Investigation of locust polartactic aggregation sensitivity to linearly polarized spectrum vector light in breeding sheds

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Abstract: This paper aimed to verify the validity of the polartactic effect induced in locusts by linearly polarized light, determine locust polartactic sensitivity characteristics, and develop a locust polarization induction light source by using manufactured violet, orange, and linearly polarized light sources. The phototactic and polartactic aggregation sensitivity of East Asian migratory locust populations raised in sheds was also investigated. The objective was to analyze the difference between locust phototactic and polartactic aggregation sensitivity and between locust polartactic aggregation response features and to discuss the polarization function mechanism and the influencing factors of the locust polartactic aggregation response. The results showed that the long- and short-spectrum properties of the violet and orange spectra affected the difference between locust phototactic and polartactic aggregation sensitivity. However, no matter what kind of spectrum was used, the polartactic aggregation effect induced in locusts by linearly polarized 0°, 90°, 180°, and 270° vector light was superior to the phototactic aggregation effect, and linearly polarized spectrum attributes did not affect the photo-induced effects caused by the sequential sensitivity vector (270°, 180°, 0°, 90°), whereas the regulation enhancement effect of light time on the sensitivity difference was related to spectral attributes. As light time was advanced to 5:30, locust polartactic aggregation sensitivity became the strongest. Spectral attributes, light time, temperature, and humidity factors in locust habitat did not change the vector sensitivity mode of locust polartactic aggregation and the vector periodic tuning response characteristics with cosine features. However, spectral attributes affected locust polartactic aggregation sensitivity, and the sensitivity to violet spectrum was superior to orange spectrum at a given light time, whereas the enhancement effect of orange spectrum with advancing light time was stronger than that of violet spectrum. The findings provide theoretical support for characterizing the specific sensitivity essence of locust phototactic and polartactic vision and determining the locust polarized spectrum induction mechanism.

Keywords: *Locusta migratoria manilensis*, linearly polarized spectrum, linearly polarized vector light, polartactic aggregation sensitivity, investigation in breeding sheds

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1 Introduction

Locust plagues are one of the most frequent and devastating pest outbreaks in agricultural settings worldwide, posing a serious threat to agriculture, animal husbandry, the ecological environment, and the agricultural economy. However, there are no effective prevention and control measures against locust plagues, leading to an over-reliance on pesticide control, which threatens the safety of agricultural production. Compared with chemical, biological, and agricultural control[1], the photo-physical locust control method depends on precision equipment and intelligent devices, which fit into the modern agricultural green pest control concept and are of great significance for ensuring food safety and human health. Unlike the successful application of phototaxis in controlling *Lepidoptera* pests, locust visual threshold tolerance induced by light intensity and the photo-physiological induction response threshold restrict the application of photo-physical control technology[2]. At present, studies on orientation of insects such as desert ants, bees, dung beetles, monarch butterflies, and beetles using sky polarization patterns[3] have revealed the natural essence of insect polartactic navigation. Further research has indicated that[4] locust polartactic navigation depends on a polarized light vector, which plays a decisive role in their polartactic orientation; its spectral properties affect the polartactic effect induced in locusts by the polarized light state. Therefore, studying the characteristics of locust polartactic aggregation sensitivity to polarized spectrum vector light, exploring their polartactic aggregation response patterns, and further determining the technical characteristics of their polartactic induction light field will identify polartactic induction application methods for locust control. This has theoretical significance for studying the polartactic properties of pests and also has practical value for polarized light induction application to pest control, which is conducive to the development of green and intelligent pest control technology systems for modern agriculture.

The natural polarization properties of skylight and the polarization phenomena of natural landscapes have led certain insects to develop the ability to analyze and receive polarized

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light[5], enabling them to use polarized light for orientation. In recent years, studies have focused on topics such as the locust polarization vision pathway, the morphological characteristics of their DRA (dorsal rim area) ommatidia that perceives polarized light, the structure and function of polarization-sensitive neuro-tissue, the specific tuning mechanism of neurons perceiving polarized light, the intrinsic expression of the CX (central complex) on polarized vector patterns, the physiological response characteristics induced by polarized light, the navigational orientation roles of the polarized and directional compasses in CX, the internal modulation mechanism of locust compound vision that perceives polarized and non-polarized information, the DoP (degree of polarization) threshold of POL-neurons (polarization-sensitive neurons) encoding AoP (angle of polarization), and the characteristics of the locust polarization opposition response[6-8]. This work provides meaningful references for using polarized light for physical control of locusts and also offers useful references for the study of locust polartactic behavior characteristics and the inductive function mechanism of polarized light in locusts. Researches have shown that[9,10] the light detected by the DRA of the locust compound eye has high intensity and optimal spectral composition or optimal E-vector orientation, and that the response of the DRA to the E-vector depends on the quantity of photons absorbed and plays a crucial role in polarization vision. Color light gradient and light polarization mode affect locust spatial orientation ability, and locusts rely on neurons sensitive to both polarized and non-polarized light, combined with the color-opponent and spatial-opponent response characteristics of LoTu1 and TuTu1 neurons, to realize the function that orients them to polarized light[11,12]. In terms of light field properties, the perceptual ability of locust polarization vision is related to spectral light characteristics, meaning that spectral and polarized light have different effects on the sensitivity of their polarization vision[13].

Meanwhile, investigation of the polartactic effect on locusts shows that their polartactic response is related to the polarization spectrum and the polarized light state and that locust orientation, preferential, and polartaxis sensitivity to specific polarization light fields means that the photoelectric stimulation mode of the polarized spectrum can effectively reset the locust polartactic response to the sensitivity vector[14,15]. Ambient polarized light affects insect biological behavior in the environment, but the polarization compass function in the locust CX differs from the function of locust polartactic behavior revealed by stimulation of linearly polarized light[16]. Current studies have mostly focused on indoor measurements of phototactic and polartactic response effects on locusts, although the lack of studies on the sensitivity difference between phototaxis and polartaxis in natural habitats and on the polartactic aggregation response sensitivity and characteristics induced in locusts by the linearly polarized spectrum vector mode restricts the application of polarized light induction to locusts.

This study, combining locust phototactic sensitivity to violet and orange monochromatic spectra with *Locusta migratoria manilensis*, used developed violet and orange single light sources and linearly polarized light sources with different polarization vectors to test locust phototactic aggregation sensitivity to spectral light and polartactic aggregation sensitivity to linearly polarized vector light in breeding sheds. The sensitivity differences between phototactic and polartactic aggregation induced by non-polarized and linearly polarized light and the influence of locust habitat on polartactic aggregation response features were analyzed to determine the vector mode and the response characteristics of locust polartactic aggregation sensitivity in natural habitats and to discuss the influencing factors and the sensitivity mechanism of their polartactic aggregation. These results can contribute to developing intelligently regulated polarization spectrum induction lamps for locusts and can provide a fundamental understanding of polarization orientation behavior mechanisms in these important pest species.

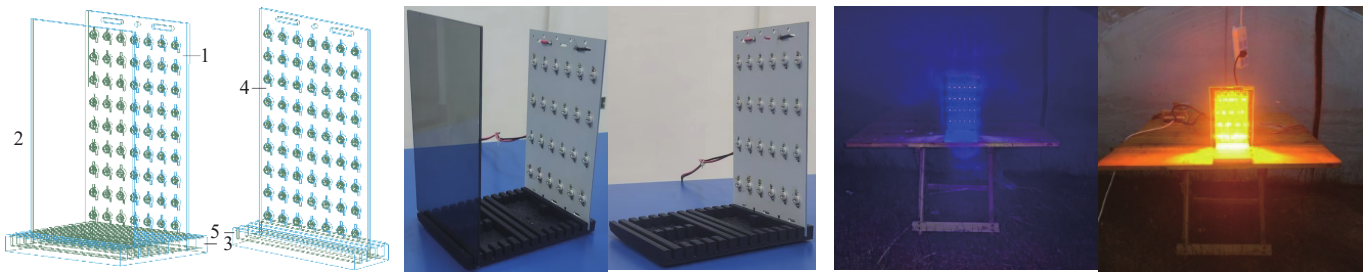
2 Materials and methods

2.1 Test insects

The experiments on locust polartactic aggregation were conducted in a screen window breeding shed (length×width×height=30 m×8 m×4 m) at the locust breeding center in Fan County, Puyang, Henan, China (35.80°N, 115.49°E) from June 1–30, 2024. The test insects were healthy adults of *Locusta migratoria manilensis*, artificially bred for multiple generations and emerging within one week. The average density of the test insects in the experimental shed was 260 locusts/m^2, and their growth was generally uniform.

2.2 Experimental light source and its arrangement in shed

To determine locust polartactic aggregation sensitivity to linearly polarized light, linearly polarized spectrum light sources and their contrast light sources were developed (Figures 1a and 1b). Two spectral wavelengths were used: violet (peak wavelength: 405 nm) and orange (peak wavelength: 610 nm) (Figure 1c).



a. Design model drawing b. Physical photograph of the setup c. Experimental light spectra used for testing

1. Spectral light source; 2. Linear polarizer; 3. Support holding the combined assembly of the spectral light source (1) and the linear polarizer (2). The linear polarizer is placed directly in front of the spectral light source, and both are fixed together on support 3; 4. Contrast light source with the same spectrum (no polarizer); 5. Support holding only the contrast light source (4). Relationship between support 3 and support 5: Support 3 holds the polarized light source assembly (spectral light source + polarizer), while support 5 holds the unpolarized contrast light source (spectral light source only). The two supports are independent and positioned side by side at the front of each breeding shed, allowing simultaneous testing under identical conditions. In the physical photograph (Figure 1b), the left support (support 3) holds the spectral light source with the linear polarizer attached to its front, while the right support (support 5) holds the contrast light source without a polarizer.

Figure 1 Lamps and their spectra for use in locust breeding shed

3W light-emitting diodes (LEDs, Hongtai Electronics Co., Ltd., Shenzhen, China) were mounted on a 2 mm-thick aluminum substrate (length×width = 200 mm×120 mm) to create spectral and contrast light sources with a 9×7 array configuration (seven violet and seven orange light sources). These light sources were fixed on supports and powered by a 12 V DC power supply. A linear polarizer (3 mm thick, length×width = 210 mm×130 mm, light transmittance: 50%, polarization rate: 95%; PL-CIR HOYA, Japan) was placed in front of the spectral light source and fixed to emit linearly polarized light. Contrast light sources were set up similarly, but without the polarizer. Thirteen linear polarizers with vectors at 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, 330°, and 360° (0°) were used. These polarizers were paired with the corresponding spectral light sources and their contrast light sources (Figure 2) to produce linearly polarized vector light and spectral light. The rated illumination of these light sources, calibrated with an illuminometer (Model XRP-3000; resolution 0.01 lx; Shenzhen Eurasia Precision Instrument Co., Ltd., Shenzhen, China), was standardized to uniform levels for testing (violet, 30,000 lx; orange, 300 000 lx) with equivalent light energy (150 mW/cm^2).

To minimize the influence of heterogeneous light on locust biological responses, seven breeding sheds were selected for the experiment (Figure 2, labeled as Ⅰ–Ⅶ, average density: 260 locusts/m^2). For each breeding shed, six linear polarizers with vectors ranging from 0° to 150° were paired with six light sources to form six linearly polarized light sources and one contrast light source (Group 1). These light sources were positioned at the front end of each breeding shed (Ⅰ–Ⅶ) for the experiment (Figure 3). Over 1-7 d, the six linearly polarized light sources and the contrast light source were rotated through the seven breeding sheds to complete the experiment. Subsequently, seven linear polarizers with vectors ranging from 180° to 360° (0°) were paired with seven light sources to form another set of linearly polarized light sources (Group 2). The seven light sources were rotated through the breeding sheds (Ⅰ–Ⅶ) over another 7-d period, completing seven trials per light source.

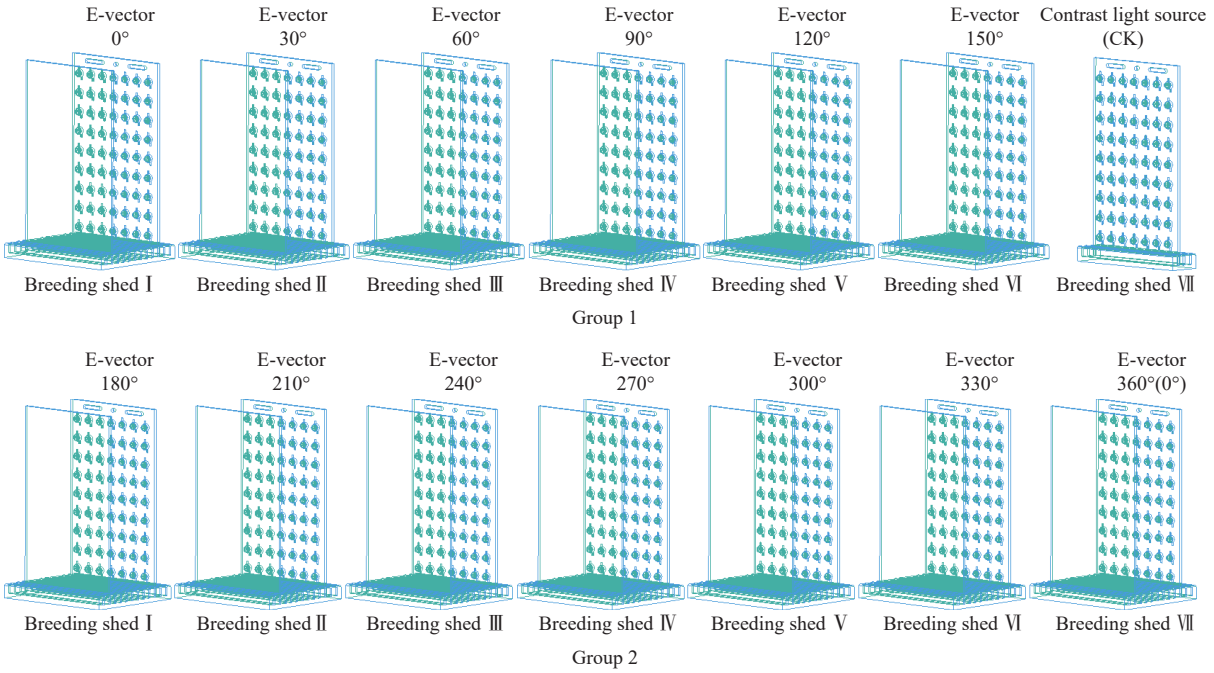


Figure 2 Light source arrangement in locust breeding sheds

Figure 3 Locust polartactic aggregation effect induced by linearly polarized light source

2.3 Experimental methods and data computation

Before each day's experiment, based on the vegetation and locust distribution density in the seven breeding sheds, one type of light source was placed at the front end of each shed (200-500 mm

above the ground for effective attraction, Figure 3). The vegetation in the breeding sheds consisted primarily of weeds including *Equisetum ramosissimum* (Equisetaceae), *Amaranthus retroflexus* and *Amaranthus spinosus* (Amaranthaceae), and *Setaria viridis* (Poaceae), with no cultivated crops present. The weed height was approximately 30-50 cm, and the vegetation coverage was approximately 20%-30% across the seven sheds. Areas with dense vegetation were avoided during light source placement to prevent confounding effects on locust distribution.

A marker line was set 1 m in front of the light source, extending across the full width (8 m) of the breeding shed front, thus defining an 8 m^2 attraction zone (8 m×1 m). The number of locusts within this zone was recorded at each observation time point. Under the same spectrum, for each experimental layout of the seven light sources of Group 1 in breeding sheds Ⅰ–Ⅶ, each light source was turned on at 19:30 and off at 5:30 the next day. Locust numbers within the marker line were counted at 19:30, 21:30, 23:30, 1:30, 3:30, and 5:30. This rotation of light sources continued daily in the breeding sheds for seven days, and each light source underwent a total of seven trials. This same method was applied to seven light sources with the same wavelength as Group 2 in sheds Ⅰ–Ⅶ. Under the violet and orange spectra, experiments were conducted in breeding sheds Ⅰ–Ⅶ using the same method for the seven light sources of Group 1 and Group 2 respectively.

For each violet and orange light source, the average locust density ρ (locusts/m^2) within the 8 m^2 marked area (8 m×1 m; see marker line in Figure 3) at the front of each breeding shed was calculated as the mean number of locusts recorded over seven trials divided by 8 (ρ = average locust numbers in seven trials/8 m^2). Then, to exclude the confounding effect of the original background density (260 locusts/m^2), the differential value (D-value) was calculated as D-value = ρ – 260 locusts/m^2. This D-value represents the net locust aggregation effect induced by the light source. For linearly polarized vector light, the locust polartactic aggregation density (ρ_1) was used to reflect the polartactic aggregation effect, whereas the locust phototactic aggregation density (ρ_2) was used to reflect the phototactic aggregation effect induced by spectral light. The differential value (D-value = ρ_1 – ρ_2 locusts/m^2) between polartactic and phototactic aggregation densities was computed to analyze the sensitivity difference of the polartactic and phototactic aggregation effect in locusts.

Although vegetation was present in the breeding sheds, the consistent placement of light sources away from densely vegetated areas and the rotation of light sources across sheds ensured that any potential bias from vegetation was evenly distributed across treatments.

Based on the results, assuming that the locusts presented similar polartactic aggregation characteristics to different linearly polarized vector lights, the mean polartactic aggregation density at different time periods from 19:30 to 5:30 was calculated to analyze the sensitivity mode and the change characteristics of the locust polartactic aggregation response to linearly polarized vector light. In addition, based on a comparison of results for locust polartactic and phototactic aggregation effects, the polartactic aggregation densities induced by linearly polarized light at 0°, 90°, 180°, and 270° were used to assess the impact of nocturnal habitat on polartactic aggregation.

2.4 Data analysis

Experimental data were statistically analyzed and correlated using SPSS 16.0 (SPSS, Inc., Chicago, IL, USA) and Excel for Windows, with further analysis conducted using custom functions written in MATLAB (Version 2021a, The MathWorks, Natick, MA, USA). Under the same spectrum, one-way ANOVA of the general linear model was used to analyze the difference in polartactic aggregation effects induced by light with the same time but different vectors, lights at different times but with the same vector, and the difference in D-values of locust polartactic and phototactic aggregation density. For multiple comparisons, the least significant difference (LSD) test was used at p=0.05, and at p=0.05, the Student's t-test was used to analyze the significance of differences among different spectrum treatments under the same vector and time. The results are shown as the mean ± standard error (SE).

3 Results and discussion

3.1 Comparison of D-values of locust polartactic and phototactic aggregation effect

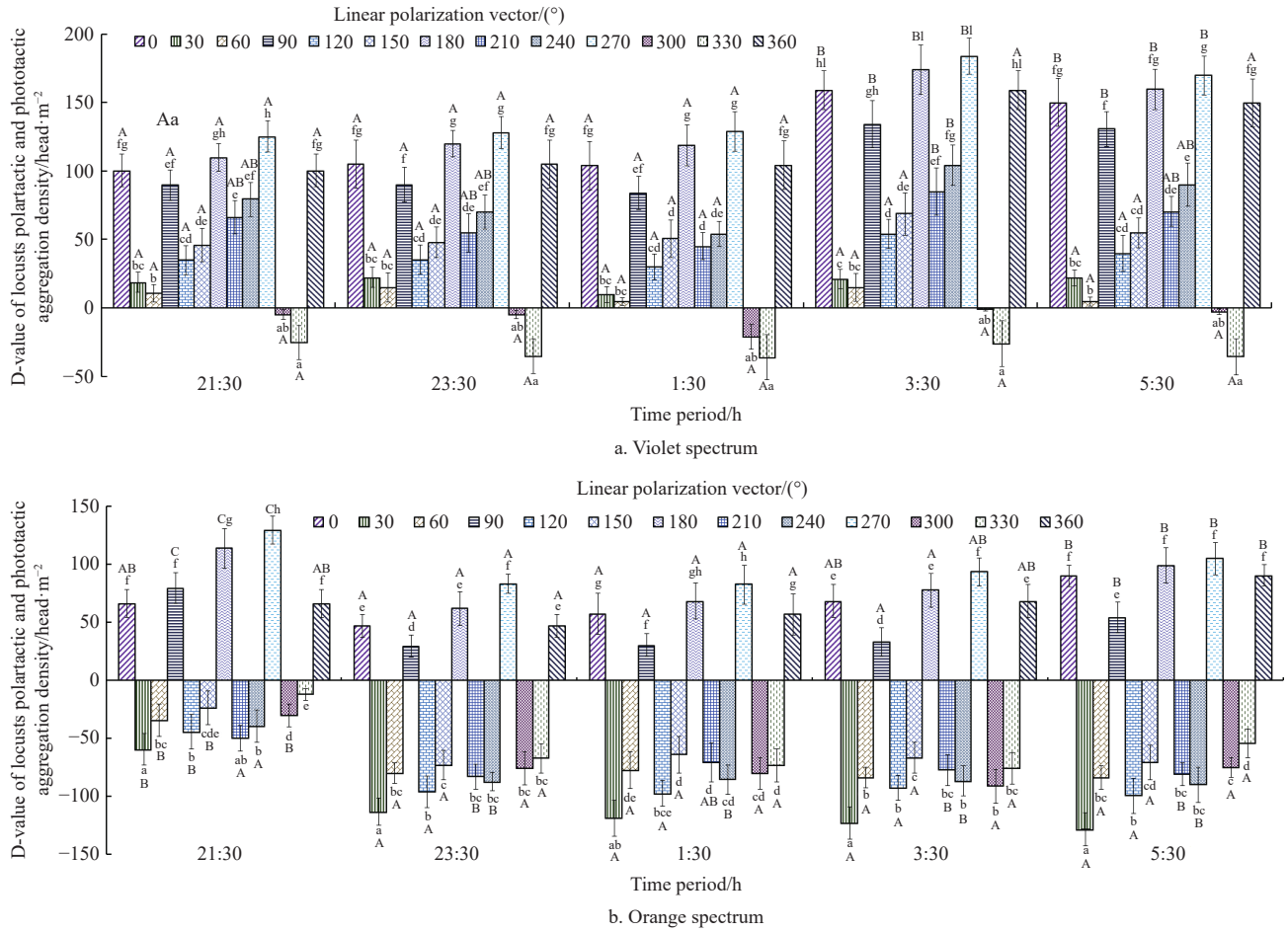
Under the same light time at night, linearly polarized vector mode significantly affected the sensitivity differences in locust polartactic and phototactic aggregation effects, which were related to spectral properties (Figure 4). Under violet spectrum, when light time was set to 3:30 and 21:30, the impact of vector mode was the most pronounced at 3:30 (F=270.538, p<0.001) and the least pronounced at 21:30 (F=2.596, p<0.05). Conversely, under orange spectrum, the vector mode had the most significant effect at 3:30 (F=276.435, p<0.001) and the least at 1:30 (F=97.684, p<0.001). For violet spectrum, at the 300° and 330° vectors, the locust polartactic aggregation effect was worse than the phototactic aggregation effect, but it was better at other vectors. In particular, the D-value was more remarkable at 0° (360°), 90°, 180°, and 270°, with its most and second-most significant values at 270° and 180° respectively. Under orange spectrum, at 0° (360°), 90°, 180°, and 270°, the locust polartactic aggregation effect was more pronounced than the phototactic aggregation effect, with the most and second-most significant D-values at 270° and 180° respectively and worse D-values at other vectors.

Under the same linearly polarized vector with different spectra, the impact of light time on the locust polartactic and phototactic aggregation effects varied. Under violet spectrum, at 180° and 270°, the influence was significant ($F_{180°}$=4.048, p=0.033; $F_{270°}$=5.329, p=0.015), whereas at other vectors, the influence was not significant (p>0.05), with the least and second-least significant D-values at 60° (F=0.023, p=0.999) and 30° (F=0.042, p=0.996) respectively. Under orange spectrum, the influence was significant (p<0.05), with the most and the least significant D-values at 240° (F=35.694, p<0.001) and 210° (F=3.684, p=0.043) respectively.

Comparatively, at 0° (360°), 90°, 180°, and 270°, the sensitivity differences in the polartactic and phototactic aggregation effects were significant, particularly at 270°, followed by 180° under the same light time. The difference was most pronounced at 270° when the light time was set to 3:30 for linearly polarized violet light and to 21:30 for linearly polarized orange light.

3.2 Polartactic aggregation effect induced in locusts by linearly polarized light

Under constant light time, linearly polarized vector mode significantly impacted the polartactic aggregation effect in locusts, with the influence degree related to spectral attributes (Tables 1 and 2). For violet spectrum, the influence of vector mode was most significant at 5:30 (F=8.656, p<0.001), followed by 3:30 (F=7.054, p<0.001), and was least significant at 1:30 (F=3.162, p<0.01), followed by 23:30 (F=4.137, p<0.01) (Table 1). For orange spectrum, the influence was most significant at 5:30 (F=18.448, p<0.001), followed by 21:30 (F=15.764, p<0.001), and was least significant at 23:30 (F=11.335, p<0.001), followed by 1:30 (F=11.820, p<0.001) (Table 2).



Notes: Under different vectors with the same light time in a, b, 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 vectors with different light times, 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).

Figure 4 Comparison of the D-values of locust polartactic and phototactic aggregation effects under different light spectra

Table 1 Locusts polartactic aggregation effect induced by linearly polarized violet light

Data title		Locusts polartactic aggregation density/head/m²					*F*-value	*p*-value
Time/h		21:30	23:30	1:30	3:30	5:30	*df*=4	
Vector/(°)	0	470.0±40.00ghA	545.0±33.00gB	625.0±33.30efC	710.0±36.19ghD	730.0±40.00hD	15.211	<0.01
	30	390.0±22.91bcdA	462.0±36.39bcdeB	531.0±29.74bcC	572.0±31.43bcCD	602.0±35.03bcdD	19.511	<0.01
	60	381.0±38.51abcdA	455.0±40.51bcdeB	526.0±34.08abcC	566.0±36.17abcCD	585.0±32.72abcD	24.230	<0.01
	90	460.0±26.46fghA	530.0±39.26fgB	605.0±36.16deC	685.0±32.72fgD	711.0±39.55ghD	18.879	<0.01
	120	405.0±32.79cdeA	475.0±25.00bcdeA	551.0±38.51cB	605.0±37.75cdC	620.0±28.87cdeD	27.446	<0.001
	150	416.0±32.19defA	488.0±38.00cdefB	572.0±36.00cdC	620.0±26.46deCD	635.0±35.00defD	14.576	<0.001
	180	480.0±40.00ghA	560.0±30.00gB	640.0±26.46efC	725.0±30.41ghD	740.0±30.00hD	33.139	<0.001
	210	436.0±37.59efA	495.0±25.98defB	566.0±33.51cdC	636.0±36.51deD	650.0±35.00efD	27.700	<0.001
	240	450.0±30.00fgA	510.0±20.00efgB	575.0±40.00cdC	655.0±35.00efD	670.0±40.00fgD	18.541	<0.001
	270	495.0±34.64hA	568.0±32.00gB	650.0±30.00fB	735.0±35.00hC	750.0±30.00hC	24.070	<0.001
	300	365.0±35.00abcA	435.0±35.00abA	500.0±36.19abC	560.0±28.87abD	577.0±37.51abcD	19.752	<0.01
	330	345.0±25.21aA	405.0±32.72aB	485.0±40.00aC	525.0±35.00aCD	545.0±20.00aD	10.322	<0.001
	360	470.0±40.00ghA	545.0±33.00gB	625.0±33.30efC	710.0±36.19ghD	730.0±30.00hD	15.211	<0.01
F-value	*df*=12	4.737	4.137	3.162	7.054	8.656		
p-value		<0.001	<0.01	<0.01	<0.001	<0.001		

Note: On the same row, under the same vector with different light time, the same capital letters indicate no significant difference (p>0.05), and different capital letters indicate significant difference (p<0.05); while on the same line, under the same light time with different vectors, the same small letters indicate no significant difference (p>0.05), and different small letters indicate significant difference (p<0.05). Table 2 is the same as Table 1.

Under the same vector, light time significantly affected the polartactic aggregation effect in locusts, but the effect varied with different spectra. For violet spectrum, the most significant effect was observed at 180° (F=36.284, p<0.001), followed by 240° (F=23.076, p<0.001), and the least significant effect at 300° (F=9.167, p<0.01), followed by 60° (F=10.040, p<0.01). For orange spectrum, the most significant effect was observed at 180° (F=23.186, p<0.001), followed by 300° (F=19.039, p<0.001), and the least significant effect at 120° (F=10.468, p<0.01), followed by 240° (F=10.918, p<0.01). The polartactic aggregation effect

increased with advancing light time, but between 3:30 and 5:30, with linearly polarized violet light, it showed no significant differences (p>0.05), whereas linearly polarized orange light showed significant differences (p<0.05).

Table 2 Locusts polartactic aggregation effect induced by linearly polarized orange light

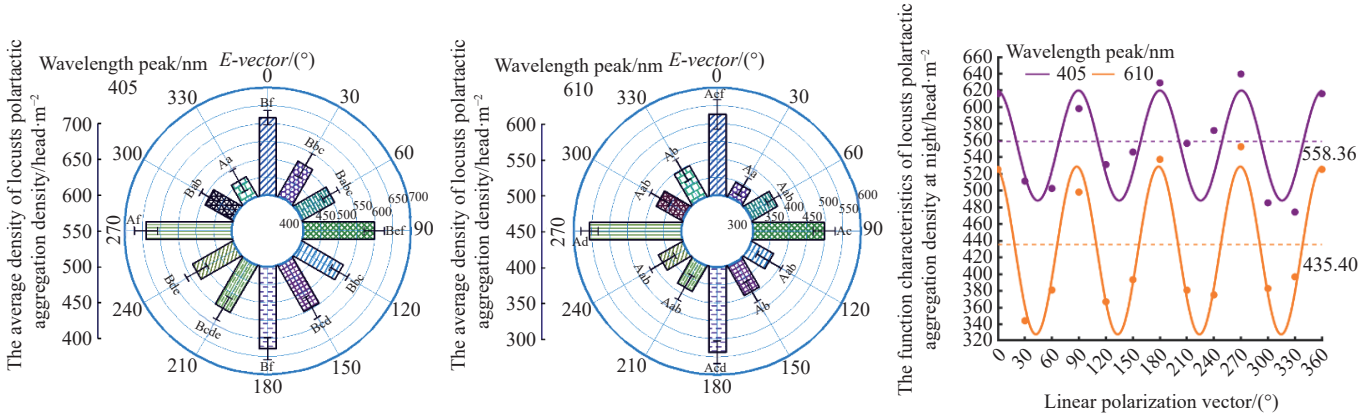
Data title		Locusts polartactic aggregation density/head/m^2					F-value	p-value
Time/h		21:30	23:30	1:30	3:30	5:30	df=4	
Vector/(°)	0	420.0±33.18cdA	460.0±34.14cdAB	517.0±33.51cdBC	580.0±26.46cdC	650.0±30.95cD	14.607	<0.001
	30	261.0±20.00aA	299.0±29.82aA	341.0±26.51aB	389.0±36.35aC	431.0±35.17aD	15.261	<0.001
	60	286.0±34.40abA	333.0±29.37abB	382.0±24.06bC	428.0±31.05abD	476.0±26.63bE	14.051	<0.001
	90	400.0±30.00cA	442.0±19.08cB	490.0±31.05cC	545.0±30.12cD	614.0±30.05bcE	14.221	<0.001
	120	276.0±26.23abA	317.0±32.51abB	362.0±27.30abC	419.0±36.04abD	461.0±37.13aE	10.468	<0.01
	150	297.0±23.90abA	340.0±35.38bB	396.0±32.00bC	445.0±30.51bD	489.0±38.97bE	16.958	<0.001
	180	435.0±34.51cdA	475.0±31.00cdA	528.0±25.00cdB	590.0±30.27dC	659.0±27.62cdD	23.186	<0.001
	210	271.0±30.51abA	330.0±33.41abB	389.0±31.87bC	435.0±39.15bD	479.0±29.02bE	13.018	<0.001
	240	281.0±30.51abA	325.0±29.00abB	375.0±28.00abC	425.0±39.51abD	470.0±38.16abE	10.918	<0.01
	270	450.0±28.51dA	496.0±32.58dB	546.0±27.50dC	606.0±35.38dD	665.0±33.60cdE	17.984	<0.001
	300	291.0±32.91abA	337.0±25.94abB	380.0±36.94bC	421.0±33.60aD	485.0±25.87bE	19.039	<0.001
	330	309.0±30.51bA	346.0±33.06bB	387.0±30.06bC	436.0±20.65bD	506.0±24.75bE	17.080	<0.001
	360	420.0±33.18cdA	460.0±34.14cdAB	517.0±33.51cdBC	580.0±26.46cdC	650.0±30.95cD	14.607	<0.001
F-value	df=12	15.764	11.335	11.820	14.454	18.448		
p-value		<0.001	<0.001	<0.001	<0.001	<0.001		

At 0° (360°), 90°, 180°, and 270°, the polartactic aggregation effect on locusts was optimal, especially at 270°, followed by 180°. Advancing the light time enhanced the polartactic aggregation effect, with the strongest effect at 5:30. Under the same light time, the polartactic aggregation effect induced by linearly polarized violet light was significantly superior to linearly polarized orange light. However, as light time advanced, the enhancement effect of linearly polarized orange light surpassed that of linearly polarized violet light.

3.3 Influence of nocturnal habitat on the change characteristics of the locust polartactic aggregation response to linearly polarized vector light

Under violet and orange spectra, different vectors of polarized light significantly affected locust polartactic aggregation sensitivity at night (p<0.001: F_{violet}=8.924; F_{orange}=15.453), but light time did not. Locusts showed the strongest polartactic aggregation sensitivity at 0°(360°), 90°, 180°, and 270°, particularly at 270°, followed by 180° (Figure 5a). Under the same vector, comparing violet and orange spectra, sensitivity was generally better for violet spectrum, but there was no significant difference between violet and orange spectra at 270° and 330°.

Meanwhile, the response characteristics of locust polartactic aggregation sensitivity to linearly polarized vector light presented cosine function change features tuned by vectors within 0°-360° vectors (Figure 5b). The response characteristics with cosine features and periodic changes were similar for both violet and orange spectra, further indicating that under the same vector, the sensitivity to linearly polarized violet light was superior. At 0° (360°), 90°, 180°, and 270°, light time significantly enhanced the locust polartactic aggregation effect (Figure 6).



a. Sensitivity mode of locusts

b. Change in locust polartactic responding to different vectors aggregation response to different vectors

Notes: Under different vectors with the same spectrum in a, 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 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.

Figure 5 Locust polartactic aggregation response characteristics to linearly polarized vector light with violet or orange spectrum

Correlation analyses showed that the locust polartactic aggregation effect was positively correlated with light time and that the correlation was most significant for the 90° vector of violet spectrum and the 270° vector of orange spectrum. However, under the same vector, when violet and orange spectra were compared, the significance of the positive correlation caused by orange spectrum

was higher than that caused by violet spectrum. Although nocturnal habitat conditions (e.g., temperature drop to 20.5°C±0.5°C and relative humidity increase to 80%±5% at 5:30) did not significantly influence the polartactic aggregation effect, linearly polarized spectrum attributes affected the action effect of light time, and the enhancement effect of longer durations of linearly polarized orange light was stronger than that of violet light.

3.4 Discussion

Insect visual systems integrate E-vector direction and wavelength information, combining polarization and light intensity to identify different polarization patterns, which generates robust compass signals and produces visual tuning opposition sensitivity responses to both polarized and non-polarized light. This interaction between linearly polarized and non-polarized light significantly influences insect polartactic and phototactic behaviors[17,18]. However, the sensitivity differences in locust phototactic and polartactic aggregation responses to heterogeneous spectral light and linearly polarized vector light in nocturnal habitats remain unclear. Our results indicated that under violet spectrum, locust phototactic aggregation sensitivity was superior to polartactic aggregation sensitivity to linearly polarized light at 300° and 330°. Conversely, under orange spectrum, locust polartactic aggregation sensitivity to linearly polarized light at 0°, 90°, 180°, and 270° was superior to phototactic aggregation sensitivity. Despite these variations, the linear polarization sensitivity vectors (0°, 90°, 180°, and 270°) consistently showed significantly higher polartactic aggregation sensitivity compared to phototactic aggregation sensitivity. This aligns with the high sensitivity of the locust DRA to specific E-vectors and the findings that locust polarization-sensitive neurons respond to spectral light in an orientation-dependent manner, that non-DRA regions dynamically regulate orientation response to spectral intensity, and that locusts perceive spectral intensity and E-vector information with sensitive oppositionality[19], implying specific driving differences in locust color vision (wavelength), light intensity vision, and polarization vision on phototactic and polartactic aggregation sensitivity[20,21].

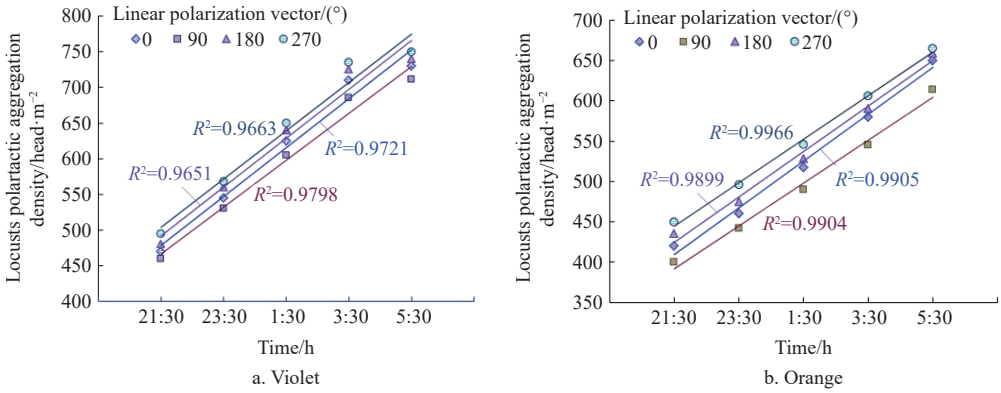


Figure 6 Relationship between polartactic aggregation effect on locusts and nighttime habitat

Therefore, the sensitivity differences in locust phototactic and polartactic aggregation were related to the polarization characteristics of linearly polarized spectrum vectors, providing a reference for elucidating the specific sensitivity mechanism of locust phototaxis and polartaxis. Linearly polarized spectrum light attributes also affected the impact of light time at night on locust phototactic and polartactic aggregation sensitivity. Under the 0°-270° vectors of linearly polarized violet spectrum, the enhancement effect of light time on differential sensitivity was strongest at 3:30, followed by 5:30, whereas under the 0°, 90°, 180°, and 270° vectors of linearly polarized orange spectrum, the enhancement effect was strongest at 21:30, followed by 5:30. These results are of great significance for understanding sensitivity changes in the locust polartactic aggregation response and have practical implications for optimizing polartactic induction operations in locusts.

Previous research has shown that locusts possess an active orientation mechanism derived from their solar polarization compass, which is crucial for spatial orientation and navigation because these require perception and integration of environmental stimuli, and that locusts use the central complex (CX) to analyze polarization vectors, patterns, and total intensity, facilitating complex visual detection and orientation behaviors in polarization environments[22,23]. Our study found that under both violet and orange spectra, the polartactic aggregation effect was relatively better induced by 0°(360°), 90°, 180°, and 270° vectors, with 270° being the best, followed by 180°. This was consistent with the alternating excitatory and inhibitory responses of locust polarization-sensitive neurons to E-vector directions at 90° intervals, indicating a preference for specific E-vector directions[24].

However, when the vector remained the same, locust polartactic aggregation sensitivity induced by linearly polarized violet light was significantly better than that induced by linearly polarized orange light, which was related to locusts effectively detecting polarization-sensitive targets based on their specific sensitivity to polarization wavelengths and the sensitivity array diagram of the polarization vector and eliminating polarization-sensitive false color perception in complex environments to maintain clarity and sensitivity to polarized light targets[25]. Furthermore, locust polartactic aggregation sensitivity to linearly polarized violet light was significantly higher than to linearly polarized orange light, which was related to their effective detection of polarization-sensitive targets based on sensitivity to specific polarization wavelengths, which enabled them to eliminate false color perceptions in complex environments and maintain clarity and sensitivity to polarized light targets[26]. Therefore, although polarized spectrum attributes do not affect the intensity of the locust polartactic aggregation response to visual sensitivity vectors, they significantly impact sensitivity to linearly polarized vectors. When light time was held constant, sensitivity to violet spectrum was significantly superior to orange spectrum, supporting findings that locust visual systems integrate linearly polarized E-vectors and spectral polarization information to achieve optimal sensitivity to polarized light and that the polarized light intensity gradient does not contribute to locust polartactic behavior[27].

However, polartactic aggregation sensitivity enhanced by light time varied with spectral attributes, potentially due to nonlinear correlation between the polarization and azimuth compasses in the locust CX, leading to spatiotemporal opposition response characteristics, as well as mediation of the reaction of non-DRA photoreceptors in locust compound eyes to polarized spectra[28]. Therefore, the dynamic tuning response threshold of locust compound vision to linearly polarized spectra, along with the spatial and temporal tuning differences of polarization neurons to heterogeneous spectra, contributed to the stronger enhancement effect of orange spectrum lighting time compared to the violet spectrum.

The finding that the enhancement effect of longer durations of linearly polarized orange light was stronger than that of violet light can be explained by the anatomical structure of the locust compound eye and its underlying neural pathways[29]. Specifically, non-DRA photoreceptors in the locust compound eye exhibit higher spectral sensitivity to long-wavelength spectra (e.g., orange light, peak at 610 nm) compared to short-wavelength spectra (e.g., violet light, peak at 405 nm). These non-DRA photoreceptors dominate the peripheral regions of the compound eye and are responsible for intensity and color vision under dim light conditions[30]. Under prolonged nocturnal illumination, these photoreceptors undergo stronger dark adaptation, allowing them to respond more effectively to orange light as night progresses toward early morning (e.g., 5:30).

In addition to the role of non-DRA photoreceptors, the locust CX also contributes to this differential enhancement. In particular, the POL-neurons in the protocerebral bridge and the lower division of the central body not only encode the E-vector direction of polarized light but also integrate temporal rhythm information via input from circadian clock neurons[31]. As light time advances, orange light more effectively activates clock-related neurons in the CX (such as those expressing the circadian protein PERIOD), thereby enhancing the polartactic aggregation response.

Complementing these mechanisms, the DRA (dorsal rim area) ommatidia, which are specialized for polarization vision, have a spectral sensitivity peak in the ultraviolet-to-violet range (around 400-420 nm)[32]. This explains why violet light induces stronger polartactic sensitivity over shorter illumination durations (e.g., 19:30-1:30), as it matches the DRA's spectral preference. However, the DRA contribution to the time-dependent enhancement effect is limited because its photoreceptors are less sensitive to long-wavelength light and exhibit weaker dark adaptation over time. Consequently, while violet light is more effective at initiating an immediate polartactic response, orange light produces a greater cumulative enhancement as light exposure duration increases. This anatomical interpretation is consistent with the nonlinear response characteristics of polarization neurons under prolonged illumination reported by Hensgen et al.[33] and the spectral sensitivity differences between DRA and non-DRA photoreceptors documented by Liu et al.[34]

Research has shown that locust polarization-sensitive neurons exhibit a polarization modulation response of excitation-inhibition opposition with chord function features to changing E-vector direction[35]. Our results indicated that locust polartactic aggregation response patterns (vector sensitivity mode, polartactic response characteristics with cosine features) were independent of spectral attributes, but that polarized spectrum attributes affected polartactic aggregation sensitivity. These observations were consistent with the findings[36] that sinusoidal modulation of locust POL-neuron activity induced by polarized varying E-vector light of long- and short-wave spectra enhances sensitivity contrast to the E-vector. Therefore, the perception specificity of locust POL neurons to polarization vectors and the sensitive recognition of polarized spectra by compound vision determine the response mode of locust polarization aggregation, but the linearly polarized spectrum attributes determine the aggregation effect and enhance the impact of the sensitivity vector. Linearly polarized light intensity does not significantly contribute to locust polartactic behavior.

4 Conclusions

This study focused on a population of *Locusta migratoria manilensis* in breeding sheds, investigating their specific sensitivity to polartactic aggregation. We examined the effects of violet and orange monochromatic light, as well as linearly polarized vector light, on phototactic and polartactic aggregation responses in locusts. Our analysis of the sensitivity changes in the locust polartactic aggregation response revealed distinct response patterns and characteristics. Our findings demonstrate that the spectral attribute did not influence the superiority of the locust polartactic aggregation response to specific vectors over the phototactic aggregation response. However, it significantly affected enhancement regulation by light time. Specifically, locust phototactic aggregation sensitivity was stronger when induced by more sensitive vectors (0°, 90°, 180°, and 270°), with violet spectrum light being more effective under the same light time. As light time advanced, the enhancement effect of orange spectrum became more pronounced. These insights deepen our understanding of the visual sensitivity mechanisms underlying locust phototaxis and polartaxis and address practical issues in using polarized light induction for locust control. The sensitivity change characteristics of the locust polartactic aggregation response clarified the specific vector response mode and the periodic tuning response characteristics with cosine features induced by linearly polarized light. These characteristics were independent of linearly polarized spectrum intensity and light time. Although linearly polarized spectrum attributes determined aggregation sensitivity, light time at night further enhanced this sensitivity. However, this study did not involve the physiological response thresholds of locusts to polarized light or the sensitive tuning effects of their polarization neurons induced by linearly polarized light. These areas warrant further investigation to fully understand the underlying mechanisms.

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