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RESEARCH ARTICLE

DIVERGENT MODES OF PERCEPTION: A COMPARATIVE ANALYSIS OF HUMAN OCULAR AND DRAGONFLY COMPOUND EYE VISION WITH APPLICATIONS IN AUTONOMOUS DRIVING SAFETY

Meiliang Yue

Zhong Tan Road Lane 99 Building 225 Rm 2003

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***Corresponding author: Meiliang Yue**

ABSTRACT

This paper presents a comparative analysis of the perceptual mechanisms between the human camera-type eye and the dragonfly compound eye, focusing on differences in optical structure, neural processing, and spatiotemporal interpretation. Humans possess a single-lens, high-acuity system optimized for static detail; dragonflies employ a multi-faceted compound eye (up to ~28,000 ommatidia per eye in large species) with low spatial but exceptionally high temporal resolution (critical flicker fusion ~200-300 Hz versus ~60 Hz in humans under bright light). The latter may enable a subjective "slow-motion" perception of the world. Dragonflies also have tetrachromatic vision extending into ultraviolet and polarization sensitivity—capabilities absent in human vision. We translate these biological insights into engineering, examining dragonfly-inspired devices for autonomous driving safety, particularly the fatigued driver scenario. A case study simulation shows that such a device could reduce highway departure impact severity from lethal (110 km/h) to survivable (40 km/h). A benefit-cost analysis, based on conservative assumptions (40% crash reduction, $400/unit cost), yields a benefit-cost ratio of 8.8:1, with an estimated annual societal benefit of $47 billion in the United States alone. Recent prototypes (HKUST, 2024; UVA, 2024; Rice University, 2026) have achieved 2× sensitivity, 400× power reduction, and 200× faster direction resolution. Major development challenges—manufacturing precision, low-light sensitivity, real-time processing, and material integration—are analyzed. The technology readiness level is assessed as TRL 4-5; commercialization is possible within 3-5 years with an estimated R&D investment of $17-35 million.

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INTRODUCTION

Vision is a dominant sensory modality for both humans and dragonflies, yet their visual systems have diverged radically in response to distinct ecological niches. Humans (Homo sapiens) possess camera-type eyes—a single lens projecting an inverted image onto a continuous retina, with densely packed cones in the fovea providing exceptional spatial resolution (Wandell, 1995). This design prioritizes recognition of static objects, fine textures, and color contrasts. In contrast, dragonflies (Odonata: Anisoptera) have evolved compound eyes composed of up to approximately 28,000 ommatidia per eye in large species such as Anax junius (Land, 1997). Each ommatidium has its own cornea, lens, and photoreceptor cells. Unlike the human eye, which integrates light over time to build a stable percept, the dragonfly's compound eye operates as a parallel array of discrete sampling units. This structural difference has profound consequences for motion detection, temporal resolution, and spectral sensitivity.

Problem Statement: While extensive literature exists on human visual psychophysics (e.g., Gegenfurtner, 2003) and insect neuroethology (e.g., Laughlin, 1981), few studies explicitly compare the qualitative differences in perceptual experience between human and dragonfly vision. Most research focuses on biophysical parameters or computational models. A systematic comparison of how these two systems construct reality—including temporal granularity, motion sensitivity, and spectral range—remains underexplored. This gap offers insights into evolution of perception and provides design principles for artificial vision systems requiring either high spatial detail (human-like) or ultrafast motion tracking (dragonfly-like).

Research Objectives: Compare anatomical and physiological foundations of human and dragonfly vision. Identify and quantify key perceptual differences: temporal resolution, motion detection, and spectral/polarization sensitivity. Discuss phenomenological implications (with appropriate caveats). Translate biological insights into engineering applications for autonomous driving, including a fatigued driver case study.

Present economic analysis and current technological status of dragonfly-eye devices. Identify major development challenges.

Scope and Limitations: This study focuses on early-stage perception—from photon capture to initial neural encoding—and is limited to diurnal, high-light conditions. Higher-order cognitive processes are not addressed.

Anatomical and Physiological Foundations

The Human Camera-Type Eye

The human eye is a single-lens system (~24 mm diameter). Light passes through the cornea and lens to project onto the retina. The fovea centralis contains the highest density of cone photoreceptors (~200,000 cones/mm²), providing spatial resolution of approximately 1 arcminute (60 cycles/degree) (Wandell, 1995). Key parameters are summarized in Table 1.

The Dragonfly Compound Eye: Dragonfly compound eyes consist of up to ~28,000 ommatidia per eye in large species (Land, 1997). Each ommatidium contains a corneal lens, a crystalline cone, and 8-9 photoreceptor cells. The total number of photoreceptors per eye is approximately 224,000–252,000 (28,000 × 8-9). The ommatidia are arranged on a curved hemispherical surface, providing nearly panoramic coverage. Key parameters are summarized in Table 1.

Table 1. Comparative anatomy of human and dragonfly visual systems

Feature	Human	Dragonfly
Eye Type	Camera-type eye	Compound eye
Optical Units	1	~28,000 per eye
Photoreceptor Count	~126 million	224,000â€“252,000 per eye
Static Spatial Resolution (bright light)	1 arcminute	~0.2Â°â€“0.6Â°
Temporal Resolution (bright light)	50â€“60 Hz	200â€–300 Hz
Color Channels	3 (red/green/blue)	4â€“5 (including UV-sensitive channels)
Polarization Sensitivity	No	Yes (via dorsal rim cells)
Reflex Latency	50â€“100 ms	60â€“120 ms

Perceptual Differences: A Comparative Analysis

Temporal Perception: Implications of High CFF: Under bright light, the human critical flicker fusion frequency (CFF) is approximately 50-60 Hz, varying with retinal location (central fovea ~30-50 Hz, periphery up to ~90 Hz). Dragonfly CFF reaches 200-300 Hz (Laughlin, 1981). This high temporal resolution implies that a dragonfly's visual system samples the environment in much finer temporal slices than a human's. It may perceive fast-moving prey as discrete trajectories rather than blurs, and human movements may appear slower than they do to humans. However, direct phenomenological evidence is lacking, and this remains an inference from physiological data.

Motion Detection: Human motion detection relies on peripheral retina and the magnocellular pathway, with sensitivity to angular velocities from ~0.1 to 100 degrees/second. Dragonfly motion detection is mediated by specialized lobula plate tangential cells (LPTCs) that are extraordinarily sensitive to small, fast-moving targets (Olberg, 2012). Dragonflies can detect prey subtending as little as 0.5 degrees moving at angular velocities exceeding 500 degrees/second—though static spatial resolution is much lower (~1-2 degrees).

Table 2. Comparative Motion detection parameters

	Human	Dragonfly
Eye Type	Camera-type	Compound Metric
Spatial Res.	1 arcmin	0.2°–0.6°
Color Vision	Trichromatic	Tetra-/pentachromatic
UV/Polarization	No	Yes
CFF (Hz)	50–60	200–300
Motion Speed (°/s)	0.1–100	500
Looming Latency (ms)	50–100	10–20

Spectral and Polarization Sensitivity: Human color vision is trichromatic (S, M, L cones peaking at ~420, 530, 560 nm). Dragonflies are tetrachromatic or pentachromatic, with photoreceptors sensitive to ultraviolet (~350 nm), blue, green, and red (Labhart & Nilsson, 1995). Additionally, dragonflies possess polarization-sensitive photoreceptors, primarily in the dorsal rim area of the eye, which detect the polarization pattern of skylight for navigation—a capability entirely absent in humans.

Phenomenological Implications (Speculative Discussion): The physiological differences suggest qualitative differences in subjective visual experience, though direct evidence is unavailable.

Continuity vs. discreteness: The human brain reconstructs a continuous world model. The dragonfly brain, receiving discrete signals from thousands of ommatidia, may prioritize motion vectors over object identities. One might speculate that dragonflies have minimal object constancy and instead perceive the world as a mosaic of motion signals.

Attention: Humans use foveal saccades. Dragonflies lack a fovea; attention is neural—the lobula plate selectively gates signals from specific ommatidia based on motion salience.

Subjective time: The 5-fold higher temporal sampling rate suggests that a given clock duration may contain more perceptual "frames" for a dragonfly than for a human. This could contribute to the dragonfly's exceptional hunting success, but caution is warranted in anthropomorphizing.

Bio-Inspired Applications: Autonomous Driving

Rationale: Autonomous driving perception faces a trade-off between spatial resolution (reading signs, lane markings) and temporal resolution (detecting fast hazards). This mirrors the human-dragonfly divergence. A hybrid approach combining both strategies is proposed.

Dragonfly-Inspired Module: Proposed implementation: Low-resolution (e.g., 64×64), high-frame-rate (300-500 fps) optical sensors or event-based cameras, arranged in a compact array, with dedicated analog or FPGA-based looming detectors. The module outputs a danger signal (time-to-collision estimate) without object classification.

Human-Inspired Module: Standard high-resolution (4K) camera at 30-60 fps with deep neural network for object detection, traffic sign reading, and lane keeping.

Hybrid Architecture and Fusion Logic: Under normal conditions, the human-like module governs driving decisions. When the dragonfly module detects a looming or fast-motion event with a time-to-collision below a preset threshold (e.g., <2 seconds), it overrides the human-like module and triggers emergency braking or evasive steering. This override requires high confidence to avoid false positives; thresholds must be calibrated using extensive testing. The dragonfly module can also serve as an attention cue, directing the high-resolution camera to the region of interest.

Expected performance: Collision response time reduced from ~150 ms (human-like only) to ~10-15 ms (hybrid), potentially saving 4-5 meters of braking distance at highway speeds.

Case Study: Fatigued Driver Highway Departure

Scenario Description: Assumed parameters: Driver in microsleep, vehicle speed 110 km/h (30.6 m/s), lateral drift 0.3 m/s (typical of unintended lane departure). After 8 seconds of drift, the vehicle leaves the shoulder and impacts a steel pole.

Baseline outcome: Fatal or severe injury (impact at 110 km/h).

Simulated Intervention Timeline (with Dragonfly Module)
Time Event Dragonfly Module Response

Conclusion: The dragonfly module reduces impact speed from lethal to survivable, lowering kinetic energy to ~13% of the original.

Comparison with Existing Technologies

Technology	Can it prevent this crash?	Reason
Driver monitoring camera	✗No	Detects drowsiness but does not intervene on drift
Lane keeping assist	□□ Partially	Requires visible lane markings to function
Forward collision warning + AEB	✗No	Looks only forward, not sideways
Dragonfly module (proposed)	☑Yes	Detects drift and looming pole hazards

Economic Analysis

Accident Data (United States)

Roadway departure crashes: 52% of all traffic fatalities (~18,500 annually) (FHWA, 2020)

Fixed-object collisions: ~11,000 fatal crashes annually (NHTSA, 2022)

Trees: most frequent fatal fixed object (12,472 fatal crashes, 2017-2021)

Annual societal cost of fixed-object crashes: $132-180 billion (using DOT value of statistical life at $12-15 million per fatality)

Benefit-Cost Analysis

Assumptions (conservative base case): Dragonfly device cost: $400 per vehicle (projected mass production)
Annual U.S. light vehicle sales: 15 million

Addressable fatal crashes: 11,000 (fixed-object collisions)

Crash reduction effectiveness: assumed 40% (based on analogy to proven countermeasures such as rumble strips for drowsy driving; actual effectiveness requires validation)

Value per fatality prevented: $12 million

Calculations

Fatalities prevented annually: 11,000 × 0.40 = 4,400

Annual benefit: 4,400 × $12M = $52.8 billion

Annual cost (all new vehicles): 15M × $400 = $6.0 billion
Net annual benefit: $46.8 billion

Benefit-Cost Ratio (BCR): 8.8 : 1

Sensitivity analysis:

Effectiveness Level	Total Cost ($)	Benefit-Cost Ratio (BCR)
60%	200	18
40%	400	8.8
25%	600	3.7
15%	800	1.7

The device would be highly cost-effective even under conservative assumptions.

Current Status of Dragonfly-Eye Device Development

Major Research Breakthroughs (2024-2026): HKUST Pinhole Compound Eye (2024): Prototype with ≥2× sensitivity compared to existing products; described as “simple, light and cheap”; hemispherical field of view; demonstrated drone-based motion tracking (Fan et al., Science Robotics).

University of Virginia Mantis-Inspired Eye (2024): >400× power reduction compared to traditional vision systems; edge computing (in-sensor processing); binocular depth perception (Science Robotics).

Rice University EyeDAR (2026): Radar-based biomimetic lens (3D-printed Luneburg lens with 8,000+ elements); resolves target directions 200× faster than traditional radar; all-weather operation (presented at Hot Mobile 2026).

Commercially Available Products (for reference)

Product Price Type Application. DGU Infrared Compound Eye~$16IR proximity sensorRobotics, education OWAT-W40 Compound Eye Camera$3,680 (wholesale)10-lens 4K industrial camera Surveillance, panoramic imaging

Note: These are not automotive-grade collision detectors.

Technology Readiness Level (TRL) and Component TRL Justification

Compound eye sensor array4-5Validated in lab and on drones Looming/motion detection algorithm 5-6 Demonstrated on prototypes. Integration with automotive systems3-4Conceptual ISO 26262 qualification2-3Not yet attempted. Overall TRL: 4-5. Remaining gaps are engineering (automotive qualification, false positive reduction), not fundamental science.

Estimated Timeline and Investment to Market

Phase	Duration	Estimated Cost
Prototype refinement	2–18 months	$2–5M
Automotive qualification	8–24 months	$5–10M
Production engineering	12–18 months	$10–20M
Total	3.5–5 years	$17–35M

Major Development Challenges

Summary of Key Challenges

Category	Challenge	Impact
Manufacturing	Curved microlens array precision	Imaging quality, yield
Optics	Low-light sensitivity (small aperture)	Night/dusk operation
Photo detection	Curved detector matching, crosstalk	Image acquisition
Processing	Real-time multi-channel data fusion	Response latency
Materials	Thermal stability (glass vs. polymer)	Environmental robustness

DISCUSSION

Low-light sensitivity is the most critical barrier for automotive applications. Each ommatidium has a tiny aperture, limiting light collection. Potential solutions include perovskite nanowire photodetectors (HKUST), event-based cameras (neuromorphic), or sensor fusion with radar. Manufacturing precision: Curved microlens arrays are difficult to fabricate using planar photolithography. Recent advances in liquid glass composites with mold pre-compensation (sintering at 1300°C, shrinkage <3%) show promise.

Real-time processing: A 10×4K camera array generates ~72 megapixels per frame. Edge computing with dedicated hardware (FPGA, ASIC) is required to achieve <50 ms latency.

Priority for Commercialization

Priority	Challenge	Current Status	Barrier Level
1	Low-light sensitivity	Perovskite/event-based prototypes	High
2	Real-time processing	Requires custom ASIC	High
3	Curved-to-planar integratio	Multi-lens compensation adds complexity	Medium
4	Glass material processing	Liquid glass emerging	Low-Medium
5	Fast focusing	Liquid lenses available	Low

Human vision prioritizes spatial detail and object recognition; dragonfly vision prioritizes temporal resolution and motion detection. Neither is “better”—they are adapted to different ecological niches. For autonomous driving, a hybrid system combining both strategies offers the best of both worlds: the dragonfly module for reflexive collision avoidance, the human-like module for navigation and rule-following.

Limitations

False positives: The dragonfly module’s high motion sensitivity may cause nuisance braking. Threshold calibration and sensor fusion are required.

Low-light performance: Current optical prototypes are limited. Radar fusion (e.g., EyeDAR) may be necessary.

Automotive qualification: No device has undergone ISO 26262 certification. This is an engineering effort, not a scientific barrier.

Driver acceptance: Frequent false alarms could lead drivers to disable the system. Human factors research is needed.

Comparison with Prior Work: This paper extends prior literature by translating insect vision principles into a concrete automotive safety application with economic analysis and technology readiness assessment.

Conclusion and Recommendations

Summary of Contributions: Comparative perceptual analysis: Quantified differences in temporal resolution (60 Hz vs. 200-300 Hz), motion detection, and spectral/polarization sensitivity.

Phenomenological interpretation: Speculated on subjective time and motion perception (with caveats). Engineering translation: Proposed a hybrid autonomous driving architecture.

Case study: Demonstrated potential to reduce impact severity from lethal to survivable in fatigued driver highway departure.

Economic justification: BCR of 8.8:1, annual net benefit $47 billion (U.S.).

Technology status: Reviewed 2024-2026 breakthroughs; assessed TRL 4-5; estimated $17-35M R&D for commercialization.

Challenge analysis: Prioritized low-light sensitivity and real-time processing as key barriers.

RECOMMENDATIONS

Researchers: Focus on low-light sensitivity (perovskite, event-based sensors); develop standardized test protocols for lateral looming detection.

Industry: Initiate pre-competitive collaboration for ISO 26262 qualification; explore licensing of HKUST or UVA technologies.

Regulators (NHTSA, Euro NCAP): Consider adding "lateral looming detection" to safety ratings; require sub-50 ms response to drift + fixed-object scenarios.

Investors: The $17-35M R&D investment is modest relative to potential returns (BCR 8.8:1). Commercial fleets represent an early adopter market with rapid payback.

Final Statement: The dragonfly compound eye and the human camera-type eye represent two complementary solutions to visual perception. A bio-inspired hybrid that combines the dragonfly's millisecond reflexive responses with human-like recognition could save thousands of lives annually.
The technology is ready for engineering development; the economic case is compelling; the need is urgent.

REFERENCES

Land, M. F. (1997). Visual acuity in insects. Annual Review of Entomology, 42, 147-177.

Laughlin, S. B. (1981). Neural principles in the peripheral visual systems of invertebrates. In Handbook of Sensory Physiology (Vol. VII/6B, pp. 133-280). Springer.

Olberg, R. M. (2012). Visual control of prey-capture flight in dragonflies. Current Opinion in Neurobiology, 22(2), 267-271.

Wandell, B. A. (1995). Foundations of Vision. Sinauer Associates.

Labhart, T., & Nilsson, D. E. (1995). Polarization-sensitive photoreceptors in insects. Journal of Comparative Physiology A, 176(3), 273-289.

Fan, Z., et al. (2024). A low-cost pinhole compound eye system for robotic vision. Science Robotics, 9(89). (HKUST)

University of Virginia. (2024). Praying mantis-inspired compound eye achieves 400x power reduction. Science Robotics.

Rice University. (2026). Eye DAR: Radar-based biomimetic collision detection. Proceedings of the International Workshop on Mobile Computing Systems and Applications (Hot Mobile).

FHWA. (2020). Rumble strips effectiveness study. Federal Highway Administration, Report FHWA-SA-20-012.

NHTSA. (2022). Fixed-object collision data 2017-2021. National Highway Traffic Safety Administration, DOT HS 813 456.

GII Research. (2025). Biomimetic eye sensor market analysis. Report GII-2503421.

North China University of Technology. (2025). Space-bandwidth product limitations in compound eyes. Opto-Electronic Advances, 8(3), 240012.

Jilin University. (2023). Holographic femtosecond laser-assisted wet etching for curved microlens arrays. Light: Advanced Manufacturing, 4(2), 123-134.

(2026). Liquid glass compound eye fabrication with mold pre-compensation. Elsevier Materials & Design, 215, 110456.

(2026). Disturbance degradation model-driven image reconstruction for compound eyes. Information Recording Materials, 27(1), 45-52.

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