FN-Merge-KameraAuge-EN-v0.1-2026-05-17

Research Note — Camera and Eye Compared

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1. Thesis

Module M1 (CATENA) showed that all measurement chains share the same structure. This module works it through on **two concrete systems**: camera and eye. Both have a lens, an aperture and an image plane; both turn incident light into a signal. The obvious inference — tested model M1 — reads: *"The camera works like the eye. The sensor corresponds to the retina; differences are gradual (resolution, quality)."*

This module's claim: the correspondence ends with the optics. At **every** subsequent station of the signal chain the systems differ not gradually but structurally — and not because one is worse, but because they solve **different tasks**.

The analogy was historically productive (Kepler, Descartes) and remains valid for the optics. As a model of image formation it misleads.

2. Assumptions

1. The optics of both systems (lens, aperture, image plane) are similar enough that differences in the subsequent stations can be considered in isolation.
2. Receptor and pixel densities are measurable and documented.
3. Dynamic range is definable as the ratio of largest to smallest distinguishable luminance.
4. Colour sampling can be described as a spatial mosaic of channel types.
5. Comparisons between systems require a **common reference quantity** — for imaging systems the visual angle, not area.

3. Mathematical model

M1 — "the camera works like the eye": sensor and retina are functionally equivalent transducer surfaces; differences are scalings.

M2 — sensor geometry. The sensor has constant density $\rho_{\text{cam}}(\varepsilon) = \text{const}$. Cone density falls with eccentricity ε (degrees from the fixation point):

$$\rho_{\text{eye}}(\varepsilon) \approx \rho_0 + (\rho_{\max}-\rho_0)\,e^{-\varepsilon/0.8} + a\,e^{-\varepsilon/6}.$$

The robust comparison runs via **angular resolution** in cycles per degree (cpd), not via areal density:

$$\text{cpd}_{\text{cam}} = \frac{N_{\text{px}}}{2\,\theta_{\text{FOV}}}.$$

M3 — dynamic range. Range in stops $B = \log_2(L_{\max}/L_{\min})$. To be distinguished are **instantaneous** range (one adaptation state) and **adaptive** total range.

M4 — colour sampling. A mosaic $M(i,j) \in \{R,G,B\}$ resp. $\{L,M,S\}$. Regularity as the fraction of matching positions under a shift by the period:

$$R = \frac{1}{N}\sum_{i,j} \mathbb{1}\!\left[M(i,j) = M(i+2,j+2)\right].$$

Symbol	Meaning	Unit
ε	eccentricity	degrees
ρ	receptor/pixel density	1/mm²
cpd	angular resolution	cycles/degree
B	dynamic range	stops
R	regularity of the mosaic	—

4. Parameters

Scenario	Setup
A geometry	eccentricity 0–40°; sensor 24 MP on APS-C (23.5 × 15.6 mm); camera angular resolution at 50° field of view
B dynamic range	sensor 13 stops; eye instantaneous 6.5, locally adapted 20, fully adapted 39.5 stops
C colour	mosaic 24 × 24; Bayer RGGB; cones L:M ≈ 2:1, S ≈ 6 %, foveola without S

Tolerance: $\varepsilon = 0$ — one structural difference suffices to refute M1.

5. Prediction

Scenario	Expectation
A	sensor constant, eye strongly falling; angular resolution comparable at the centre
B	sensor superior instantaneously, eye superior when adapted — ranking reverses
C	Bayer strictly periodic, cone mosaic irregular; S fraction far below 25 %

6. Falsification criterion

M1 is refuted as soon as a difference is demonstrated that **cannot** be represented as a scaling: a different distribution form, a reversal of ranking depending on conditions, or a different channel structure.

7. Competing models

- **K1 — camera analogy (M1):** tested baseline; historically introduced by Kepler and Descartes.
- **K2 — foveation as a resource strategy:** high resolution only at the centre of gaze, compensated by fast eye movement; saves nerve fibres and processing.
- **K3 — adaptation instead of range:** the eye shifts its working window instead of enlarging it.
- **K4 — active vision (Gibson, O'Regan & Noë):** seeing is an activity, not image reception; the saccade is part of the perceptual process.
- **K5 — objective-function argument:** sensors are designed for reproducibility, eyes for invariance and survival relevance.
- **K6 — evolutionary constraint:** the inverted vertebrate retina (blind spot, light path through the nerve layer) is a developmental legacy, not an optimisation — cephalopods have the everted arrangement.

8. Domain of failure

- **Source situation.** Receptor densities after Curcio et al. (1990), historically Østerberg (1935); sensor data from manufacturer specifications. All values **scatter considerably** between individuals and measurement methods. The L:M ratio varies individually between roughly 1:1 and 16:1 without those affected noticing any difference.
- **The areal density comparison is unsuitable for performance statements.** Retina and sensor have different sizes and focal lengths. It shows only the **distribution form**; for performance comparisons the angular resolution serves. (See section 11, correction.)
- **The camera's angular resolution depends entirely on the lens.** With a telephoto lens it clearly exceeds the eye, with a wide angle it falls below. An absolute comparison without stating focal length is meaningless.
- **Dynamic range figures are conventions.** "13 stops" depends on the chosen noise criterion; "6.5 stops" for the eye likewise on the criterion for "simultaneously distinguishable".
- **No comparison of processing.** Image signal processor and visual cortex are left out — the largest differences lie there, but so does the greatest uncertainty.
- **Only one eye, only one sensor type.** Compound eyes, mirror eyes, Foveon and organic sensors are missing (see wishlist N2).

9. Simulation

Numerical evaluation in `kamera_auge_simulation.py`:

1. Scenario A: density profiles over eccentricity; centre/periphery ratio; angular resolution of both systems.
2. Scenario B: dynamic ranges in stops and decades; test for reversal of ranking.
3. Scenario C: generation of both mosaics; channel fractions; regularity; S fraction in the central foveola.

Results in `kamera_auge_results.json`, plot as `kamera_auge_szenen.svg` (four subplots).

10. Result

10.1 A — sensor geometry

Quantity	Eye	Sensor
density at centre	$1.80 \cdot 10^5$ /mm²	$6.55 \cdot 10^4$ /mm²
density at 40°	$4.5 \cdot 10^3$ /mm²	$6.55 \cdot 10^4$ /mm²
centre/periphery ratio	**39.8**	**1.0**
area fraction at peak resolution	~0.01 %	100 %

Angular resolution (the robust comparison):

System	cycles/degree
eye, fovea	60
eye, 20° eccentricity	6
camera (24 MP, 50° field of view)	60

Assessment M1: refuted.

10.2 B — dynamic range

System	Stops	Decades
sensor (full frame, base ISO)	13.0	3.91
eye, instantaneous	6.5	1.96
eye, locally adapted	20.0	6.02
eye, fully adapted	39.5	11.89

Instantaneously the sensor is superior by 6.5 stops; fully adapted the eye by 26.5 stops. **Assessment M1: refuted.**

10.3 C — colour sampling

Quantity	Bayer	Cone mosaic
channel 1 (R / L)	0.250	0.642
channel 2 (G / M)	0.500	0.290
channel 3 (B / S)	0.250	0.068
regularity	**1.000**	**0.528**
S fraction in the central foveola	—	**0.000**

Assessment M1: refuted.

11. Assessment

M1 ("the camera works like the eye") is refuted in all three scenarios — at three different stations of the signal chain from Module M1.

Scenario A yields the most surprising finding. The naive expectation would be that one system beats the other in resolution. In fact they are **practically level** at the centre: around 60 cycles per degree for the eye in the fovea, likewise for a 24 MP camera with a normal lens. The difference lies not in the peak value but in the **area**. The camera delivers this resolution across the entire image; the eye across about 0.01 % of the visual field. At 20° eccentricity it has fallen to a tenth.

From this the saccade follows. Because only a tiny section is sharp, the eye must jump three to four times per second to scan the scene. **The sharp, complete image we believe we see exists at no point in time on the retina** — it is assembled over time. Scenario A is thus also a continuation of the perception strand: what we take for a likeness is a construct (Module 02, L1, L5). The camera does not need this construction because it resolves equally everywhere.

Scenario B shows that the question is wrongly posed. “Who has more dynamic range” has no answer without a time specification. Instantaneously the sensor wins clearly — in a single adaptation state the eye sees only about 6.5 stops simultaneously, the sensor 13. Across adaptation this reverses: nearly 40 stops, about twelve decades, from starlight to sunlight.

These are two different **solutions**: range versus tracking. The sensor enlarges the window, the eye shifts it. Both have a price. The eye’s price rarely appears in such comparisons: adaptation costs **time** (dark adaptation up to 30 minutes) and makes **absolute brightness judgements impossible**. Nobody can estimate the luminance of a surface in cd/m^2; a sensor delivers reproducible absolute values. This is precisely why light is measured with instruments and not with the eye — and precisely why the transfer-curve compression from Module M1 (scenario B) is the fitting solution here, not a deficiency.

Scenario C shows two opposing design decisions. The Bayer matrix is strictly periodic (regularity 1.0) with even channel distribution. The cone mosaic is irregular (0.53), strongly L-weighted, and the S fraction lies at about 7 % instead of 25 %. **In the central foveola there are no S cones at all** — at the point of sharpest vision blue is not sampled.

Both decisions produce different errors. Periodicity leads to **moiré**: when a fine periodic pattern meets a periodic grid, spurious structures arise — the same phenomenon as the aliasing from Module M1, only spatial. Irregularity avoids moiré but produces noise instead. The missing blue fraction is barely noticeable because sharpness information comes from the light-dark channel anyway (Module L3, opponent colours) — a division of labour the camera does not have.

The core: objective function, not quality. In all three scenarios the question “which system is better” is unanswerable because the systems solve different tasks. The sensor is designed for **reproducibility and absolute values**: same scene, same numbers, measurable and comparable. The eye is designed for **invariance, contrast and survival relevance at minimal cost**: detect what moves, recognise the same object under any illumination, manage with as few nerve fibres as possible. **The fovea is not a poor sensor matrix but a different solution** — high resolution only where one is currently looking, plus a fast gaze system.

This confirms the finding from Module M1 at a concrete level: the transducer is not neutral but designed for a task. Whoever measures it against a foreign task finds deficiencies that are none.

On the correction of the first version. The first draft compared cone density per mm^2 directly with pixel density per mm^2 and derived a “crossover at 1.07°”. This is unusable for performance statements: retina (focal length ~17 mm) and sensor (focal length depending on lens) map different angles onto different areas, so densities per mm^2 are not comparable. The comparison was converted to **angular**

resolution; the density curves remain but now show only the distribution form. Only this made the actual finding visible (equal peak resolution, different area). Documented rather than silently corrected (workshop line).

12. Next test

Module N2 Animal Eyes (OCULI) as the obvious continuation: compound eye, mirror eye, pit eye; convergence of the camera eye in vertebrate and cephalopod; UV and polarisation vision. There the objective-function thesis is tested against a broader material base.

Possible extension v0.2: image signal processor versus visual cortex; temporal resolution (shutter speed versus flicker fusion); rolling shutter versus saccadic suppression; real MTF curves instead of density models.

Appendix A — Cross-references

- Practice explanation: `PRAXIS-KameraAuge-EN.md` · Companion paper: `BEGLEITPAPIER-KameraAuge-EN.md`
- Tool: `CAMERA-COMPARATA.html`
- Code: `kamera_auge_simulation.py` · Plot: `kamera_auge_szenen.svg` · Data: `kamera_auge_results.json`
- **Modules used:** M1 signal chain (structure), 04 camera model, 05 lenses, 09 colour mixing, L3 opponent colours, L1/L5 (construction)
- **Planning document:** `MERGE-ARCHITEKTUR-v0.1-2026-05-17.md`

Appendix B — External stocktaking

- **Curcio et al. (1990)** — receptor densities of the human retina.
- **Østerberg (1935)** — historical first survey.
- **Roorda & Williams (1999)** — cone mosaic in vivo, individual L:M scatter.
- **Bayer (1976)** — colour filter array, US patent 3,971,065.
- **Land & Nilsson (2012)** — *Animal Eyes*, comparative optics.
- **O'Regan & Noë (2001)** — sensorimotor theory of vision.

What the workshop note adds: the bringing together into a comparison along the signal chain from Module M1; the conversion to angular resolution as a common reference quantity; the finding of equal peak resolution at completely different area; the objective-function thesis as a replacement for the quality question.

Appendix C — Sources

- Curcio, C. A.; Sloan, K. R.; Kalina, R. E.; Hendrickson, A. E. (1990). Human photoreceptor topography. *J. Comparative Neurology* 292:497–523.
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- Roorda, A.; Williams, D. R. (1999). The arrangement of the three cone classes in the living human eye. *Nature* 397:520–522.
- Land, M. F.; Nilsson, D.-E. (2012). *Animal Eyes*. 2nd ed., Oxford University Press.
- O'Regan, J. K.; Noë, A. (2001). A sensorimotor account of vision and visual consciousness. *Behavioral and Brain Sciences* 24:939–1031.

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