Peculiar influence of linearly polarized spectrum illumination patterns on the sensitivity characteristics of locust response to polarized light

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Abstract: This study investigated the influence of different linearly polarized spectrum lights on locusts polartactic response characteristics linearly polarized vector sensitivity mode and polartactic response) by using linearly polarized spectrum vector light module and experimental device. The objective was to clarify the vector sensitivity characteristics and functional effect of linearly polarized light spectrum intensity on locusts polartactic response, determine the influence specificity of linearly polarized spectrum illumination properties on locusts polarization-related behavior. When spectrum and illumination were constant, locusts polartactic response, presenting the response feature of sine and cosine function change specificity, was related to spectrum attribute. The visual acuity effect stimulated by violet spectrum was the best, whereas the optical distance modulation effect induced by orange spectrum was the strongest. When illumination was enhanced, locusts vector sensitivity mode shifted to present the specific sensitivity prompted by light intensity at long distance and inhibited by light intensity at short distance. Moreover, the regulating function of violet spectrum was the strongest, and the regulatory mutation effect of orange spectrum was the least significant. Simultaneously, locusts polartactic sensitivity to 300° vector at 100 lx, whereas to 240° vector at 1000 lx of linearly polarized violet light was the strongest. Locusts polartactic aggregation and visual tendency sensitivity to 90° vector at 100 lx, whereas to 270° vector at 1000 lx of linearly polarized violet light was the strongest. The heterogeneous regulation function of different linearly polarized spectrum couplings with light intensity led to significant variations in locusts vector sensitivity mode. This was derived from the antagonistic and specific tuning characteristics of locusts polartactic vision, reflecting the integrated output effect of locusts vector dependence regulated by linearly polarized spectrum intensity attribute. The findings were significant for the construction of pest polarization induction light sources and the investigation of the sensitive physiology pathway of locusts polarization vision.
Keywords: *Locusta migratoria*, linearly polarized light, spectrum illumination pattern, locusts polar axis response, vector
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1 Introduction

The phototactic induction capture and management of agricultural Lepidoptera, Coleoptera, and other pests have realized the ecological management strategy of “plant protection, biological protection, resource conservation, and environmental protection”[1,2]. However, Orthoptera locusts show more complex influence factors than phototactic applications to nocturnal moths, restricting the realization of phototactic locust capture and management induced by light. At present, research breakthroughs on locusts polarization sensitivity nerve organization structure and behavior physiology[3,4] are expanding the regulatory factors of locusts phototactic vision physiology stimulation and biological response. This indicates a potential direction for determining novel photo-stimulation modes. Therefore, studies of the polar axis effect induced in locusts by the polarized light spectrum property and the peculiar vision sensitivity essence of their polarization vision are of great significance for developing electromechanical equipment to regulate and kill locust pests by long-distance induction using a polarized spectrum light source, to achieve practical application of polarization induction for locust control and to reveal the nature of locusts polarization behavior.

Researchers[5-9] have pointed out that locusts and other insects perceive external light sources through visual organs. However, sensitivity differences among visual pigments perceiving different spectra, movement of the screening pigments, and adaptation of visual system structure to the light environment make different lights have different functional effects on the precise position and activities of locusts and cause differences in the reaction of their visual physiology, which in turn affects locusts directional selectivity and their motion persistence in the direction of the light source. Moreover, researchers[10-13] have shown that locusts rely on the polarization E-vector tuning mode of DRA ommatidia to sensitively match the sky polarization type and realize the behavioral orientation function, but these responses are generated by receiving the entire polarization mode through numerous ommatidia arrays and neurons. And the directional navigation function of locusts polarization vision has prompted the research on locusts physiological sensitivity mechanism induced by polarized light.

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Further studies have indicated that locusts polarization sensitivity opposition characteristics and light transmission patterns formed by the microvilli arrangement in the rods make locusts generate an E-vector sensitivity orientation and monitoring response to linearly polarized light, causing physiological nerve excitation and driving the control of activity behavior. In locusts central complex, the neurons that are most sensitive to horizontal and nearly vertical polarized light make the response sensitivity to polarized light at least two log units higher than to non-polarized light, which increases the sensitivity of locusts compound vision by 15%-30%[14,15]. However, a sensitive vector model of locusts polartactic response and research into the functional effect of the linearly polarized light spectrum attribute on locusts polartactic response behavior, according to locusts perception and orientation mechanism to linearly polarized light information, have not been involved at present. A paucity of research on the unique sensitivity of locusts polartactic response and the technical properties of locusts polarization induction light field has restricted development of a locust polarization spectrum induction machine.

In this study, using the combination of an LED module with the characteristics of different light spectra and a linearly polarized vector implementation mode, locusts polartactic response and vector sensitivity mode under different linearly polarized light spectrum intensities were investigated to analyze the specific vector sensitivity characteristics and the photo-induced influence of locusts polartactic response. The intent was to obtain the technical parameters and the influence factors of locust induction by linearly polarized light spectra and to discuss the locust polarization behavior regulation mechanism and the sensitive response mechanism of locusts polarization vision. This study will assist in developing polarization induction lamps for pest control and in providing a fundamental basis for locusts polarization induction behavior mechanism.

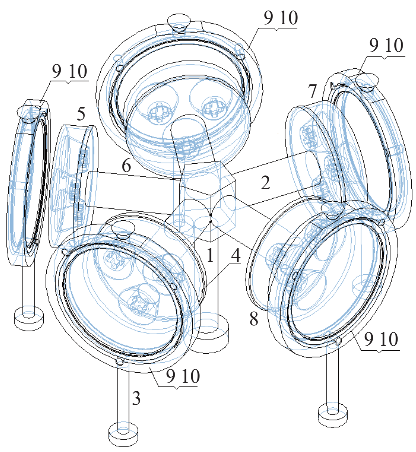
2 Materials and methods

2.1 Test insects

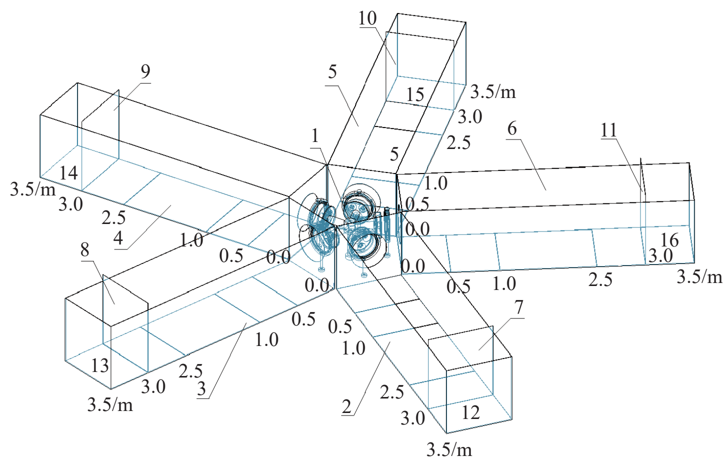
Locusts (*Locusta migratoria manilensis*) were obtained from an artificial breeding facility at Handan, Hebei, China, and were maintained in a laboratory colony under a photoperiod of L12:D12. Locusts were fed with forage. Locusts were fed with forage. Experiments were conducted between 20:00 and 24:00 when the adult locusts were most activity. All experiments were performed in a room at 27°C-30°C.

2.2 Linear polarization generator module

Three light-emitting diodes (LED, 3W/pcs) were welded onto a *Φ*55 mm aluminum substrate to make a light source powered by a 12 V adjustable DC power supply for the test. Five single light sources with wavelength peaks of 365 (UV), 400 (violet), 465 (blue), 520 (green), and 610 (orange) nm respectively were used in the test (items 4-8 shown in Figure 1a). The five light sources, spaced 72° apart, were fixed by support connection 2 and placed on the support frame 1. Linearly polarized light for the test was then generated by passing a light spectrum through the *Φ*60-mm linear polarizer (light transmittance rate: 50%; polarization rate: 95%). The linear polarizer was installed on the circular vector-adjusting frame supported by support frame 2, and the vector-adjusting frame adjusted the linear polarizer to form linearly polarized vectors at 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, 330°, and 360° (0°). The linearly polarized illumination formed by the light spectrum passing through the linear polarizer was calibrated by the illuminometer (Model: XRP-3000, Resolving power: 0.01 lx, Shenzhen Eurasia Precision Instrument Co., Ltd., Shenzhen, China). The linearly polarized illuminations used in the test were 100 and 1000 lx.



a. Generator module for linearly polarized light



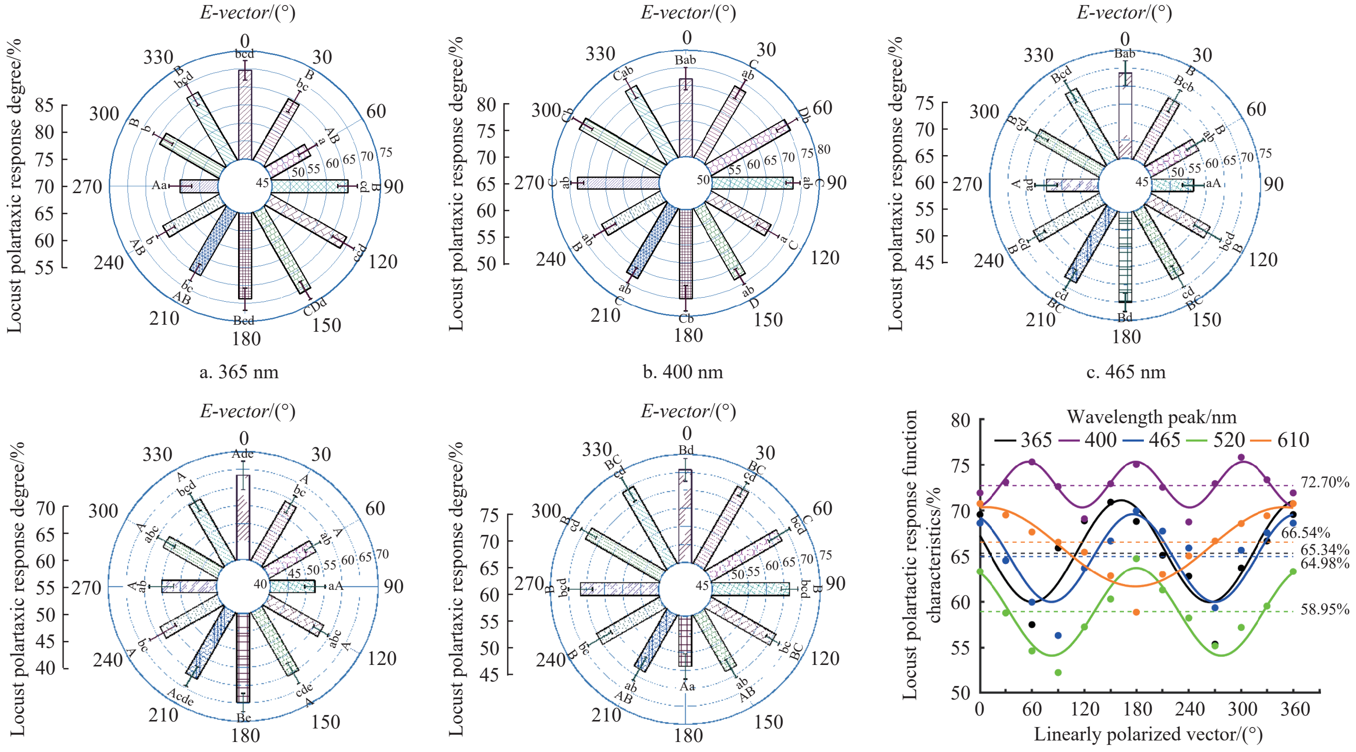
b. Device for testing locusts polarization response characteristics

1.Support frame 1; 2.Support connection; 3.Support; 4-8.UV, violet, blue, green, and orange light; response behavior channels 1-5; 9. Linear polarizer; 10. Vector-adjusting frame. 1.Linearly polarized light source system; 2-6.Locusts polartactic frame 2; 7-11. Channel gates 1-5; 12-16.Locusts reaction chambers 1-5.

Figure 1 Experiment devices used in the test

2.3 Experimental device

Figure 2 shows the device developed to test locusts polartactic response. The linearly polarized light source system was placed in front of the five locusts polartactic response behavior channels 1-5 arranged circumferentially at intervals of 72°. Linearly polarized light was projected into each response channel through the central hole, and the five light sources of linearly polarized light source system 1 were adjusted circumferentially to form linearly polarized light with the same vector, but different wave spectra, or with the same wave spectra, but different vectors in the corresponding response channel. Locusts polartactic response behavior channels 1-5 and the corresponding locusts reaction chambers 1-5 were arranged to form a straight channel (length×width×height: 3.5 m×0.5 m×0.4 m) separated at 3.0 m by channel gates 1-5, respectively. The channel division section is shown in Figure 1 and serves to determine locusts polartactic response sensitivity to linearly polarized light.



a. 365 nm
b. 400 nm
c. 465 nm
d. 520 nm
e. 610 nm
f. Function change characteristics

Notes: Under different linearly polarized victors with the same spectrum in a, b c, d, e, respectively, the same lowercase letters indicate that the difference was not significant (p>0.05, LSD), whereas different lowercase letters indicate significant differences (p<0.05, LSD); Under the same linearly polarized vectors with different spectra, the same capital letters indicate that the difference was not significant (p>0.05, Student's t), whereas different capital letters indicate significant differences (p<0.05, Student's t) in a-e. The same as below.

Figure 2 Change characteristics of locusts polartactic response to linearly polarized illumination of 100 lx

2.4 Experimental methods

With the intent of providing each vector with the same illumination of linearly polarized light, the five groups of test insects (30 locusts/group) were prepared. Before the experiment, the light sources were arranged, using the vector-adjusting frame, the five linear polarizers were set to the same polarized vector, the illuminometer was used to calibrate the linearly polarized illumination at the central hole of each channel to the desired illumination level for the test, and the five groups of test insects were placed in the corresponding reaction chambers 1-5 for 30 min dark adaptation. During the test, the light sources and gates were opened to test locusts polartactic response with 30 min lighting time; locusts were tested three times at intervals of 20 min. By adjusting the placement direction of the five light sources in the system by rotating them by 72° in turn under the same vector, the five groups of test insects in the five channels were tested three times, and the five light sources were tested in turn. Finally, each test vector was obtained by adjusting the linear polarizer with the vector-adjusting frame, and using the above methods, the locust polartactic response was tested to completion under the same vector, but different spectra. Under 100 and 1000 lx of linearly polarized illumination, presenting each linearly polarized vector for each of the five spectra, the tests were completed in sequence using the same method. After each test, insect numbers distributed in each section of the five channels were counted.

2.5 Data computation and analysis

For the test data under the vector corresponding to each linearly polarized spectrum, with the mean number of insects from the 15 experiments distributed over 0.0-0.5, 0.0-1.0, 0.0-2.5 m (n_1, n_2, n_3), locusts visual trend intensity (%), polartactic aggregation degree (%), and polartactic response degree (%) were calculated as n_1/30×100%, n_2/30×100%, n_3/30×100% respectively to reflect the functional effect of linearly polarized spectral vector light mode on locusts visual trend, polartactic aggregation, and polartactic response sensitivity (locusts polartactic response).

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

3 Results and discussion

3.1 Locusts polartactic response characteristics to linearly polarized spectrum vector mode

Under 100 and 1000 lx, when the spectrum was constant, different vectors regulated locusts polartactic response sensitivity and presented differential functional effects (Figure 2a-2e, 100 lx: F_{365nm}=7.299, F_{465nm}=4.871, p<0.001; F_{400nm}=1.474, p>0.05; F_{520nm}=3.951, F_{610nm}=3.372, p<0.01; Figures 3a-3e, 1000 lx: F_{365nm}=5.241, F_{400nm}=4.998, p<0.001; F_{610nm}=2.844, p<0.05; F_{465nm}=1.743, F_{520nm}=2.001, p>0.05). Locusts polartactic response presented sine and cosine function change features regulated by continuous vectors (Figure 2f, Figure 3f).

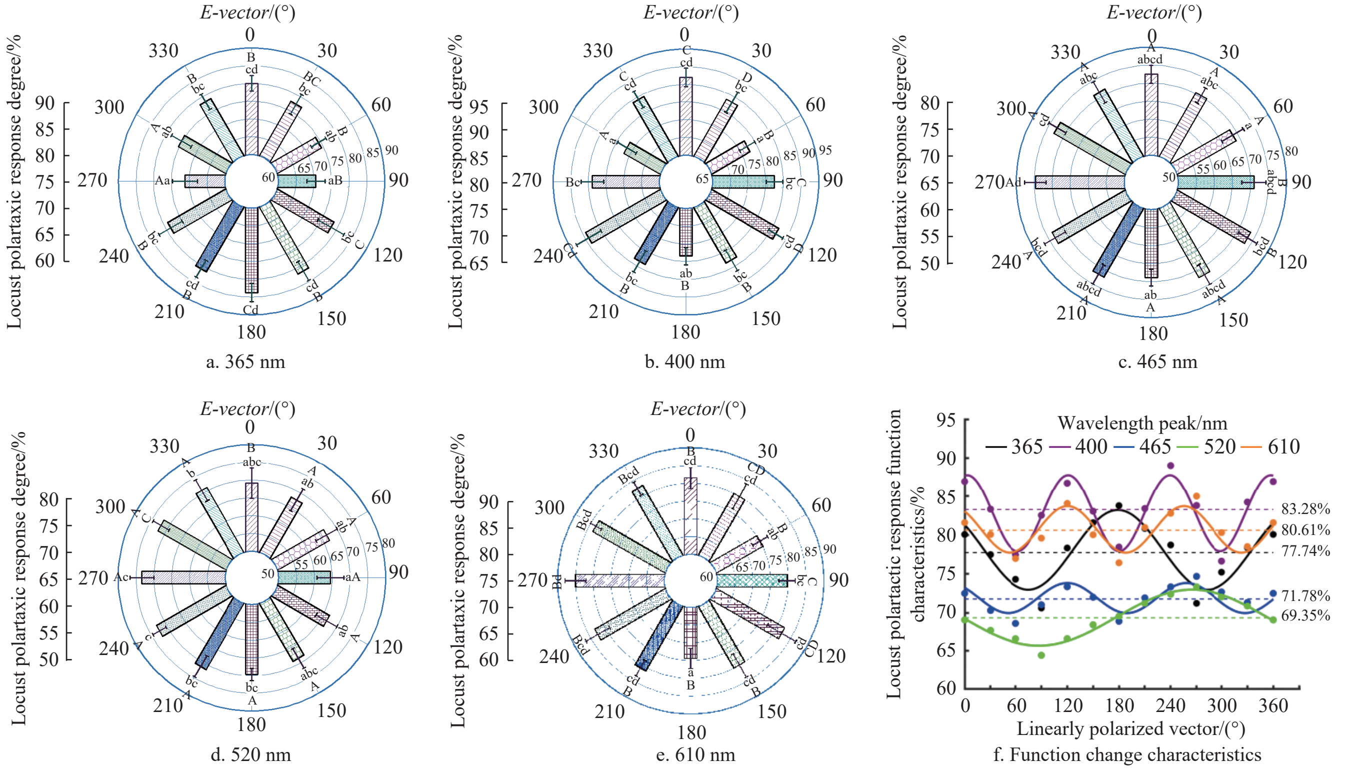


Figure 3 Change characteristics of locusts polartactic response to linearly polarized illumination of 1000 lx

Under 100 lx, when spectrum varied, the response period of the chord function induced by the continuous vectors also varied (Figure 2f). Under 0°-360° vectors, the cosine response feature induced by blue and green, orange, UV spectra presented change sensitivity induced by the vector in 2 periods, 1 period, and 2 periods respectively with 30° phase angle. The sine response feature induced by violet spectrum presented change sensitivity in 2.5 periods, meaning that continuous vectors with the same spectrum regulate locusts polartactic response and determine the sensitivity difference of the chord function change. In the response sensitivity, the photo-induced effect of 150°, 60° under UV spectrum, 300°, 240° under violet spectrum, 180°, 90° under blue and green spectra, and 0° (360°), 180° under orange spectrum was the best and the worst respectively. Under violet spectrum, the difference in the photo-induced effect between 180° and 240° was the most significant (p<0.01).

Under 1000 lx, compared with 100 lx, when spectrum varied, the polartactic response characteristics and the response period induced by the continuous vectors also varied (Figure 3f). Under 0°-360° vectors, locusts polartactic response sensitivity induced by UV and violet spectra showed the cosine response feature in 2 and 3 periods respectively; that induced by blue and orange spectra, green spectrum showed the sine response feature in two periods with 30° phase angle and in one period respectively. Thus, the regulation effect of different vectors on locusts polartactic response showed the differential change sensitivity of the chord function. In locusts polartactic response sensitivity, the photo-induced effect of 180°, 90° under UV spectrum, 240°, 300° under violet spectrum, 270°, 60° under blue spectrum, 270°, 90° under green spectrum, and 270°, 180° under orange spectrum was the best and the worst respectively.

The influence of different spectra on locust polartactic response sensitivity varied significantly under the same linearly polarized illumination and vector. When illumination was 100 lx (Figures 2a-2e), the influence of the spectrum under 0° vector was not significant (F=2.737, p=0.090), but that under other vectors was significant; that under 240° and 90° was not the most significant (F=3.715, p=0.090) and the most significant (F=30.943, p=0.000) respectively. The photo-induced effect of violet spectrum was optimal, whereas those of orange spectrum under 180° and those of green spectrum under other vectors were the worst. When illumination was 1000 lx (Figures 3a-3e), the spectrum significantly affected locusts polartactic response sensitivity. Under 300° and 180°, the influence of spectrum was not the most significant (F=7.175, p=0.005) and the most significant (F=20.516, p=0.000) respectively. The photo-induced effect of green spectrum was the worst under 270°-300° and that of orange spectrum was the best under other vectors.

When illumination was increased, and spectrum was constant, variations in light intensity changed locusts polartactic chord function response characteristics significantly. When both spectrum and vector were constant, light intensity affected locusts polartactic response sensitivity. Under blue spectrum with 180°, light intensity inhibited while under blue spectrum with 210°, violet spectrum with 60°, 180°, 330°, light intensity enhanced locusts polartactic response sensitivity, but the effect was not significant (p>0.05). Under other vectors, the enhancement effect of light intensity was significant, with the effect under orange spectrum at 240° being the most significant, followed by violet spectrum at 240° (p<0.001). By comparison, under 100 lx, the photo-induced effect of violet spectrum with 300° was the best, however, compared with 180° and 60°, the difference was not significant (p>0.05). But when illumination increased to 1000 lx, the photo-induced effect of violet spectrum with 240° was the best, followed by orange spectrum with 270°.

3.2 Locusts polartactic aggregation characteristics to linearly polarized spectrum vector mode

Under 100 and 1000 lx, when spectrum remained the same, linearly polarized vector significantly affected locusts polartactic aggregation sensitivity (Figures 4a-4e, 100 lx: F_{365nm}=5.060,

F_{465nm}=9.427, F_{520nm}=8.908, F_{610nm}=9.023, p<0.001; F_{400nm}=1.474, p<0.01; Figures 5a-5e, 1000 lx: F_{365nm}=7.050, F_{400nm}=7.128, F_{610nm}=15.642, p<0.001; F_{465nm}=3.032, F_{520nm}=3.109, p<0.01), and locusts polartactic aggregation presented sine and cosine function change characteristics induced by the continuous vectors(Figure 4f, Figure 5f).

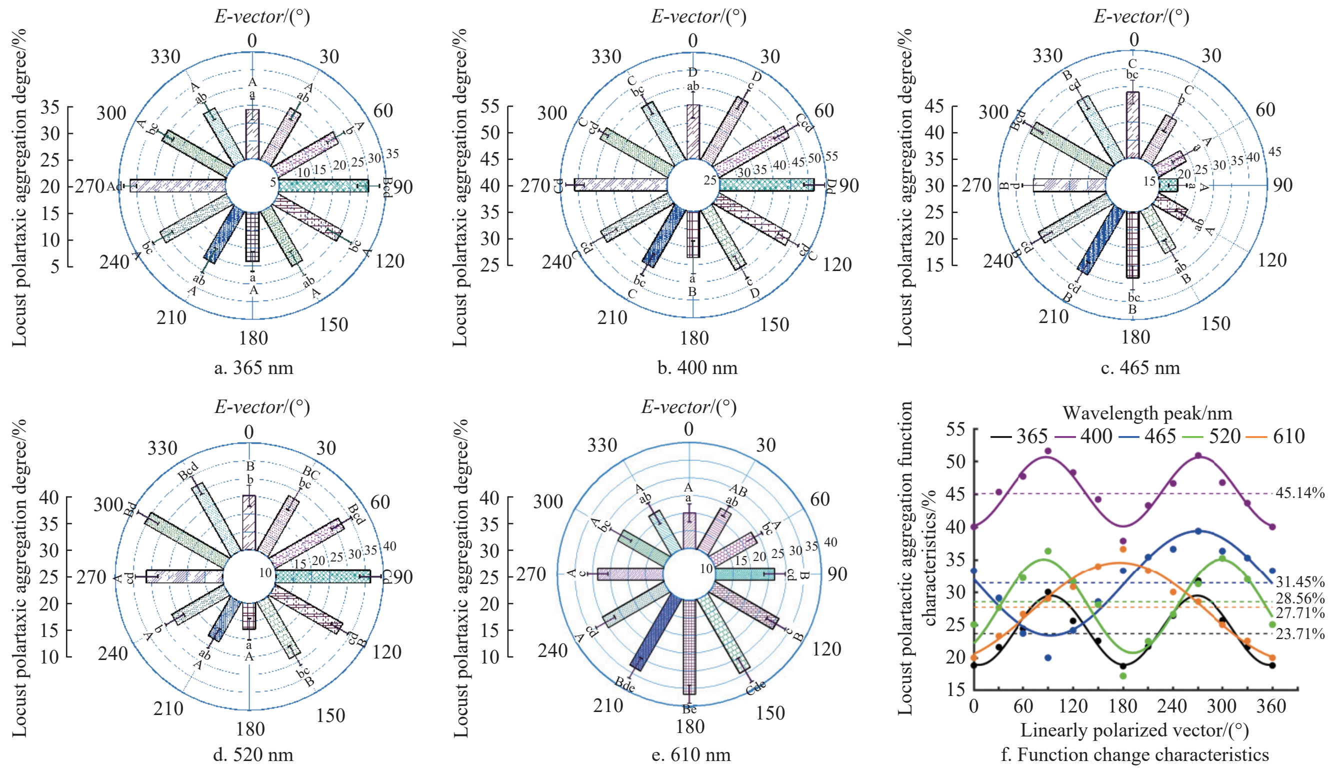


Figure 4 Change characteristics of locusts polartactic aggregation sensitivity to linearly polarized illumination of 100 lx

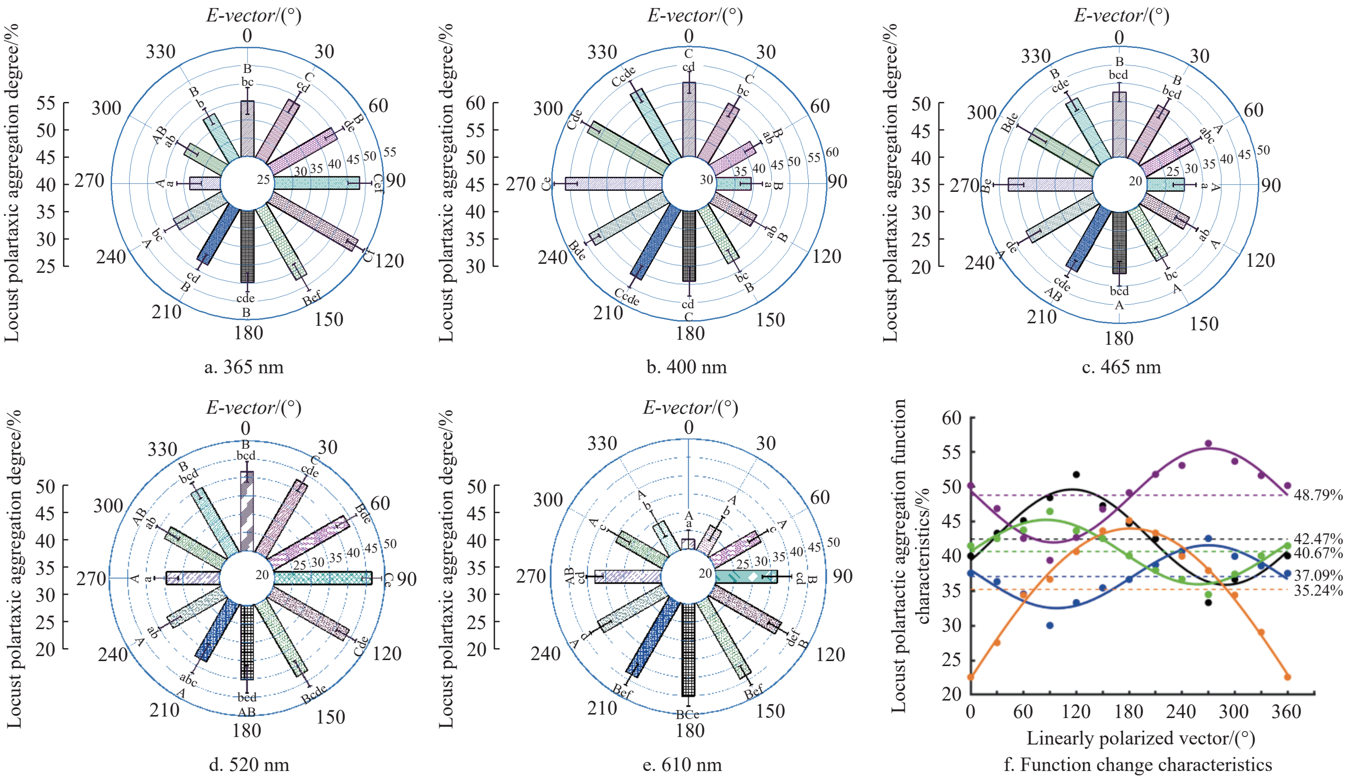


Figure 5 Change characteristics of locusts polartactic aggregation sensitivity to linearly polarized illumination of 1000 lx

When illumination was 100 lx, under 0°-360° vector, variations in the spectrum affected the chord function periodic characteristics of locusts polartactic aggregation response (Figures 4a-4e). Under UV, violet, green, and orange spectra, locusts generated negative cosine aggregation response characteristics and showed vector modulation change sensitivity in one or two periods (Figure 4f). The negative sine aggregation response characteristics induced by blue spectrum presented a change in sensitivity regulated by the vector in one period, meaning that this vector light mode regulated locusts polartactic aggregation under the same spectrum and presented a sensitivity difference in the chord function change. And locusts polartactic aggregation degree induced by UV and blue spectrum at 270°, violet and green spectrum at 90°, orange spectrum at 180° was the best respectively.

Under 1000 lx, compared with 100 lx, when spectrum varied, the continuous 0°-360° vectors modified the change in the chord function periodic characteristics of locusts polartactic aggregation response (Figure 5f). Under blue spectrum, the polartactic aggregation sensitivity induced by 180°-360° vectors was better than that induced by 0°-180°, whereas under UV spectrum (green and violet spectra), the polartactic aggregation sensitivity showed the sine (negative sine) function response characteristics respectively in one period, and the sensitivity induced by 0°-180° vectors was superior (inferior) to that induced by 180°-360°. With spectrum held constant, locusts polartactic aggregation modified the vector sensitivity of the chord function change. And locusts polartactic aggregation degree induced by UV spectrum at 120°, violet and blue spectra at 270°, green spectrum at 90°, orange spectrum at 180° was the best respectively.

With illumination and vector held constant, spectral attributes significantly affected locusts polartactic aggregation sensitivity. When the illumination was 100 lx (Figures 4a-4e), under 150°, 90°, the influence of the spectrum was not the most significant (F=15.725, p=0.000) and the most significant (F=50.849, p=0.000) respectively. When the illumination was 1000 lx (Figures 5a-5e), under 150°, 0° (360°), the influence was not the most significant (F=5.518, p=0.016) and the most significant (F=29.149, p=0.000) respectively.

When illumination increased, with the spectrum held constant, the influence of light intensity on locusts polartactic aggregation chord function response characteristics changed. Under 60°, 180°, 330° of violet spectrum, light intensity significantly inhibited locusts polartactic aggregation sensitivity (p<0.05); under other vectors of different spectra, light intensity enhanced the sensitivity, but the enhancement effect was significantly different. By comparison, under 100 lx, locusts polartactic aggregation sensitivity to violet spectrum was better, whereas when illumination increased to 1000 lx, that to UV spectrum with 60°-150°, as well as that to violet spectrum with other vectors was better, and that to violet spectrum with 270° was optimal.

3.3 Locusts visual trend response characteristics to linearly polarized spectrum vector mode

Under 100 and 1000 lx, when spectrum was constant, the influence of linearly polarized vector on locusts visual trend sensitivity was different (Figures 6a-6e, 100 lx: F_{365nm}=3.407, F_{400nm}=3.610, p<0.01; F_{465nm}=2.530, p<0.05; F_{520nm}=1.090, F_{610nm}=0.918, p>0.05; Figures 7a-7e, 1000 lx: F_{365nm}=4.458, F_{465nm}=3.529, F_{610nm}=3.482, p<0.01; F_{520nm}=2.438, p<0.05; F_{400nm}=2.082, p>0.05), and locusts visual trend intensity presented sine and cosine function change characteristics induced by the continuous vectors (Figure 6f and Figure 7f).

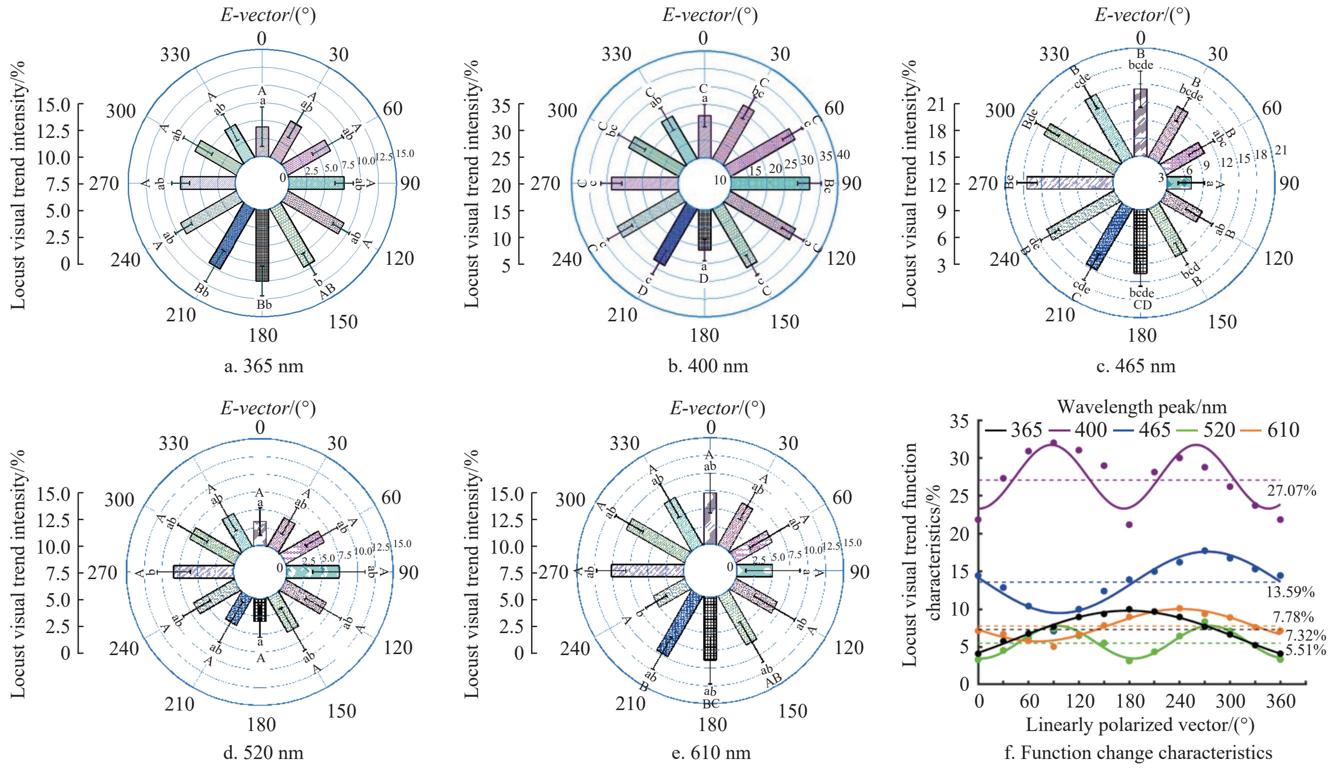


Figure 6 Change characteristics of locusts visual trend sensitivity to linearly polarized illumination of 100 lx

When illumination was 100 lx, under 0°-360° vectors, locusts visual trend intensity presented the chord function periodic response characteristics changed by spectrum (Figure 6f). UV and green spectra made locusts generate negative cosine response features and present a change sensitivity modulated by the vector in one and two periods respectively. Blue and orange spectra made locusts generate negative sine response features and present a change sensitivity regulated by the vector in one period. With the spectrum held constant, the vector mode regulated locusts visual trend intensity and presented a sensitivity variation in the chord function change. And locusts visual trend intensity induced by UV spectrum at 180°, blue and green spectra at 270°, orange spectrum at 240° was the best respectively.

Under 1000 lx, compared with 100 lx, when spectrum varied, the 0°-360° continuous vectors made the chord function periodic characteristics of locusts visual trend response change (Figure 7f). Under UV (violet) spectrum, locusts visual trend sensitivity presented sine change response features induced by vectors in one and two periods with 30° phase angle respectively. Under blue and green (orange) spectra, the sensitivity presented cosine (negative cosine) change response features respectively induced by vectors in two periods, which means that locusts visual trend intensity modified the vector sensitivity change difference of the chord function. And locusts visual trend intensity induced by UV spectrum at 120°, violet, orange, blue and green spectra at 270° was the best respectively.

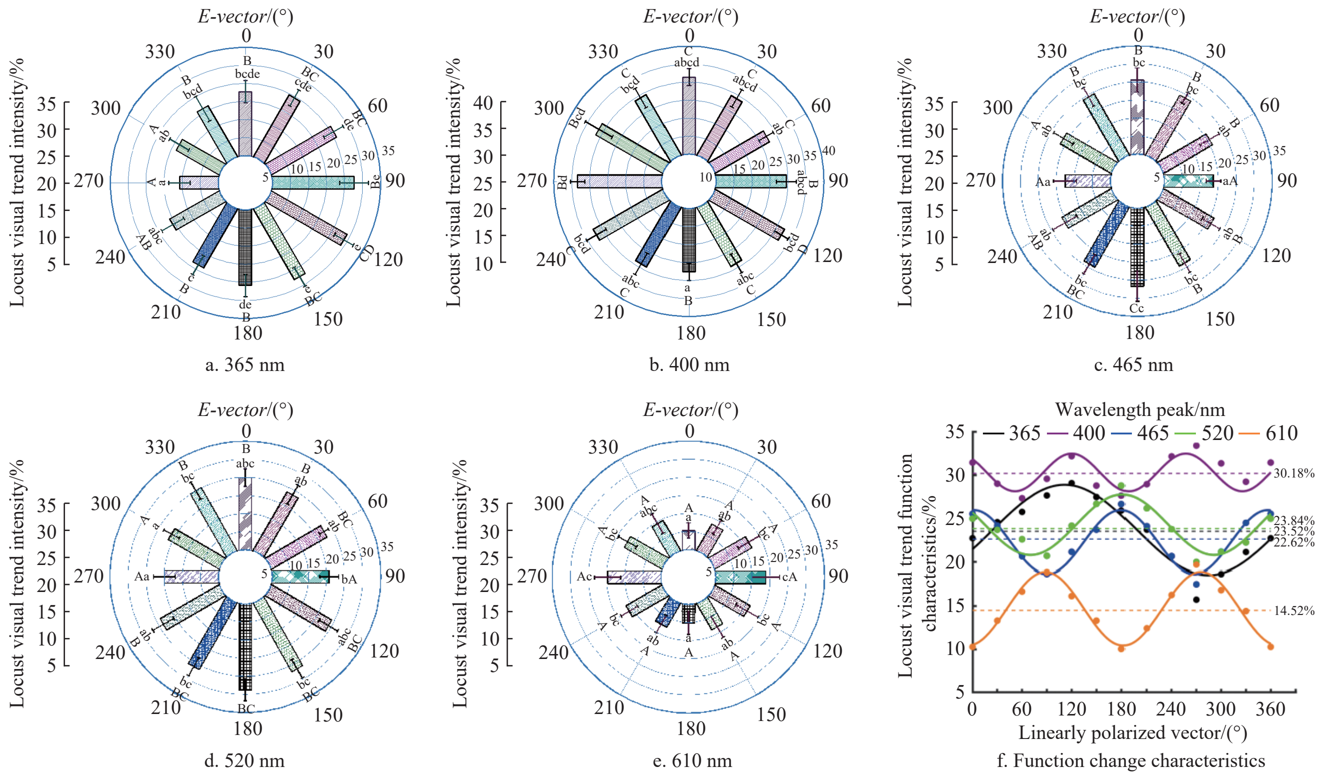


Figure 7 Change characteristics of locusts visual trend sensitivity to linearly polarized illumination of 1000 lx

With illumination and vector held constant, spectral attributes significantly affected locusts visual trend sensitivity. When illumination was 100 lx (Figures 6a-6e), under 180°, 270°, the influence of the spectrum was not the most significant (F=17.255, p=0.000) and the most significant (F=55.818, p=0.000) respectively. When illumination was 1000 lx (Figures 7a-7e), under 60°, 0° (360°), the influence was not the most significant (F=7.141, p=0.006) and the most significant (F=26.039, p=0.000) respectively.

When illumination increased, under the same vector of UV, blue, and green spectra, light intensity significantly enhanced locusts visual trend chord function response characteristics (p<0.05). Under 30°-240° of violet spectrum, the regulatory effect of light intensity was not significant (p>0.05), but under other vectors, the enhancement effect was significant (p<0.05). Under 0° and 180°-210° of orange spectrum, the enhancement effect was not significant (p>0.05), but under other vectors, it was significant (p<0.05). By comparison, under 100 lx, locusts visual trend sensitivity to violet spectrum was better, but when illumination was 1000 lx, that to green spectrum with 180° and that to violet spectrum with other vectors was better, and that to violet spectrum with 270° was optimal.

3.4 Discussion

Researchers have pointed out that locusts receive and respond to the entire polarization mode through many ommatidia arrays and neurons, which form the sensitive directional response of polarization vision, and the sinusoidal polarization reception mode responds to the linearly polarized 0°-180° vector signal of the blue spectrum[16]. However, the vector response mode of locusts polarization vision and their polartactic response to heterogeneous polarized light spectra with different illuminations is not clear. The findings of this study also revealed that locusts polartactic response to 0°-360° continuous vectors exhibited the sine and cosine function change response characteristics caused by vector sensitivity disparity, and when illumination was constant, spectral attributes determined the chord function property of locusts vector periodic response. When spectrum was constant, light intensity regulated the vector sensitivity model of locusts chord function periodic variation. However, when illumination increased, the regulatory effect of linearly polarized light spectrum intensity changed the vector sensitivity model of locusts polartactic response. The regulatory mutability effect of violet light intensity was optimal, and the enhancement effect of orange light intensity on locusts polartactic response sensitivity was the strongest, whereas the regulatory mutability effect of orange light intensity on locusts polartactic aggregation and visual trend sensitivity to the vector model was not the most significant. These results have positive significance for explaining the essence of the specific vision sensitivity of locusts polartactic vision and their polarization vector perception response mechanism and have practical value for the application of polarized light induction in locusts.

Under 0°-360° vectors, the results of this study showed that under violet and blue spectra at 100 lx and under UV spectrum at 1000 lx, the vector periodic phase sensitivity chord function characteristics of locusts polartactic aggregation and visual trend responses did not change, although they were significantly different from locusts usual polartactic response. Under other spectra, the sensitivity characteristic of locusts polartactic response changed significantly, along with the change induced by the UV and orange spectra at 100 lx. However, that induced by the violet and orange spectra at 1000 lx was more significant. When illumination increased (100 lx to1000 lx), under the blue and orange spectra, the vector periodic phase sensitivity chord function response characteristics did not change. Under other spectra, the sensitivity response characteristics changed significantly, and locusts polartactic response presented the specific vector sensitivity response characteristics induced by a linearly polarized spectrum, which was excited by intense linearly polarized light at a long distance, but inhibited at a short distance. These results originated from the opposition characteristic of the polarization sensitivity interneurons in locusts brain, which is the antagonistic output effect of the spectral polarization sensitivity pair in the eyes of DRA to continuous vector direction[17]. The photo-distance control effect of linearly polarized light intensity is consistent with the result that locusts polarization sensitivity neurons tune different polarization vectors to minimize the influence of light intensity on locusts polarization analysis[18].

Meanwhile, other studies have shown that locusts visual response sensitivity is related to the total sensitivity of the locust visual system to light information, the photo-induced vision state change, and the difference in the photo-induced function effect of the heterogeneous light attributes. The perceptual specificity of locusts polarization-sensitive (POL) neurons to the polarization vector and the sensitive recognition of spectral intensity by compound vision cause the driving and controlling effects of different spectrum vector light movement responses to varying[19-22]. Thus, the vector sensitivity response mode difference of the chord function periodic variation of locusts polartactic response originated from the visual sensitivity difference induced by linearly polarized hetero-spectral light intensity and from the specific tuning characteristics of locusts polarization vision to a linearly polarized vector under hetero-spectral light intensity; in contrast, the tuning response period of the chord function reflected the degree of fast and slow modulation of locusts polarization vision to the linearly polarized vector light mode. In locusts polartactic response, the response period under the orange spectrum at 100 lx was the longest, whereas the response period change regulation under the violet spectrum at 1000 lx was the most significant. The chord function tuning property of the vector response reflected the antagonistic driving effect of locusts polarization vision on linearly polarized light spectrum intensity, and when illumination was increased, the enhancement and regulation effect of periodic function change induced by the linearly polarized UV and violet spectrum respectively was the strongest.

Researchers have pointed out that locusts vision is extremely sensitive to polarized light and that the POL neurons have a polarization antagonism characteristic to polarized vector stimulation, generating the alternating excitation and inhibition change characteristic of such vectors[23,24]. The results of this study showed that locusts polartactic response to polarized light vector stimulation showed the regulatory response characteristics of chord function periodic change. The periodic alternation between excitation and inhibition that was peculiar to the chord function response to vector light mode was related to linearly polarized spectrum attribute. The visual sensitivity regulation effect induced by linearly polarized violet and green spectra was the best and the worst respectively. The photo-distance modulation effect of linearly polarized orange spectrum was the strongest, originating from the polarization opposition reaction effect of UV and green polarization photoreceptors of locusts DRA region and the comprehensive function output results of the spectral heterogeneity sensitivity of the ommatidia in locusts visual system[25,26]. This caused a difference between the vector sensitivity mode and the response strength when illumination was constant, but spectrum varied. The most significant effects were the photo-distance mutability effect induced by UV and orange spectra at 100 lx and the effect induced by blue, green, and orange spectra at 1000 lx. Once the illuminance was increased, the luminance regulatory function caused locusts spectrum vector sensitivity mode to change, displaying the sensitive effect deviation of chord function tenability, which arises from the tuning processing difference of bilateral POL neurons with the same morphology, but distinct physiology types in locusts DRA region to vector distribution mode[27-29]. The spectral photo-induced vector sensitivity mode showed continuous variation in the chord function vector; the regulatory effect of linearly polarized orange and violet light intensity on the vector sensitivity change was not the most significant and the most significant respectively.

4 Conclusions

When a particular group of locusts was exposed to linearly polarized illumination, the vector sensitivity response discrepancy characteristics of specific chord function periodic tenability were observed. This was related to the vector sensitivity mode caused by linearly polarized spectrum attributes; the visual sensitivity regulation impact of linearly polarized violet and green spectra was the best. The photo-distance modulation effect of linearly polarized orange spectrum was the strongest. When illumination increased, linearly polarized light spectrum intensity attribute caused the linearly polarized vector sensitivity response model (response period, chord function property) for locusts to change in a specific manner. The regulatory mutability effect of linearly polarized violet spectrum light intensity was optimal, whereas that of linearly polarized orange spectrum light intensity was not remarkable. Meanwhile, locusts polartactic sensitivity induced by linearly polarized violet spectrum with a 300° vector was strongest at 100 lx, whereas that with a 240° vector at 1000 lx was the strongest. Locusts polartactic aggregation and visual trend sensitivity induced by linearly polarized violet spectrum with a 90° vector were strongest at 100 lx, whereas at 1000 lx, those induced with a 270° vector were the strongest. However, the vector sensitivity intensity patterns of locusts polartactic response to different spectra were significantly different. Thus, using the optimal vector of locusts visual sensitivity to linear violet spectrum, under the photo-distance regulation function of linearly polarized light intensity, the polartactic induction impact of locusts can be successfully improved by combining the flexible tuning stimulation function of the ideal vector with locusts visual sensitivity to linearly polarized orange spectrum.

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[References]

[1] Zhang L, Lecoq M, Latchininsky A, Hunter D. Locust and grasshopper management. Annu. Rev. Entomol., 2019; 64: 15–34.

[2] Kim K N, Huang Q Y, Lei C L. Advances in insect phototaxis and application to pest management: A review. Pest. Manag. Sci., 2019; 7(28): 118–126.

[3] Liu Q H, Gao X G, Zhou G T, Zhou Q. Influence of polarized vector mode of polarization spectrum light state on the polarized response effect of *Locusta migratoria*. Acta Agriculturae Zhejiangensis, 2022; 34(8): 1762–1771.

[4] Bech M, Homberg U, Pfeiffer K. Receptive fields of locust brain neurons are matched to polarization patterns of the sky. Current Biology, 2014; 24(18): 2124–2129.

[5] Mouritsen H. Long-distance navigation and magnetoreception in migratory animals. Nature, 2018; 558(8): 50–59.

[6] Yang X F, Wei G S, Ma A H, Ran H F, Li J C, Liu X X. Research advances in ultraviolet vision in insects. Journal of Plant Protection, 2022; 49(1): 131–145.

[7] Liu Q H, Jiang Y L, Miao J, Gong Z J, Li T, Duan Y, Wu Y Q. Photoreceptive reaction spectrum effect and phototactic activity intensity of locusts visual display characteristics stimulated by spectral light. Int J Agric & Biol Eng, 2021; 14(2): 19–25.

[8] Jundi B, Homberg U. Receptive field properties and intensity response functions of polarization-sensitive neurons of the optic tubercle in gregarious and solitarious locusts. J Neurophysiol, 2012; 108: 1695–1710.

[9] Horváth G. Polarized light and polarization vision in animal sciences. Vision Research, 2014; 8(4): 61–70.

[10] Schmeling F, Tegtmeier J, Kinoshita M, Homberg U. Photoreceptor projections and receptive fields in the dorsal rim area and main retina of the locust eye. J Comp Physiol A, 2015; 202: 585–599.

[11] Kinoshita M, Stewart F J. Retinal organization and visual abilities for flower foraging in swallowtail butterflies. Current Opinion in Insect Science, 2020; 42: 76–83.

[12] Farkas A, D Száz Á E, Barta A, Mészáros Á, Hegedüs R, et al. Mayflies are least attracted to vertical polarization: a polarotactic reaction helping to avoid unsuitable habitats. Physiology & Behavior, 2016; 5: 219–227.

[13] Michiyo K, Keram P, Homberg U. Spectral properties of identified polarized-light sensitive interneurons in the brain of the desert locust Schistocerca gregaria. Journal of Experimental Biology, 2007; 210(8): 1350–1361.

[14] Liu Q H, Jiang Y L, Zhou Q. Spectral vision acuity reaction detection of phototactic response of locusta migratoria to LED light signal. Transactions of the CSAM, 2016; 28(2): 338–344.

[15] Krapp H G. Sensory integration: neuronal filters for polarized light patterns. Current Biology, 2014; 24(18): 840–841.

[16] Liu Q H, Jiang Y L, Miao J, Gong Z J, Li T, Duan Y, Wu Y Q. Changes in the visual response and thoracic temperature of *Locusta migratoria manilensis* stimulated by LED spectral light. Pakistan Journal of Zoology, 2020; 52(1): 355–362.

[17] Heinze S, Homberg U. Maplike representation of celestial E-vector orientations in the brain of an insect. Science, 2007; 315: 995–997.

[18] Zou S G, Liu T, Ma Y C, Zhang P C, Liu Q H. Influences of DRA and non-DRA vision on the visual responses of locusts stimulated by linearly polarized and unpolarized lights. Int J Agric & Biol Eng, 2023; 16(3): 15–22.

[19] Liu Q H, Jiang Y L, Miao J, Gong Z G, Li T, Duan Y, et al. Regulation of visual sensitivity responses in locusts stimulated by different spectral lights. Pakistan J. Zool., 2019; 51(6): 2245–2255.

[20] Liu Q H, Jiang Y L, Miao J, Gong Z J, Li T, Duan Y, Wu Y Q. Study on the Visual Response of *Frankliniella occidentalis* to Ultra Violet-Visible Spectroscopy with Different Wavelength Ranges. Journal of Biobased Materials and Bioenergy, 2021; 15(4): 497–503.

[21] Schmeling F, Wakakuwa M, Tegtmeier J, Kinoshita M, Bockhirst T, Arikawa K, et al. Opsin expression, physiological characterization and identification of photoreceptor cells in the dorsal rim area and main retina of the desert locust, Schistocerca gregaria. Journal of Experimental Biology, 2014; 217(19): 3557–3568.

[22] Liu Q H, Wang X F, Zhao M F, Liu T. Synergistic influence of the capture effect of western flower thrips (*Frankliniella occidentalis*) induced by proportional yellow-green light in the greenhouse. Int J Agric & Biol Eng, 2023; 16(1): 88–94.

[23] Beck M, Althaus V, Pegel U, Homberg U. Neurons sensitive to non-celestial polarized light in the brain of the desert locust. Comparative Physiology A, 2023; 209: 907–928.

[24] Mappes M, Homberg U. Behavioral analysis of polarization vision in tethered flying locusts. Journal of Comparative Physiology A Neuroethology Sensory Neural & Behavioral Physiology, 2004; 190(1): 61–68.

[25] Liu Q H, Zhao M Q, Miao J, Fu G C, Wu Y Q. Influences of yellow and green lights on the visual response of western flower thrips and field verification. Int J Agric & Biol Eng, 2022; 15(4): 49–56.

[26] Hu L M, Gao L J, Fan Z G, Chen Z M, Zhang Y Y. Study on polarization light navigation method of neural processing mechanism of *Cataglyphis*. Journal of Electronic Measurement and Instrument, 2013; 27(8): 703–708.

[27] Dreyer D, Frost B, Mouritsen H, Adrien Lefèvre, Warrant E. A guide for using flight simulators to study the sensory basis of long-distance migration in insects. Frontiers in Behavioral Neuroscience, 2021; 15: 678–936.

[28] Liu Q H, Wu Y Q, Zhao M F. Photo-induced visual response of western flower thrips attracted and repulsed by their phobotaxis spectrum light. Int J Agric & Biol Eng, 2022; 15(2): 48–57.

[29] Hensgen R, Zittrell F, Pfeifer K, Homberg U. Performance of polarization-sensitive neurons of the locust central complex at diferent degrees of polarization. J Comp Physiol A, 2022; 208: 387–403.