

Why are insects attracted to light?

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Abstract

The sight of insects swarming around lamps is ancient and well known, but the reasons for this behavior remain disputed. We propose that attraction to light is not merely a sensory accident, but an adaptive strategy during nuptial flights: under certain conditions, flying toward a light source can be the optimal way to encounter mates, because it aligns flight with pheromone gradients and reproductive dispersal. We developed an agent-based model to test this hypothesis, varying inertia/slip and the acceleration produced by pheromone. The results corroborate that light-oriented flight is strongly advantageous under a broad range of conditions, reaching fixation in over 90% of replicates when slipperiness is high. In addition, the simulations reveal an abrupt transition between regimes in which non-directed flight is favored and regimes in which light-directed flight is favored. This transition is controlled by inertia/slip and pheromone acceleration and is illustrated by phase diagrams. Control simulations without the directional advantage recovered the neutral expectation of 50% blue fixation, confirming that the effect is not an artifact of the model implementation. The primary implication is ecological: if the hypothesis is correct, electric lamps exploit a reproductive strategy and disrupt nuptial flights at the stage when reproduction is most consequential. The transition adds a mechanistic dimension, showing that small changes in flight dynamics can switch populations between radically different behavioral regimes. These findings, if confirmed empirically, would reframe attraction to light as a reproductive trap and add urgency to mitigating light pollution for insect conservation.

Keywords

Insect attraction to light; nuptial flight; pheromone; light pollution; agent-based simulation; phase transition; insect conservation.

Introduction

This article presents a new answer to an old enigma. The sight of insects swarming around artificial lights is ancient and ubiquitous. From streetlamps to porch lights, electric illumination draws many insect orders in numbers that can be staggering; the earliest written records date back to the Roman Empire (Ford 1955; Gardiner 1995; Fabian et al. 2024). Despite its familiarity, the behavior remains poorly understood.

Several explanations have been proposed. Some are physiological: insects fly toward light as an escape mechanism, seeking an opening in the foliage (Mazokhin-Porshnyakov 1960); thermal radiation from lamps attracts flying insects (Callahan 1965); or artificial lights blind insects, causing erratic flight and trapping them near the source (Robinson and Robinson 1952; Hsiao 1973). Others concern orientation. Fabian et al. (2024), using a high-tech apparatus and a refined empirical methodology, concluded that insects swarm around lamps because they tend to keep their backs facing the light. An older and more influential account holds that insects use the Moon as a navigational beacon and mistake electric lamps for it (von Frisch 1950; Sothibandhu and Baker 1979).

The navigational account deserves special attention. Many insects fly long distances in search of resources and must return home, which requires not only memory but a navigation mechanism. A simple and elegant strategy is to maintain a constant angle between the flight trajectory and the straight line to a distant light source. In the natural world, the Sun and the Moon served as such guides, both effectively at optical infinity. Electric lamps disrupted this mechanism: insects mistake nearby artificial lights for their natural beacons and are led off course. This explanation accounts for the small fraction of insects that approach lamps in spiral trajectories, a result of maintaining a fixed angle to the source. It is ingenious and, we believe, correct — but it clarifies only a small portion of the swarms around lamps. We therefore treat it as complementary to, not in competition with, our hypothesis.

The dorsal-light account of Fabian et al. (2024) also deserves comment. We have no doubt that insects behave as these authors meticulously describe. However, we believe they have mistaken causes for consequences. An airplane banking in a turn tilts its upper surface toward the center of the turn; if a light source sits at that center, the airplane's dorsal side faces the light. Any flying object in curved flight presents its dorsal side to the center of the curve — not as a response to the light, but as a consequence of the geometry of curved flight. The same geometry applies to an insect circling a lamp. The observation that insects turn their backs to the light is therefore not evidence of a dedicated dorsal-light response; it is what any flying body does when its trajectory curves around a source. The cyclist analogy makes the point in a more familiar setting: a cyclist following a circular path around a streetlight also tilts and turns their back to the light. But the airplane case is the more direct parallel, because it shares with the insect the property that matters here — flight. Insects do not circle lamps because they are compelled to turn their backs to the light; they turn their backs to the light because they are circling the lamps. Causes and consequences can become entangled. If the dorsal-light response were a dedicated mechanism, it should operate even without curved flight — for example, in an insect flying in a straight line past a lamp. This is a testable prediction.

A growing body of experimental evidence shows that artificial light at night (ALAN) disrupts mate location in insects. In the winter moth (*Operophtera brumata*), field experiments found that 53% of females caught on non-illuminated trunks had mated, whereas only 13–28% of females caught on illuminated trunks had mated, and light also reduced the number of males attracted to synthetic pheromone lures (van Geffen et al. 2015).

In the fall webworm (*Hyphantria cunea*), no pairs mated under ALAN, whereas 18% mated under ambient light (Tanino-Springsteen et al. 2025). In both cases, light interferes with the behavioral step that the nuptial-flight hypothesis addresses: the location of a mate during flight. The two literatures — empirical studies of ALAN and theoretical models of nuptial flight — have developed largely independently, and the hypothesis we propose here is an attempt to connect them.

Here we propose that attraction to light is not a sensory accident but an adaptive strategy during nuptial flights. In many insects, reproductive success depends on locating mates while dispersing across a landscape. Pheromone gradients provide directional information that can be greatly reinforced when individuals already share, in advance, a preferred flight direction toward potential mates. A distant light source can serve as a common reference, offering a complementary cue: it is visible from afar, stable in position, and can align flight with the direction of reproductive dispersal. Before electric lights, orienting

toward such a source may well have been an advantageous way to encounter mates — a strategy that lamps now hijack.

Testing this hypothesis requires a model that integrates flight dynamics, pheromone response, and light orientation across a broad parameter space. We developed an agent-based model in which each insect is represented as an individual with position, velocity, slipperiness (the rate at which agents lose velocity), and two behavioral rules: acceleration along pheromone gradients and orientation toward a light source. The model is deliberately minimal, so that the contribution of each parameter can be isolated. Agents are heterogeneous only through stochasticity; the collective outcome — whether a population becomes fixed for light-directed or non-directed flight — emerges from individual rules. The model is not calibrated to any particular species; it is a theoretical tool for isolating the conditions under which light-directed flight is favored.

We use the model to address three questions. Can light-oriented flight during nuptial flights be advantageous? If so, under which conditions? Finally, how robust is this advantage to variation in flight dynamics and pheromone-driven acceleration? To answer them, we sweep slipperiness, pheromone-driven acceleration, and the presence or absence of light orientation, and we track the fraction of simulated populations that reach fixation for light-directed behavior. The simulations corroborate the hypothesis: over a wide range of parameters, light-oriented flight is strongly favored. In addition, the sweeps reveal an abrupt transition between regimes in which non-directed flight predominates and regimes in which light-directed flight predominates. This transition is controlled by slipperiness and pheromone-driven acceleration and is illustrated by simulated trajectories and phase diagrams. We treat it as a secondary finding: it adds a mechanistic dimension to the main claim, showing that small changes in flight dynamics can switch populations between radically different behavioral regimes.

The ecological implications may be greater than previously thought. If attraction to light is a reproductive strategy, then electric lamps do not merely kill insects incidentally; they exploit a behavioral rule that evolved for mate finding. The result is a reproductive trap that disrupts nuptial flights precisely when insects are reproductively active. Our simulations suggest that the mortality caused by light pollution may be far more severe than previously assumed, because it acts on reproduction rather than on foraging or dispersal alone. This reframing has direct consequences for conservation: mitigating light pollution is not only about reducing deaths, but about protecting the behavioral rules on which insect populations depend.

Methods

1. Purpose

The model tests the hypothesis that a heritable bias toward a distant light source can spread in a population that performs nuptial flights, because it aligns the flight paths of carriers and increases encounter rates. It also quantifies how this advantage depends on two parameters: slipperiness, a composite parameter that captures both the viscosity of the medium and the inertia of the agent, and controls how quickly an agent loses velocity; and pheromone-driven acceleration, the strength of the response to a potential mate's trail.

2. Entities, state variables, and scales

The model has two types of agents: males and females. Each agent has a position (x, y) in a two-dimensional toroidal space of 1530×800 units, a velocity vector, and a color (blue or red). Blue and red represent two heritable variants of the orientation rule. Blue agents, when the directed condition is on, carry a bias toward a preferred direction (the "light source"). Red agents do not. Each agent also has a radius (4 units for males, 7 units for females). Females have a trail: a triangle of length 310 units and half-angle 10° , oriented opposite to their velocity. The trail represents the pheromone plume left by the female. Time is discrete. A generation corresponds to a complete round of copulations followed by reproduction. For the trail-geometry sensitivity analysis (see Results), the domain was set to a square torus (1100×1100 units) to ensure isotropic conditions.

The two-dimensional space is a deliberate simplification. Insects fly in three dimensions, but in natural conditions many insects tend to fly within a narrow band of altitude. The model isolates the geometry of trail encounter in the horizontal plane, where pheromone trails are laid and detected. A three-dimensional cone would dilute the pheromone signal and make trail detection even less likely for males on non-aligned trajectories, which would strengthen, not weaken, the advantage of aligned flight. The 2D approximation is therefore conservative with respect to the main result.

The trail is modeled as a static geometric triangle rather than a decaying plume. In nature, pheromone decays over time and diffuses, so the effective detection distance is finite. Whether exponential decay alters the transition reported here is an open question for future work.

3. Process overview and scheduling

Each generation proceeds in four steps. (i) Males and females move according to their behavioral rules. (ii) When a male's position falls inside a female's trail triangle, the male locks onto that female and accelerates toward her. (iii) When a male comes within collision distance of a female, a copulation occurs and the male is removed. (iv) After a fixed number of copulations (50), reproduction occurs: offspring are produced according to the color of the parents, and a new generation is created. The simulation ends when one color goes extinct — that is, when all agents of one color have disappeared. The surviving color is the fixed color, and the generation at which extinction occurs is the fixation generation.

4. Design concepts

Basic principles. The model combines two ideas: (a) a shared orientation rule aligns flight paths and increases encounter rates, and (b) the advantage of the rule depends on flight dynamics and on the strength of pheromone response. The model is not about insect cognition; it is about the population dynamics of a heritable behavioral rule.

Emergence. Fixation of one color is not imposed. It emerges from individual encounters and reproduction. The transition between regimes in which blue or red fixes is an emergent property of the parameter space.

Adaptation. Agents do not adapt within their lifetime. The behavioral rule is fixed. Adaptation occurs across generations, through differential reproduction.

Fitness. Fitness is realized through copulations. A male that copulates leaves offspring. A male that does not copulate leaves none. The color of the offspring depends on the colors of the parents (see Reproduction below).

Interaction. Males interact with females through the trail-detection region. When a male's position falls inside a female's trail triangle, the male locks onto that female and accelerates toward her. This is the only direct interaction between agents.

Stochasticity. Initial positions and directions are random (fixed speed). The preferred direction of blue agents is drawn from a uniform distribution each generation. When the directed condition is on, blue agents move along this direction; red agents always move randomly. The choice of female among multiple detected trails is random. Offspring color from mixed pairs is random with probability 0.5. Seeds are fixed per replicate for reproducibility.

Observation. The primary output is the fixed color (blue or red) and the fixation generation. Secondary outputs are the mean and standard deviation of fixation generation, and the runtime per condition.

5. Initialization

Each replicate starts with 200 males (100 blue, 100 red) and 8 females (4 blue, 4 red). Positions are drawn uniformly from the toroidal space. Velocities are drawn from a uniform angular distribution with speed 2.0. The preferred direction of blue agents is drawn from a uniform distribution on $(0, 2\pi)$. The simulation runs until one color goes extinct.

6. Input data

The model does not use input data. It is a theoretical model.

7. Submodels

Movement:

Each male updates its velocity as follows. If the male is locked onto a female, it accelerates toward her with acceleration equal to the pheromone parameter. If the male is not locked onto a female, it accelerates along its current direction with a base acceleration (0.21), and, if the male is blue and the directed condition is on, it also applies a small correction toward the preferred direction (0.05). The velocity is then multiplied by the slipperiness parameter (inertia/viscosity), which controls how quickly the agent loses velocity. Females move with constant velocity, except that blue females under the directed condition also apply the preference correction. All agents move on a torus, so they reappear on the opposite side when they leave the space.

Trail detection:

Each female has a trail triangle of length 310 and half-angle 10° , oriented opposite to her velocity. A male detects a female when his position falls inside her trail triangle. When multiple females are detected, the male locks onto one at random. If the male is already locked onto a female, the lock is maintained as long as he remains inside her trail; otherwise, he may lock onto another detected female.

Copulation:

When a male comes within collision distance (male radius + female radius) of a female, a copulation occurs. The male is removed from the population, and the copulation count is incremented. The colors of the pair are recorded for reproduction.

Reproduction:

After 50 copulations, a new generation is created. Each copulation produces 4 male offspring. If both parents are blue, all offspring are blue. If both are red, all offspring are red. If the parents have different colors, each offspring is blue or red with probability 0.5. In addition, 8 female offspring are produced. Each female offspring is assigned the colors of a randomly chosen parent pair, with the same rule. The new generation thus has 200 males and 8 females, preserving the sex ratio and population size.

Extinction and fixation:

The simulation ends when all agents of one color have disappeared. The surviving color is recorded as the fixed color, and the generation at which extinction occurs is recorded as the fixation generation. If blue goes extinct, red is fixed, and vice versa.

8. Parameters and simulation protocol

The model has two free parameters: slipperiness (inertia/viscosity) and pheromone-driven acceleration. We varied slipperiness over nine values (0.93, 0.94, 0.95, 0.955, 0.96, 0.965, 0.97, 0.98, 0.99) and pheromone over six values (0.35, 0.45, 0.55, 0.65, 0.75, 0.85). This gives a 6×9 grid of 54 conditions. For each condition, we ran 80 replicates, for a total of 4,320 replicates. Each replicate used a deterministic seed derived from the base seed 42 and the condition parameters, ensuring reproducibility. The directed condition was on (blue agents carried the light bias) for all conditions. The simulation was run until fixation or until a maximum of 10,000 generations; no replicate reached the maximum.

The ranges of slipperiness (0.93–0.99) and pheromone-driven acceleration (0.35–0.85) were chosen to span the transition observed in preliminary runs, from regimes in which non-directed flight predominates to regimes in which light-directed flight predominates. These values are not calibrated to a particular species; the model is theoretical and exploratory. The grid is dense enough to resolve the transition and to serve as an embedded sensitivity analysis: because both parameters are varied independently across a wide range, the robustness of the result can be assessed directly from the phase diagram.

9. Controls and null expectation

To verify that the model does not introduce systematic bias in the absence of the directional advantage, we ran a negative control in which the directed condition was off (`blue_directed = no`), using a 2×3 grid of pheromone (0.45, 0.75) and slipperiness (0.93, 0.96, 0.99) values, with 80 replicates per condition (480 replicates in total). In this control, blue agents do not apply the preference correction, so neither color has a directional advantage. An independent null dataset of 100,000 replicates, simulated with the same fixation criterion as the batch (males only), yielded a blue fixation fraction of 0.5002 (50,016 of 100,000), statistically indistinguishable from 0.5.

Having established that the model is neutral in the absence of a directional advantage, we next asked whether the biased trait can invade from a single mutation.

10. Invasion test

To test whether the biased trait can invade from a single mutation, we ran two scenarios, each with 5,000 replicates. In the first (A1), one biased male was introduced into a population of 199 unbiased males and 8 unbiased females. In the second (B1), one unbiased male was introduced into a population

of 199 biased males and 8 biased females. Under neutrality, a single mutant is expected to reach fixation in 0.5% of replicates. In A1, the biased mutant reached fixation in 1.00% of replicates (50 of 5,000), twice the neutral expectation and significantly above it. In B1, the unbiased mutant reached fixation in zero of 5,000 replicates, far below the neutral expectation. The asymmetry between the two scenarios quantifies the frequency-dependent nature of the advantage: the biased trait is modestly favored when rare, but its absence becomes strongly deleterious once the population is aligned.

11. Computational environment

The model is implemented in Python 3. The batch runner uses joblib for parallel execution. The analysis uses numpy, scipy, and matplotlib. Code and data are available at:

<https://github.com/GustavoGollo/Insects-Code> .

Results

We simulated the agent-based model across a grid of 54 conditions, varying slipperiness (9 levels, 0.93–0.99) and pheromone-driven acceleration (6 levels, 0.35–0.85). For each condition, we ran 80 replicates and recorded the fraction of replicates in which the light-directed behavior (f_{blue}) reached fixation (f_{blue}). The results reveal a strong dependence on both parameters and an abrupt transition between regimes dominated by non-directed versus light-directed flight.

Validation against negative control and null expectation

Before interpreting the parameter sweeps, we verified that the model behaves neutrally when the directional advantage is removed. In the negative control (`blue_directed = no`), the overall blue fixation fraction was 0.485 (233 of 480 replicates), which is not significantly different from the null expectation of 0.5 (binomial test, $p \approx 0.52$). The six control conditions were homogeneous with respect to each other ($\chi^2 = 5.15$, $df = 5$, $p \approx 0.40$), indicating that neither pheromone nor slipperiness introduces a systematic bias in the absence of light orientation.

An independent null dataset of 100,000 replicates, simulated with the same fixation criterion as the batch (males only), yielded a blue fixation fraction of 0.5002 (50,016 of 100,000), statistically indistinguishable from 0.5 (binomial test, $p \approx 0.92$). The distribution of fixation generations in the negative control (mean ≈ 35.6 , median ≈ 29.0 , SD ≈ 23.1) was comparable to that of the null dataset (mean = 36.83, median = 30.0, SD = 24.86), and the difference between the two blue fixation fractions was not significant (two-proportion test, $p \approx 0.52$).

These results confirm that the model does not introduce systematic bias when the directional advantage is absent. Any deviation from 0.5 observed in the directed condition can therefore be attributed to the light-orientation mechanism itself, rather than to artifacts of the random number generator, initialization, or scheduling.

Overall Patterns and Phase Transition

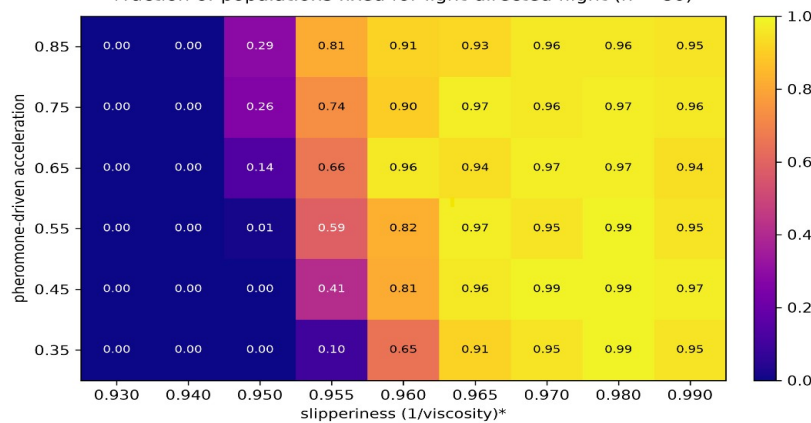
Figure 1 presents a heatmap of f_{blue} across the parameter space. The map reveals three distinct regions:

Low Slipperiness (0.93–0.94): $f_{\text{blue}} \approx 0$ for all pheromone levels. Non-directed flight (red) is universally favored.

Intermediate Slipperiness (0.95–0.96): A transition zone where f_{blue} increases sharply with slipperiness and pheromone. For example, at pheromone 0.55, f_{blue} rises from 0.0125 at slipperiness 0.95 to 0.8250 at 0.96.

High Slipperiness (0.97–0.99): $f_{\text{blue}} > 0.90$ across all pheromone levels, indicating strong selection for light-directed flight.

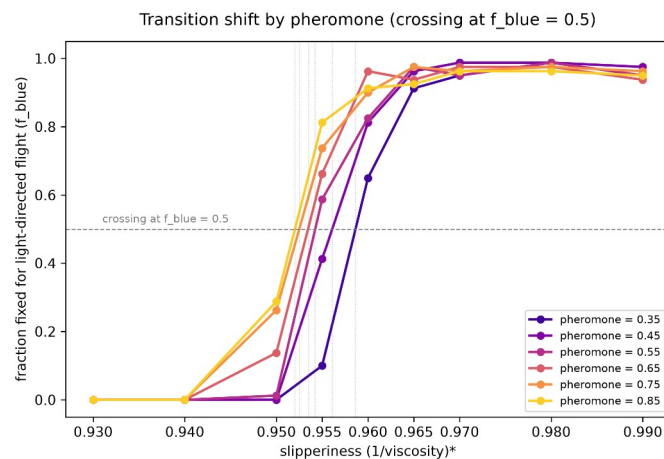
Figure 1. Fraction of populations fixed for light-directed flight. Heatmap of f_{blue} (fraction of replicates in which blue reached fixation, $n = 80$ per condition) as a function of slipperiness (x-axis) and pheromone-driven acceleration (y-axis).



* Slipperiness is inversely proportional to the viscosity of the medium.

Three regimes are visible: low slipperiness (0.93–0.94), where red is universally favored; an intermediate transition zone (0.95–0.96) where f_{blue} rises sharply; and high slipperiness (0.97–0.99), where blue reaches fixation in over 90% of replicates. *See note in figure.

The transition between the low-slipperiness (red-favoring) and high-slipperiness (blue-favoring) regimes is abrupt, not gradual (Figure 2). For a fixed pheromone level, small changes in slipperiness can shift the population from near-zero to near-complete fixation of blue. This step-like behavior is a hallmark of a phase transition, controlled by the interplay between flight dynamics and pheromone response.



* Slipperiness is inversely proportional to the viscosity of the medium.

Figure 2. Transition shift by pheromone. f_{blue} as a function of slipperiness for six pheromone-driven acceleration levels. Dashed horizontal line marks $f_{\text{blue}} = 0.5$, the threshold for the transition. Dotted vertical lines mark the slipperiness value at which each curve crosses 0.5 (values listed in the Results). Higher pheromone levels shift the crossing point to lower slipperiness, showing that stronger pheromone response compensates for weaker inertial persistence. *See note in figure.

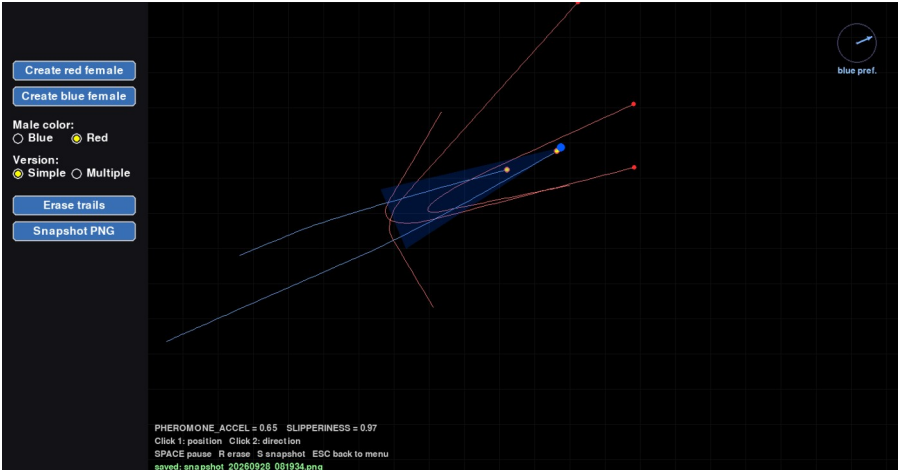
Mechanistic Interpretation of the Regimes

To understand *why* each regime favors a particular behavior, we can examine the movement dynamics of individual agents.

Regime 1: High Slipperiness (Blue Favored). When slipperiness is high, agents retain velocity, and small accelerations can lead to sustained directional movement. Blue agents, by aligning with the light source, effectively synchronize their flight direction. This synchronization increases the probability of

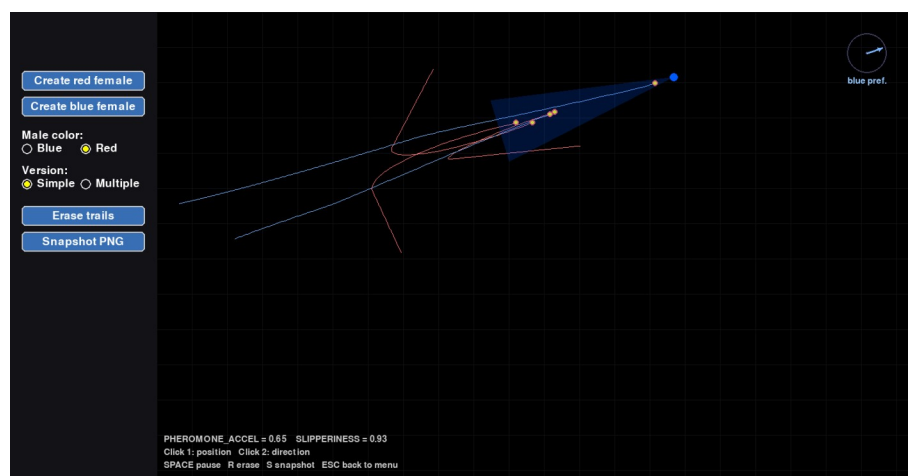
copulating after encountering aligned females, whereas crossing trajectories tend not to result in copulation, as inertial effects prevent males from intercepting females. Figure 3A illustrates this: blue agents show clear aligned trajectories in the same direction, which favors blue-blue copulation. Blue males tend not to slip out of blue trails because their trajectories are aligned in advance. The same is not true for red agents, whose paths are not aligned.

Figure 3A. High slipperiness favors aligned flight. Trajectories of two blue males (light blue) and three red males (light red) over a short time window, with a blue female (blue dot) and her pheromone trail (shaded triangle). Under high slipperiness, agents are subject to a strong inertial regime. Blue males, sharing a preferred direction with the female, enter the trail at a shallow angle and need only a slight correction to reach her. Red males, moving in random directions, enter the trail at oblique angles, curve toward the female, but slip out of the trail before making contact. The alignment of blue trajectories converts a small directional bias into a large advantage in encounter rate.



Regime 2: Low Slipperiness (Red Favored). When slipperiness is low, agents lose velocity quickly, rendering inertial effects irrelevant. Under such conditions, a male that encounters a pheromone trail will inevitably reach the female and copulate, since he will not slip out of the trail—as often occurs at higher slipperiness. In such regimes, an orthogonal flight path toward females is the optimal strategy. Because female trails are much longer than they are wide, an orthogonal encounter is far more probable than an aligned one. This gives red (non-directed) males a selective advantage over blue (light-directed) males. Figure 3B illustrates this: at low slipperiness, the absence of inertial effects means that both red and blue agents are equally capable of copulating upon encountering a female trail, since neither variant slips out of it. In contrast, blue males likely encounter fewer pheromone trails because their flight paths are parallel to those of blue females.

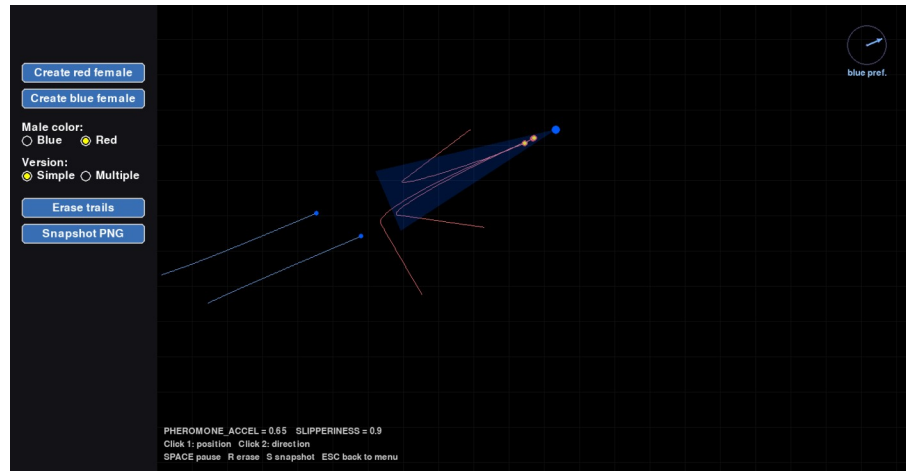
Figure 3B. Low slipperiness favors orthogonal flight. Trajectories of two blue males (light blue) and three red males (light red) over a short time window, with a blue female (blue dot) and her pheromone trail (shaded triangle). Here, agents are subject to a higher viscosity, so a male that enters a pheromone trail does not slip out of it: any entry probably results in copulation. Because the trail is much longer than it is wide, an orthogonal trajectory (typical of red males) is far more likely to intersect it than a parallel one (typical of blue males). Blue males, by aligning with the female's direction, reduce their probability of crossing her trail. Red males therefore have a selective advantage in this regime.



Regime 3: Very Low Slipperiness (Red Strongly Favored). A third, more extreme regime appears when slipperiness is very low. Here the viscosity of the medium is so high that it not only eliminates

inertial effects but also reduces the speed of agents to the point where a parallel approach can no longer close the distance. A blue male flying parallel to a blue female — the configuration that was advantageous at high slipperiness — now becomes a liability: he appears to chase her without ever closing the gap, because both lose momentum at the same rate and the initial separation is preserved. A red male approaching orthogonally, by contrast, still intersects the trail and reaches the female.

Figure 3C. Very low slipperiness imposes an additional penalty on blue males. With very low slipperiness, the medium's viscosity slows agents so much that a blue male moving parallel to a blue female appears to be chasing her without ever closing the distance, while a red male approaching orthogonally intersects her trail and reaches her. In this regime, the parallel alignment that favors blue males at high slipperiness becomes a liability.



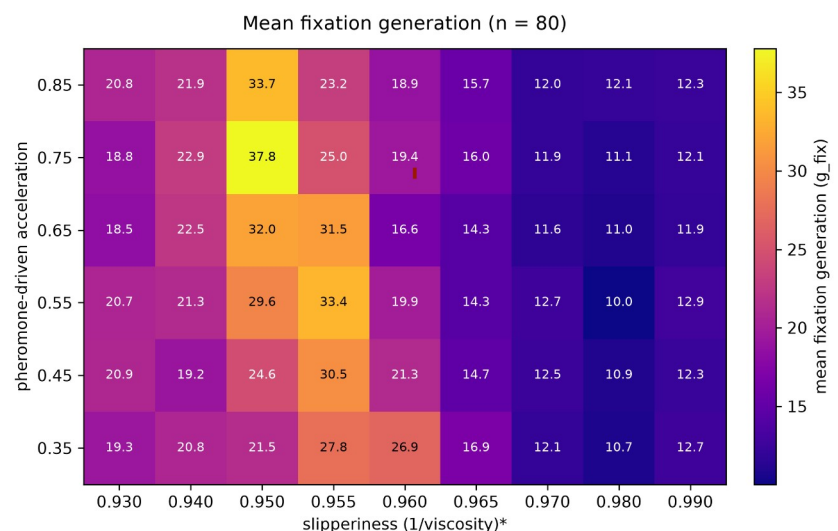
The Role of Pheromone. The

pheromone parameter modulates the strength of attraction to female trails. High pheromone acceleration counterbalances high slipperiness, reducing its effect. However, this effect is asymmetric. At low slipperiness, strong pheromone response favors copulation during orthogonal encounters—which are more probable than aligned ones—giving red agents a selective advantage over blue agents. At high slipperiness, by contrast, even strong pheromone response cannot overcome the advantage of aligned flight, and blue agents still prevail. This interaction explains the shape of the transition zone in Figure 1.

Fixation Generation

The mean generation at which fixation occurred (g_{fix}) varied systematically across the parameter space (Figure 4). Fixation was fastest in the high-slipperiness, intermediate-pheromone corner ($g_{fix} \approx 10$ generations), where one strategy was clearly favored, and slowest in the transition zone ($g_{fix} \approx 33\text{--}38$ generations), where the two strategies coexisted for longer before one displaced the other. In the low-slipperiness, red-favoring regime, fixation was intermediate ($g_{fix} \approx 19\text{--}22$ generations). This pattern is consistent with the interpretation that the duration of the mixed-state period depends on how decisively one strategy outcompetes the other: when the advantage is strong, fixation is rapid; when the two strategies are near-equivalent, the population fluctuates for longer before one goes extinct. The comparison with Figure 1 shows that the transition zone — where neither strategy is dominant — is also the zone where fixation takes longest.

Figure 4. Mean fixation generation across the parameter space. Mean number of generations required for one color to reach fixation (g_{fix}) as a



* Slipperiness is inversely proportional to the viscosity of the medium.

function of slipperiness (x-axis) and pheromone-driven acceleration (y-axis). Cells are colored by g_{fix} ; values are means over 80 replicates per condition, regardless of which color fixed. Fixation is fastest in the high-slipperiness, intermediate-pheromone corner ($g_{\text{fix}} \approx 10$ generations) and slowest in the transition zone ($g_{\text{fix}} \approx 33\text{--}38$ generations), where the two strategies coexist for longer before one displaces the other. The pattern mirrors the phase diagram in Figure 1: the transition zone, where neither strategy is dominant, is also where fixation takes longest.

Sensitivity to Trail Geometry

The baseline trail geometry (length 310, half-angle 10°) was used as the default for all simulations. To test whether the advantage of the biased type depends on this choice, we varied trail length (155, 310, 465 units) and half-angle (5° , 10° , 20°), running 5 replicates of 20,000 copulations per configuration. The advantage of the biased type was positive in all tested geometries, ranging from 1.04 to 1.13, with the baseline lying near the peak of the curve. Trails that were shorter (155), longer (465), narrower (5°), or wider (20°) all reduced the advantage relative to the baseline. The sensitivity analysis shows that the qualitative result does not depend on the specific choice of trail geometry, though the magnitude of the effect is modulated by it.

Summary of Findings

In summary, the simulations corroborate our hypothesis that light-oriented flight can be strongly advantageous during nuptial flights. The advantage is governed by an abrupt transition controlled by slipperiness and pheromone-driven acceleration: high slipperiness and sufficient pheromone response favor the spread of light-directed behavior, while low slipperiness or weak pheromone response lead to its disappearance. The duration of the mixed-state period depends on how decisively one strategy outcompetes the other — when the advantage is strong, fixation is rapid; when the two strategies are near-equivalent, the population fluctuates for longer. These results provide a mechanistic basis for the ecological implications discussed below.

Discussion

Most insects that swarm around lamps do so, we propose, as a strategy that maximizes the efficiency of their nuptial flights. Under ancestral conditions, flying toward the Moon increased their likelihood of a successful mating flight. Electric lamps now hijack this mechanism.

The reasoning is straightforward: at certain times, individuals of many insect species take to the air in search of mates. These nuptial flights are brief and risky: the faster a mate is found, the shorter the exposure to predators. A random search is viable, and was very probably the ancestral state. But a male whose flight direction happened to align with that of potential partners would have an advantage over competitors who could not: he would reach a mate sooner, on average, and leave more descendants. Females would also benefit if their flight direction were known to males, since this would allow them to find a mate faster and return sooner to the relative safety of the ground — or, depending on the species, to mate with more partners.

But the greatest advantage for the female lies elsewhere: by being found more often by males capable of aligning with her direction, she produces offspring that inherit the very trait that increases their own fitness. Since fitness is ultimately determined by the number of descendants, females that mate with such males leave potentially fitter offspring (Gollo 2024) — offspring that inherit the trait that increases mate-finding success — than females that do not, thereby increasing their own fitness.

But how could a male guess such vital information? How could he discern the intentions of females — information as important for insects as for any sexually reproducing species? The answer is that nothing needs to be guessed, and no information needs to be possessed. Insects do not know the flight direction of their partners, but they behave as if they did.

For this advantage to arise, the simulations show that, besides a certain amount of luck, or drift, all that is needed is a trivial mutation in an individual of a species that engages in nuptial flights. By inducing a bias toward light, the mutation compels its carriers, during the nuptial flight, to head toward the Moon. Initially, the first mutant and its few descendants gain nothing from it. As long as only a small fraction of the population carries the trait, it is effectively neutral.

But if a non-negligible fraction of the population inherits the bias to perform nuptial flights preferentially toward the Moon, this group will behave as if its members knew the flight direction of one another. This group will be moving in the direction most likely to lead to encounters within the group, even before detecting one another, succeeding more often than lineages that lack this trait. Over generations, the selective advantage of those who behave as if they knew the direction of potential partners increases the size of the group carrying the trait, strengthening the advantage over generations. Simulations show that, under such conditions, the trait spreads within a few tens of generations, eventually displacing lineages that behave as if they did not know the flight direction of their potential mates.

It is worth being explicit about the status of the "as if." It is not a claim about insect cognition, it is a functional description: the shared orientation rule produces the same increase in encounter rates that would obtain if individuals knew their partners' flight direction. The formulation is explanatory precisely because it identifies the problem that the rule solves - mate finding under uncertainty - without postulating that individuals possess the information that a solution to the problem would seem to require. Males do not know the flight direction of their potential partners, but they behave as if they did, and that is enough. The simulations make this precise. The transition between regimes in which non-directed flight predominates and regimes in which light-directed flight predominates is abrupt, controlled by slipperiness and pheromone-driven acceleration. Below a critical combination of parameters, the trait is neutral or deleterious; above it, it is strongly favored. This is consistent with the verbal argument: the advantage of a shared orientation rule depends on the flight dynamics and on the strength of pheromone-driven acceleration, not on the frequency of carriers. Small changes in these parameters can switch populations between regimes, which is why the transition is abrupt. The abruptness is therefore a property of the flight dynamics, not of population composition.

The ecological implication is direct. If attraction to light is a reproductive strategy, then light pollution interferes with reproduction, not merely with foraging or dispersal. The mortality caused by lamps may therefore be more severe than previously assumed, because it acts precisely when insects are at the reproductive stage. This is consistent with the growing recognition that light pollution is a driver of insect declines (Owens et al. 2020), and that its effects extend beyond direct mortality to mechanisms, ecology, and evolution (Desouhant et al. 2019). Mitigating light pollution is not only about reducing deaths, but about protecting the behavioral rules on which insect populations depend.

Two caveats follow. First, the hypothesis applies to insects that perform nuptial flights. Many insects attracted to lamps do not, and for them other mechanisms are likely at work. Second, the rule is advantageous only when the reference is distant and stable. Nearby artificial lights break the geometry of

the rule, turning an adaptive strategy into a trap. This is consistent with the finding that species relying on celestial cues are especially vulnerable to light pollution (Dacke et al. 2013; Foster et al. 2021).

Conclusion

We proposed that the attraction of insects to artificial lights is not a sensory accident but an adaptive strategy hijacked by electric illumination. Under ancestral conditions, orienting nuptial flights toward a distant and stable light source — the Moon — would have aligned the flight paths of conspecifics and increased encounter rates, giving carriers of the bias a reproductive advantage. Electric lamps break the geometry of this rule: they are nearby, not at optical infinity, and they turn an adaptive strategy into a reproductive trap.

The agent-based simulations reported here support this hypothesis. Across a broad grid of slipperiness and pheromone-driven acceleration, light-directed flight was strongly favored whenever flight dynamics allowed agents to retain directional momentum and pheromone response was sufficient to sustain pursuit. Under those conditions, the light-directed variant reached fixation in the great majority of replicates, often within a few tens of generations. When slipperiness was low or pheromone response weak, the advantage disappeared and non-directed flight prevailed. The transition between these two regimes was abrupt, not gradual: small changes in flight dynamics switched populations between radically different behavioral outcomes.

This abruptness is itself informative. It shows that the advantage of a shared orientation rule is not a matter of degree but a property of the flight regime. The transition is controlled by the interplay between inertia and pheromone response, not by the frequency of carriers, which is why it appears as a step rather than a slope. The phase diagrams make this visible and give the hypothesis a mechanistic dimension that verbal argument alone could not provide.

Crucially, the effect is not an artifact of the model implementation. When the directional advantage was removed, the negative control recovered the neutral expectation of 50% blue fixation, and an independent null dataset of 100,000 replicates did the same. The control conditions were homogeneous with respect to each other, and their fixation-generation distribution matched that of the null. Any deviation from neutrality in the directed condition can therefore be attributed to the light-orientation mechanism itself. This validation matters because it rules out the most common alternative explanations for a positive result in an agent-based model: biased random number generation, initialization artifacts, or scheduling effects.

The ecological implications are direct. If attraction to light is a reproductive strategy, then light pollution disrupts the very process it exploits — not merely with foraging or dispersal. Lamps do not simply kill insects incidentally; they exploit a behavioral rule that evolved for mate finding and disrupt it precisely when insects are reproductively active. The mortality caused by artificial light may therefore be far more severe than previously assumed, because it acts on the reproductive stage rather than on the foraging stage alone. This reframes light pollution not only as a source of mortality but as a driver of insect declines (Owens et al. 2020), with consequences that span mechanisms, ecology, and evolution (Desouhant et al. 2019). Mitigating light pollution is not only about reducing deaths; it is about protecting the reproduction strategies on which insect populations depend.

These findings have practical implications for conservation. If attraction to light is a hijacked reproductive strategy, mitigation should focus not only on reducing light intensity but on restoring the geometry of the night sky. Downward-directed, full-cutoff lighting and spectra that do not mimic celestial cues — amber or red rather than blue-white — can reduce the hijacking of the flight vector, allowing insects to recover the geometry of infinity required for their nuptial flights.

Two caveats delimit the scope of the claim. First, the hypothesis applies to insects performing nuptial flights. Some insects attracted to lamps are not displaying this behavior, and for them other mechanisms are likely at work. The navigational account of von Frisch (1950), in particular, remains complementary rather than competing. Second, the advantage depends on the geometry of the reference. The rule assumes a source at optical infinity; nearby artificial lights violate this assumption, turning an adaptive strategy into a trap. That asymmetry is consistent with the finding that species relying on celestial cues are especially vulnerable to light pollution (Dacke et al. 2013; Foster et al. 2021).

The model is deliberately minimal and theoretical. This is a strength for testing the hypothesis, because the simplifications isolate the contribution of each parameter, but it also defines the limits of the claim. What the simulations establish is that the proposed mechanism is sufficient to generate the observed pattern under a broad range of conditions, and that it does so through an abrupt transition controlled by flight dynamics. Whether the mechanism is operative in any given species is an empirical question that the model cannot answer. It does suggest, however, that the mechanism may be particularly relevant for large-bodied species — such as beetles — that perform nuptial flights and are subject to strong inertial influence.

Future work can close the gap between a theoretical mechanism and an empirically grounded ecological claim in several ways. The most direct test of the hypothesis consists of fertility analysis of insects captured in light traps. If attraction to light is a reproductive strategy executed during nuptial flights, then females intercepted by lamps should be disproportionately composed of individuals that are still reproductively active — mated or seeking mates, with egg loads not yet depleted. Dissecting captured females to record mating status, egg load, and ovarian developmental stage, and comparing them against females from the natural population sampled by non-light methods, would directly test whether light traps intercept insects before, during, or after their reproductive peak. A second test would use a dual-choice trap design to determine whether attraction to light is modulated by the search for mates. Traps would be arranged in a factorial design with four treatments: light only, sexual pheromone only, light plus pheromone, and a control with neither. If insects are engaged in nuptial flight, the light-plus-pheromone treatment should capture significantly more individuals than the sum of the two single-cue treatments, indicating a synergistic effect. Such synergy would demonstrate that the insect was in a mate-searching state and that light acted as a distractor or convergence point during that search. If light alone captures as many individuals as the combination, the behavior may be generic positive phototaxis, which would weaken the nuptial-flight hypothesis.

A third test would compare insects captured at different times of year in order to determine whether light traps capture a higher percentage of insects during the nuptial flight period of the species, while other traps capture a fraction of individuals of the same species predominantly at other times. A fourth step would consist of measuring flight dynamics and pheromone response in species known to perform nuptial flights, in order to determine where they fall in the parameter space explored here. Comparing the

predictions of the nuptial-flight hypothesis with those of the dorsal-light response in species that differ in their reliance on celestial cues would allow the explanations to be distinguished empirically. Each of these steps would convert a theoretical possibility into a testable ecological claim.

A fifth test would exploit a specific prediction of the model that has not yet been tested empirically. The simulation shows that light-directed flight is favored when agents retain velocity — that is, when inertial effects dominate over viscous damping. Translated to biology, this predicts that reliance on celestial cues during nocturnal nuptial flights should scale with body mass and flight inertia: large, fast-flying insects with limited aerodynamic maneuverability should be the most likely to align with the moon, whereas small, agile insects should be less dependent on celestial references, because they can pursue individual pheromone trails directly. This prediction is consistent with the observation that the best-documented cases of celestial orientation in nocturnal flight involve large-bodied species — dung beetles (Dacke et al. 2013; Foster et al. 2021) and the large yellow underwing moth *Noctua pronuba* (Sotthibandhu & Baker 1979). A comparative test across species that vary in body mass and flight dynamics, measuring both the strength of celestial orientation and the parameters that enter the model (inertia, pheromone response, flight speed), would directly test this prediction. If celestial orientation strengthens with increased inertia, the model's central mechanism is supported; if it does not, the nuptial-flight hypothesis loses one of its specific predictions.

But the urgency may not wait for that program. The central and most disturbing implication of this study is that artificial lights probably kill insects precisely when killing them matters most. The study suggests that lamps do not intercept insects foraging in the middle of their lives, when their reproductive contribution is already largely realized. They probably intercept insects in flight in search of mates, at the very moment they are investing in reproduction. The individual dies upon mating, so that the cost is not merely one death, but the descendants it would have produced. What the simulations suggest is that the mortality caused by light pollution is not comparable to mortality from other sources because it is concentrated at the reproductive stage.

Thus, if attraction to light evolved as a strategy to optimize mate finding, then light pollution is not an incidental risk, but a systematic disruption of the reproductive core of insect populations, and the decline it drives may be more severe than counts of dead insects around lamps have ever suggested. If the hypothesis is correct, the cost imposed by artificial light is not only measured in individual deaths, but also in reproductive events that fail to occur.

Declarations

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the author used DeepSeek, ChatGPT, and Claude to assist with code development, translation, and text editing. After using these tools, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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Data Availability

The agent-based model, the batch runner, the null-model simulations, the invasion tests, and the trail-geometry sensitivity analysis are implemented in Python and available at <https://github.com/GustavoGollo/Insects-Code>. The repository includes all scripts, the raw output files, and a README describing how to reproduce each analysis. All simulations use deterministic seeds and are therefore fully reproducible.

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