by the same spectra coupling with different polarized detection violet vectors (Figure 5a: at 1000 lx, $F_{365\ nm}$=9.054, p=0.000; $F_{400\ nm}$=8.641, p=0.000; $F_{465\ nm}$=10.927, p=0.000; $F_{520\ nm}$=8.035, p=0.000; $F_{610\ nm}$=16.137, p=0.000; Figure 5b: at rated illumination, $F_{365\ nm}$=5.643, p=0.002; $F_{400\ nm}$=11.168, p=0.000; $F_{465\ nm}$=4.332, p=0.007; $F_{520\ nm}$=10.048, p=0.000; $F_{610\ nm}$=11.434, p=0.000). Under 1000 lx, the locusts showed strong trend sensitivity at 0°, followed by 180°, and weak sensitivity at 270°, followed by 90°. The differences between 90° and 270° and between 0° and 180° were not significant (p>0.05). Under rated illumination, the locusts had strong trend sensitivity at 180°, followed by that at 30°, when coupled with UV and violet spectra. When coupled with blue, green, and orange spectra, the trend sensitivity at 180° was strong, followed by that at 30°. However, the sensitivity at 270° coupling with different spectra was poor, followed by that at 90°.

Using the same polarization detection vector but different coupled spectra had varying effects on the locusts' visual trend sensitivity. Under 1000 lx (Figure 5a), the influence of the spectrum was the most significant at the 330° vector (F=17.560, p=0.000), followed by the 90° one (F=12.338, p=0.001), whereas the influence was the least significant at the 30° vector (F=8.066, p = 0.004), followed by the 270° one (F=8.959, p=0.002). Under rated illumination (Figure 5b), the influence was the most significant at the 30° vector (F=56.382, p=0.000), followed by the 210° one (F=50.220, p=0.000), but the influence was the least significant at the 120° vector (F=21.023, p= 0.000), followed by the 180° one (F=23.573, p=0.000). However, when the vector was the same, the locusts showed strong trend sensitivity when coupled with violet spectra, followed by orange spectra. Under 1000 lx, the locusts demonstrated weak sensitivity when coupled with UV spectra, followed by green spectra. Under rated illumination, the locusts showed weak sensitivity when coupled with green spectra, followed by blue spectra.

Under 1000 lx, the locusts showed the strongest trend sensitivity to 0° coupling with violet spectra, followed by 180°, but had no significant difference between them. Comparison of the 0° and 180° vectors coupling with orange spectra revealed that the difference was not significant (p>0.05). The locusts showed the weakest trend sensitivity to 270° coupling with UV spectra, followed by 90°. Under rated illumination, the locusts presented the strongest trend sensitivity to 210° coupling with violet spectra, followed by 30°, and the weakest aggregation sensitivity to 270° coupling with green spectra, followed by 90°.

When illumination increased from 1000 lx to rated illumination, coupled light intensity affected the locusts' visual trend sensitivity, which related to linear polarization detection violet vector illumination and the coupled spectrum intensity attribute. Under UV and violet spectra, coupled light intensity enhanced trend sensitivity and changed the strong sensitivity vector from 0° and 180° to 210° and 30°. At 30° and 210°, the enhancement effect was remarkable (p<0.05). Under blue, green, and orange spectra, coupled light intensity did not change the sensitivity vector, but under blue and green spectra, light intensity inhibited the sensitivity vector. Under orange spectra, light intensity intensified trend sensitivity. Meanwhile, under rated illumination, the trend sensitivity to the 210° vector coupling with violet spectra was the strongest, followed by the trend sensitivity to the 30° vector.

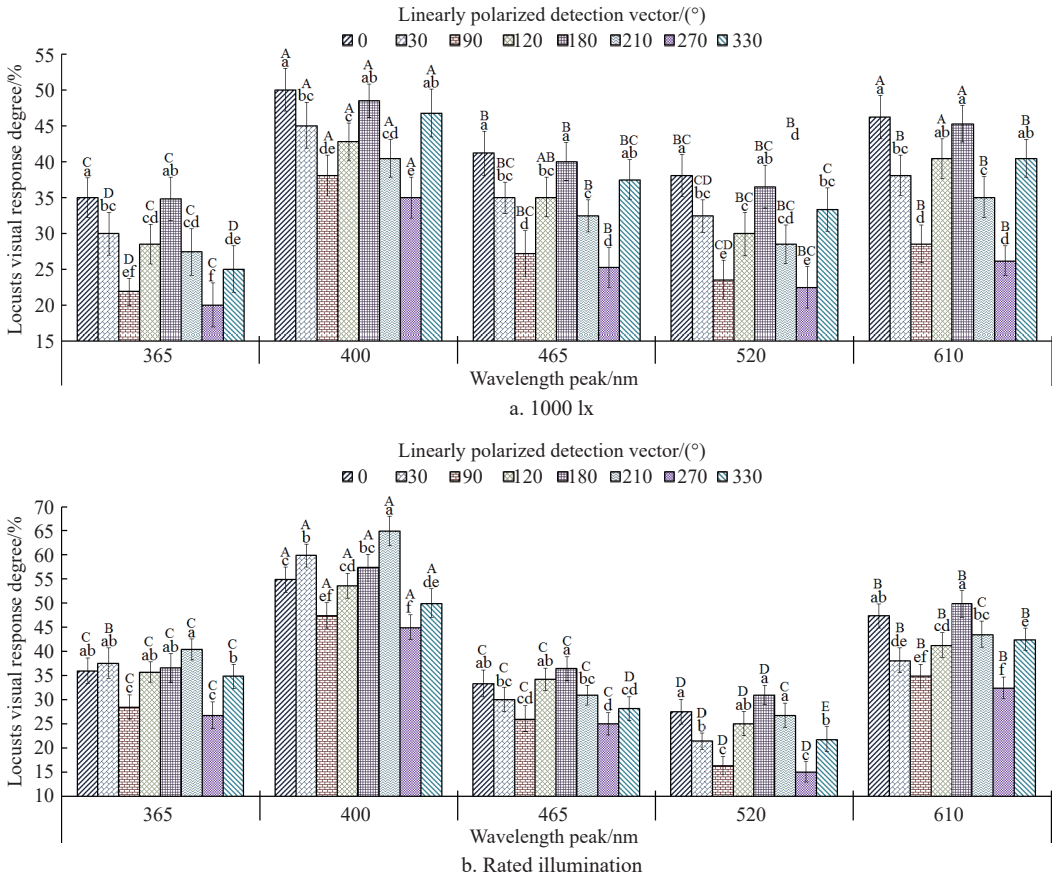


Figure 5 Locusts' visual trend sensitivity to linear polarization detection violet light coupled with spectral light

3.4 Discussion

Researchers have reported that locusts rely on the recognition of the polarization-sensitive vector and the stimulation of the nonpolarized spectrum light gradient to complete spatial direction orientation[19,20]. However, the interaction between various spectra and linearly polarized detection vectors and their collective effect on locusts' phototactic and polarotaxic response effect remain unclear. We found that when the vector was the same, the coupled spectrum attribute affected the sensitivity of the locusts' visual response effect; the locusts exhibited strong response sensitivity to orange and violet spectra and strong aggregation and trend sensitivity to violet and orange spectra. When the coupled spectra were the same, under 1000 lx, the sensitivity of the locusts' visual response effect was related to the linear polarization detection vectors, showing strong sensitivity to 0° and 180° and weak sensitivity to 90° and 270°. However, under rated illumination, sensitivity was related to the optical distance effect of coupled light. It showed strong response sensitivity to 90° and 270° coupling with UV, violet, and blue spectra and weak sensitivity to 0° and 180°; strong sensitivity to 0° and 180° coupling with green and orange spectra and weak sensitivity to 90° and 270°; strong aggregation and trend sensitivity to 210° and 30° coupling with UV and violet spectra and 0° and 180° coupling with blue spectra; and weak sensitivity to 90° and 270° coupling with different spectra.

These findings align with those of previous studies that reported that the interaction between polarized and spectral lights influences locusts' visual perception and response characteristics[21,22]. Thus, locusts' visual behavioral intensity can be feasibly manipulated through the optical parameters of polarized and spectral lights[23,24]. In this study, the locusts' visual sensitivity perception mode to the linear polarization detection vector was related to the coupling light intensity of polarized detection light and spectral light. The coupled illumination did not affect the visual sensitivity perception mode under 1000 lx but influenced it under rated illumination. Under 1000 lx, the optical distance of coupling light regulated visual sensitivity to heterogeneous spectra, changing the locusts' visual sensitivity spectrum. Under rated illumination, the optical distance of coupling light regulated the locusts' visual sensitivity to the linear polarization detection vector, thus changing the locusts' visual sensitivity vector induced by the coupled spectrum. These results are crucial for elucidating the locust polarization vision response mechanism and constructing locust polarization spectrum induction technologies.

Previous research has indicated that locusts rely on skylight gradients and polarization types for spatial orientation and long-range flight navigation. When the stimulus brightness of nonpolarized light decreases, the polarization vector mode becomes crucial for locusts' orientation response. Furthermore, locusts' visual sensitivity effects are related to spectral light characteristics[25]. The results of this study further indicated that as the illumination increased, the coupling light intensity of polarized detection vector light and spectral light regulated the sensitivity of the locusts' visual response effect, which was related to the coupled spectrum attribute. The inhibitory mutagenicity effect on response sensitivity at 0° and 180° under UV spectra and the stimulatory mutagenicity effect on response sensitivity at 90° and 270° under violet and blue spectra of light intensity were remarkable. Meanwhile, under green and orange spectra, light intensity did not affect the response sensitivity to the vector and presented inhibitive and intensive function effects, respectively. Under UV and violet spectra, light intensity changed aggregation and trend sensitivity. The mutagenicity effect at 210° and 30° and the reinforcement

effect at 90° and 270° were remarkable. Under blue, green, and orange spectra, light intensity did not affect the aggregation and trend sensitivity to the vector. The reinforcement effect on aggregation sensitivity at 90° and 270° and the inhibition effect on aggregation sensitivity at 0° and 180° were substantial and not remarkable, respectively. Meanwhile, under blue and green spectra, light intensity inhibited trend sensitivity, and at 0° and 330°, the inhibition effect was remarkable. Under orange spectra, light intensity intensified trend sensitivity, and at 90° and 270°, the reinforcement effect was substantial.

These results indicate that the combination of polarization vision and spectral vision dynamically regulates how locusts receive and respond to light intensity and polarization distribution patterns[26,27]. The specific dependence and antagonistic regulatory adaptation mechanisms of locusts' non-DRA vision to heterogeneous spectral intensity and the antagonistic dependence of DRA vision on polarization vectors further affect the influence of light intensity on locusts' phototactic and polarotaxic vision[28,29]. Therefore, when illumination increases, the coupled spectrum attribute affects the regulatory mutagenicity effect of light intensity on locusts' visual response effect, which is related to linear polarization detection vector light originating from the reciprocal regulation effect of heterogeneous spectrum illumination and linear polarization detection vector illumination.

Previous studies have demonstrated that the photoinduction effect induced by polarized violet light is optimal, and light intensity can affect the vectors of locusts' visual sensitivity[30,31]. In our study, we observed that under the coupling of linear polarization detection violet vector light and spectral light, the locusts' visual sensitivity vector remained constant as long as the illumination was below the rated illumination. This finding highlights the specific sensitivity mode induced by the coupled spectrum attribute and the effect of the coupled spectrum attribute on the sensitivity of locusts' visual response effect, which shows strong sensitivity to orange and violet spectra. Meanwhile, the linear polarization detection vector affected the photoinduced influence of the spectral property. Under rated illumination, the response sensitivity to 180° coupling with orange spectra was the strongest, followed by 0°, and the aggregation and trend sensitivity to 210° coupling with the violet spectrum was the strongest, followed by 30°. The coupling of linear polarization detection light with spectral light generated partially polarized light. The illumination and polarization degrees of this partially polarized light were altered (strong at 0° and 180° and weak at 90° and 270°). Moreover, the locusts' visual response effect was related to the coupling stimulation effect of polarization degree, light intensity, and specific spectrum sensitivity, which was particularly relevant to the coupling effect of polarized short-wave spectra (violet) and homogeneous short-wave spectra (violet). This coupling effect easily caused the locusts to approach the light sources in an orderly manner, resulting in close-range enhancement. Meanwhile, the coupling effect of polarized short-wave spectra (violet) and heterogeneous long-wave spectra (orange) was prone to cause disordered locusts to generate ordered responses, resulting in the long-range induction effect.

4 Conclusions

This study contributes to understand the intricate relationships between linear detection polarization violet vector light coupled with various spectral lights and locust visual response effect that are influenced by varying illuminations, and the most obvious finding was that the coupled spectral light attributes changed locust visual sensitivity vectors when the illumination of different spectral light source increased to rated illumination with the same light energy. The second aim of this study was to determine the influence of polarized and spectral light interactions on the sensitivity of locust visual response effect to specific vectors. The results showed that locust visual response effect depended on the coupled spectral attributes which also affected the regulatory mutagenic effect of light intensity as illumination increased, showing the response sensitivity to 180° induced by orange light, the aggregation and trend sensitivity to 210° induced by violet light when illumination increased to rated illumination. Moreover, our findings demonstrate that linear detection polarization violet light coupled with violet light, linear detection polarization violet light coupled with orange light, can serve as a valuable strategy for enhancing locusts polarotactic sensitivity, and regulating the sensitive vector for locusts polarotactic vision changed by the coupled spectral light distance under different coupled light intensities. These findings, although explorative and requiring in depth investigation, provide valuable theoretical support for understanding polarotactic orientation mechanisms in locusts, and insights that may facilitate the development of polarization induced light sources for attracting locusts.

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