

An aberration-corrected bionic eye for full-colour vision and event-driven motion detection

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Vision sensors are central to machine vision and intelligence. However, conventional planar devices rely on multielement optics and external processors to correct optical aberrations. This approach constrains miniaturization, reduces power efficiency and generally limits the field of view. Curved sensors can provide compact, aberration-corrected imaging, but their resolution has been below practicable levels. Here we present a bioinspired bionic eye system based on a hemispherical tandem artificial retina. This high curvature image sensor achieves a pixel density of 1,905 ppi with 367,500 total pixels, providing full-colour imaging across 300–800 nm and an aberration-corrected field of view exceeding 160°. Furthermore, the tandem design enables in-sensor, event-driven motion detection. Compared with frame-based imaging, this approach reduces the demand for bandwidth by over 99.95% and achieves a motion recognition accuracy of 98.6%. This work addresses the resolution bottleneck of hemispherical sensors and highlights their promise as compact, multifunctional vision applications.

Evolution has developed sophisticated biological vision systems that offer superior capabilities, particularly in achieving aberration-free vision across ultrawide fields and efficiently detecting spectral and motion information. These superior vision abilities are especially crucial for cyprinid fish inhabiting dimly lit environments. Their aberration-free vision stems from two key adaptations: a curved retinal geometry that corrects field curvature aberrations, and a unique assembly of cone cells at varying depths within the retina. This arrangement aligns with the different focal lengths of various wavelengths of light, effectively correcting chromatic aberrations¹. The effective detection of spectral and motion information is achieved by retinal neurons. The response of cone cells to specific wavelength ranges ensures broad

spectral vision, while motion sensing is facilitated by the ON and OFF retinal ganglion cells (RGCs)². These cells are sensitive to changes in light intensity over time and are capable of encoding temporal dynamic visual information. The elegant optical design and effective detection abilities of these animals provide accurate environmental perception, while simultaneously reducing the computational load on the brain and decreasing energy consumption.

The above high-performance vision capabilities are vital for a broad range of technological applications including drones, autonomous vehicles and robotics. However, current imaging systems are primarily based on frame-based planar silicon image sensors, which limit the system performance in multiple respects. The planar detector

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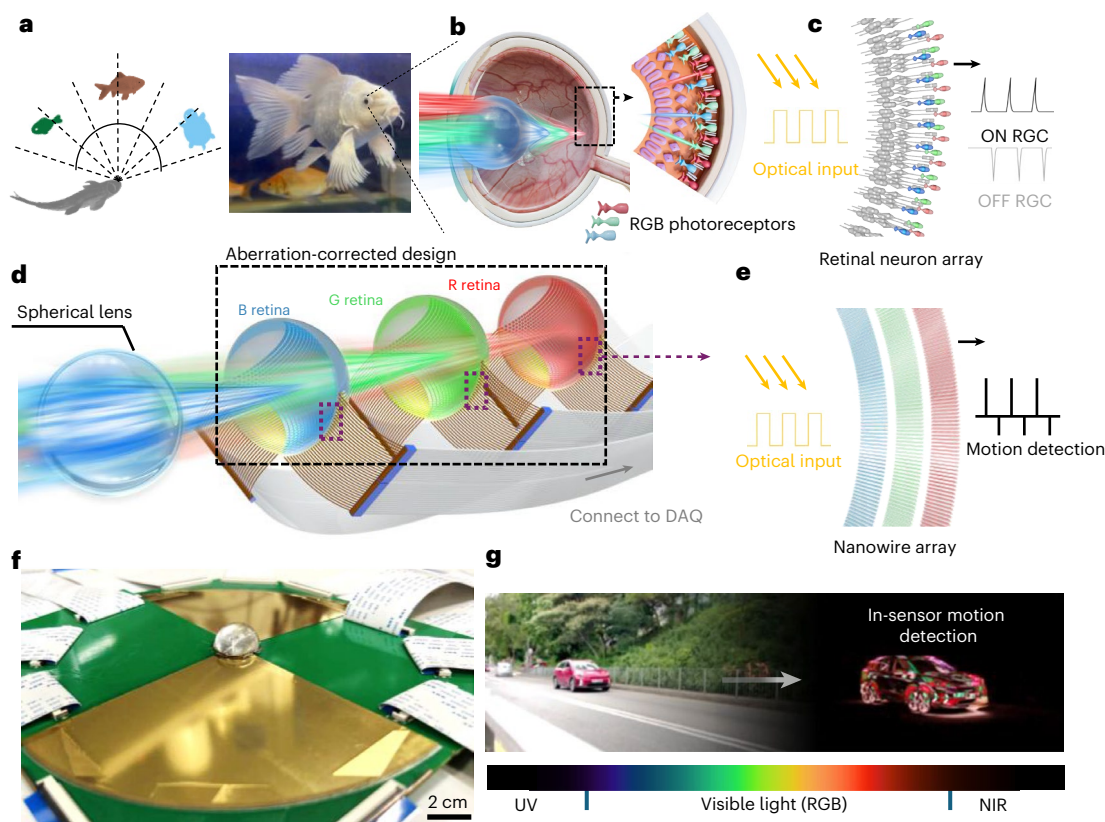


Fig. 1 | Biological vision and biomimetic design. **a**, Schematic ultrawide FoV vision of fish eyes with spherical lens and a photograph of a cyprinid fish. **b**, Schematic of a cyprinid fish eye, along with its neuron structure. **c**, A retinal neuron array with effective motion-processing functions. **d**, Schematic structure

of our bionic eye device. DAQ, data acquisition. **e**, The THE-BRENA structure with full colour motion detection ability. **f**, Photograph of the integrated bionic eye device. **g**, Full colour motion detection ability.

geometry, which is typically fabricated with conventional micro-fabrication processes, has serious field curvature aberration problems even with complex lenses³. For a silicon CMOS/CCD image sensor, the spectrum information is detected via a single-layer image sensor in combination with a colour filter array, which causes even lower light absorption efficiency^{4–6}. Furthermore, the planar-image-sensor-based camera system inevitably has chromatic aberration due to the focal length dispersion for different colours⁷. And unlike a biological retina, which can extract features of interest via in-retina computing, conventional frame-based image sensors require additional computation units. Such a separated design leads to signal redundancy and high energy consumption, especially for motion detection and recognition (MDR) systems that need to process rich temporal dynamic information^{8–11}.

Inspired by the vision system of cyprinid fish, in this study we present a high-performance bionic eye. This device utilizes a tandem hemispherical biomimetic retinal neuron array (THE-BRENA) featuring distinct red (R), green (G) and blue (B) retina layers. The hemispherical geometry of the device not only provides an ultrawide field of view (FoV) exceeding 160° but also corrects field curvature aberrations effectively. The tandem architecture, coupled with precisely engineered perovskite bandgaps, enables full colour vision across a broad spectral range (300–800 nm). Our unique approach to correcting chromatic aberration involves strategically aligning the RGB retinas with the respective focal points of RGB light, enhancing image clarity. Additionally, retinal neuron functions are mimicked using core–double-shell perovskite–metal oxide heterojunction nanowire arrays. This arrangement supports self-powered, event-driven photoresponse, making the system highly suitable for MDR applications. Notably, the device achieves a high pixel density of

1,905 pixels per inch (ppi) and a high fill factor (close to 300%) due to the utilization of a three-dimensional (3D) laser-engraving method for electrode patterning and the tandem retinal design. Ultimately, our bionic eye device boasts 367,500 pixels ($350 \times 350 \times 3$), achieving a practical resolution (benchmark figure shown in Supplementary Fig. 1). Compared to conventional cameras, this bionic eye offers substantial improvements in energy efficiency (being self-powered) and computational efficiency (reducing bandwidth demand by >99.95%) for MDR applications. When integrated with a convolutional neural network–long short-term memory (CNN-LSTM) model, the system demonstrates exceptional motion detection accuracy, achieving 98.57% after only five training epochs. Overall, this work introduces a groundbreaking bioinspired vision sensor design that offers the possibility to largely enhance the performance of next-generation intelligent systems.

Structure of the bionic eye

Figure 1 illustrates a biomimetic architecture that effectively emulates natural vision systems. Unlike the planar image sensors prevalent in contemporary artificial vision systems, many animals have evolved a curved retinal configuration, which supports a compact and efficient visual apparatus. Cyprinid fish (Fig. 1a,b), for example, have near spherical lenses, allowing them to capture optical information across an ultrawide FoV. Additionally, their retinas exhibit a stratification of cone cells that aligns with the chromatic dispersion, facilitating sharp optical focus across a broad spectral range, as illustrated in Fig. 1c. It is worth noting that most cyprinid fish rely solely on gradient-index lenses to mitigate chromatic aberrations and achieve strong visual performance. Meanwhile, some species—such as rudd—have evolved vertically stacked retinal structures to further enhance full colour information detection⁴. Spectrum detection is achieved through

narrow-band cone cells, which possess wavelength-dependent sensitivity, enabling these fish to perceive a vibrant underwater world. Upon the detection of optical stimuli by the photoreceptor cells, the signals are relayed to bipolar cells and RGCs for subsequent processing and encoding. The processing of motion information involves the ON and OFF RGCs. An ON RGC generates excitatory responses, while an OFF RGC provides inhibitory signals in reaction to increases or decreases in light intensity, respectively. As a result, moving objects are distinguishable from the static background. These powerful features, including geometric correction of optical aberrations, reliable spectrum detection ability and in-retina computing of motion information, are crucial for the survival of these fish.

Inspired by the highly efficient vision architecture observed in cyprinid fishes, we have designed a bionic eye based on the THE-BRENA, which is schematically shown in Fig. 1d,e. The hemispherical detector design corrects field curvature aberration. The tandem design corrects chromatic aberrations while leveraging full colour vision. Figure 1f shows photographs of the integrated device. Additionally, the device boasts motion sensitivity facilitated by an event-driven photoresponse. Mirroring the motion signal detection found in retinal neurons, the nanowire structure is activated only when alterations in the visual scene occur, thus permitting the direct capture of motion data as illustrated in Fig. 1g. This feature significantly improves the computational and energy efficiency of the entire system. Hence, the fusion of advanced optical design and in-sensor processing capabilities has enabled the successful development of our THE-BRENA device.

Full colour and event-driven photoresponse of THE-BRENA

The burden of processing vast amounts of data is a significant obstacle for MDR systems. As depicted in Supplementary Fig. 2, traditional frame-based MDR systems necessitate numerous processing stages and extensive signal communications. This complexity results in low computational and energy efficiency. Event-driven devices, such as dynamic vision sensors, offer the potential for real-time analysis of temporal dynamic vision information^{12,13}. Nonetheless, dynamic vision sensor technology involves complex circuitry to detect changes in light intensity, as shown in Supplementary Fig. 3. This complexity leads to several limitations: a low fill factor of <30%, an inability to determine the exact amplitude of events and difficulties with spectrum differentiation. Moreover, integrating these components into a curved substrate presents a formidable challenge. Therefore, the pursuit of a full-colour MDR device that delivers high-fidelity imaging combined with energy and computational efficiency remains challenging.

Intriguingly, high-density retinal neurons have a commendable ability to detect and process visual information as illustrated in Fig. 2a. Inspired by cyprinid fish vision, we have developed our THE-BRENA structure, as shown in Fig. 2b. Each active unit consists of a core-double-shell structure composed of perovskite–NiO–In₂O₃ nanowires, capable of detecting and processing colour and motion information in real-time under a 0-V bias. This structure is underpinned by three layers of porous aluminium membranes (PAMs) that boast well-aligned nanochannels for incorporating light-sensing materials. The biomimetic vertical assembly of light absorption nanowires results in a fill factor close to 100%. Furthermore, because three pixels with different colour selectivity are vertically stacked within each active area, the device's effective fill factor can reach up to 300%. The spatial efficiency of the bionic eye significantly surpasses those of state-of-the-art MDR devices as listed in Supplementary Table 1^{8–11,14,15}. It is worth noting that our bionic eye boasts 367,500 pixels, exceeding the pixel counts of commercial planar event sensors (for example, Sony IMX 637, IMS647), which have up to ~320,000 pixels.

Spectral information is crucial for accurately capturing and reconstructing visual scenes^{16–18}. The tandem design of our THE-BRENA structure results in enhanced full colour imaging capabilities. Perovskites

(MAPbCl₃, MAPbBr₃ and MAPbI₃) were selected for the absorption layers due to their exceptional optoelectronic properties and adjustable energy bands. Figure 2c illustrates the spectral sensitivity of the three channels. Each type of perovskite corresponds to a distinct spectral sensitivity, enabling precise spectrum detection. The fabrication process and material characterization results are presented in Supplementary Figs. 4–6. Specifically, each layer shows the highest responsivity near its band edge, while longer wavelengths penetrate deeper (Supplementary Fig. 7), thereby increasing the active area at the perovskite–NiO interface and the current spike amplitude.

Motion information is processed via the event-driven photoresponse. Figure 2d illustrates the energy band diagram of the MAPbX₃–NiO–In₂O₃ structure, which forms an energy well for hole accumulation. Based on this, the device develops a self-powered event-driven photoresponse. Specifically, under a 0-V bias, the device generates positive or negative current spikes in response to increases or decreases in light intensity, respectively, and exhibits no response to static illumination. Figure 2e–g illustrates the photoresponse of pixels on each of the three layers, respectively. THE-BRENA structure encodes both the occurrence and the amplitude of changes in the optical input to achieve accurate motion detection. Meanwhile, THE-BRENA operates effectively in low-light conditions (down to 11, 2 and 0.78 $\mu\text{W cm}^{-2}$ for B, G and R illumination, respectively). Supplementary Fig. 8 illustrates the current–voltage (*I*–*V*) curves for each layer. The tandem three-layer structure, as shown in Fig. 2h, enables the device to distinguish colour spectra. Supplementary Fig. 9 illustrates light penetration of different wavelengths in the tandem structure. Figure 2i and Supplementary Figs. 10 and 11 further illustrate the photoresponse of the three channels under illumination by different wavelengths. Supplementary Fig. 12 shows the relative spectral sensitivity of the three channels. Analogous to the biological eye, which relies on three types of photoreceptor cells yet perceives a wide range of colours, our bionic eye demonstrates full colour response capability across a broad spectral window from the ultraviolet to the near-infrared (NIR, 300–800 nm). Due to the overlap of the spectral sensitivity curves, certain wavelength ranges trigger a dual-channel response. With three channels and two such overlap regions, the device can resolve at least five distinguishable spectral bands. A detailed introduction to the pixel-level photoresponse performance can be found in Supplementary Figs. 13–15 and in Supplementary Text. Such an event-driven photoresponse is derived from its perovskite–metal-oxide heterostructure as depicted in Supplementary Figs. 16–19 and detailed in Supplementary Text. Apart from typical motion-related applications, the device also shows dual-functional photoresponse behaviour as shown in Supplementary Fig. 20. By applying a bias of 3 V to the device, it can be switched from event-sensor mode to standard photodetector mode, which makes it flexible for different machine vision tasks.

In general, we have developed the THE-BRENA structure with the aim of accurately detecting and efficiently processing spectral and temporal dynamic optical information. The following section further discusses the integration of high-density arrays on hemispherical substrates and explores the application of the THE-BRENA bionic eye in MDR systems.

Integration of the high-resolution bionic eye

High-curvature image sensors hold significant potential in wide-FoV machine vision systems; however, because conventional micro-electronic fabrication processes are designed for planar substrates, pixelation on curved substrates remains a persistent challenge^{19–27}. Hemispherical nanowire arrays fabricated by PAM growth methods can directly create high-density sensing units on hemispherical geometries, but they still require high-density hemispherical electrodes for readout^{28–31}. To address this bottleneck challenge, we have developed a 3D laser-engraving method for passive matrix fabrication on hemispherical nanowire arrays. Supplementary Fig. 21 and

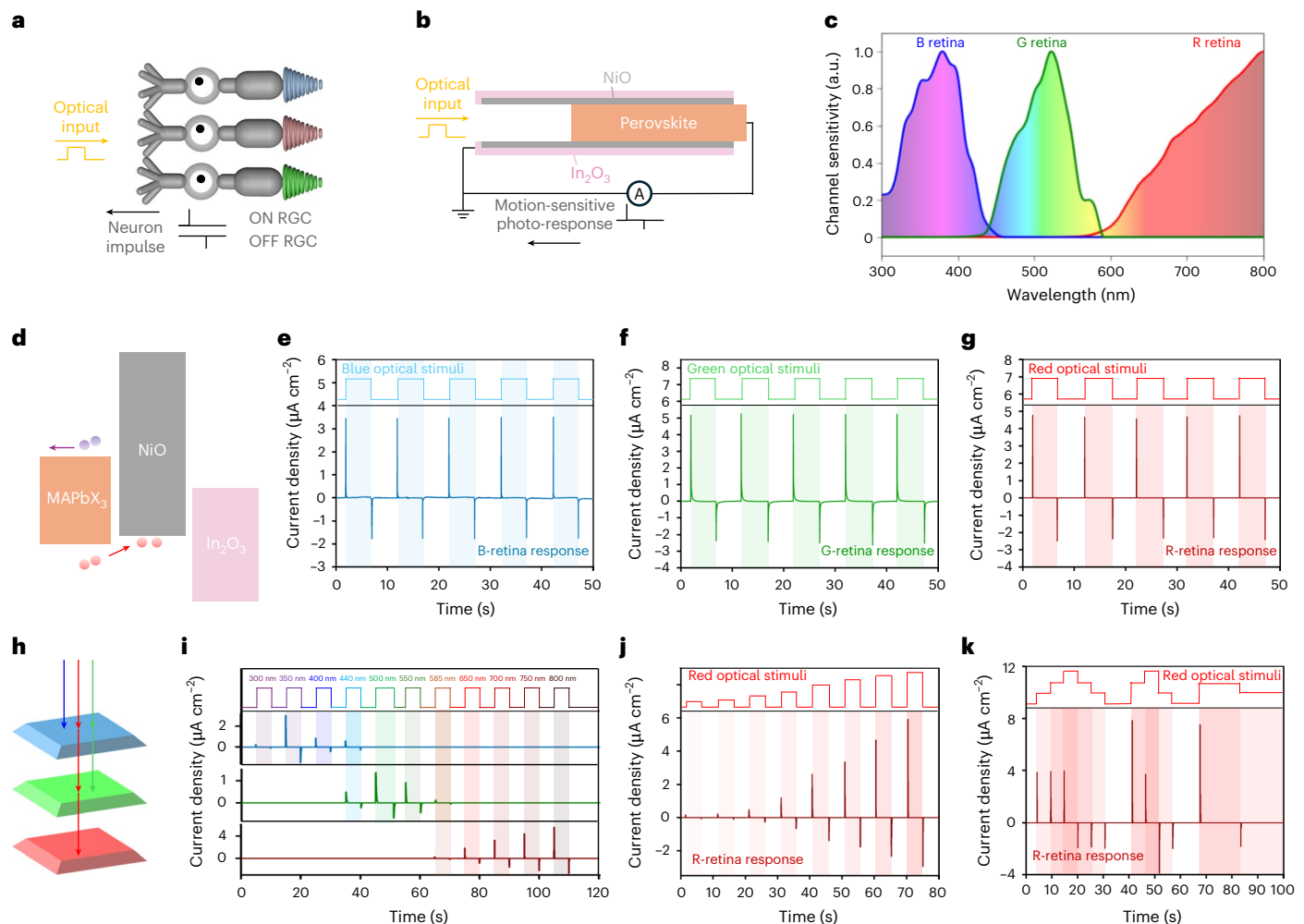


Fig. 2 | Self-powered photoresponse of the bionic eye system. **a**, Schematic illustration of the retinal structure and its biological photoresponse. **b**, Schematic of the nanowire structure and its biomimetic photoresponse behaviour. **c**, Spectral sensitivity of the B-, G- and R-retina layers. **d**, Energy band diagram of the perovskite–NiO–In₂O₃ structure. **e–g**, Event-driven photoresponse under periodic illumination: B retina at 405 nm, 1.15 mW cm^{−2} (**e**); G retina at 520 nm, 1.62 mW cm^{−2} (**f**); R retina at 650 nm, 1.28 mW cm^{−2} (**g**). **h**, Schematic

of the tandem pixel unit. **i**, Photoresponse of a tandem pixel unit under broadband illumination (300–800 nm) at ~1 mW cm^{−2}. **j**, Photoresponse of an R-retina pixel at 650 nm with light intensities of 0.04, 0.06, 0.14, 0.32, 0.64, 0.96, 1.28 and 1.60 mW cm^{−2}. **k**, Photoresponse of an R-retina pixel at 650 nm under light intensities of around 1, 2 and 3 mW cm^{−2}. All photocurrent curves were measured at 0-V bias.

Supplementary Video 1 illustrate the fabrication process. The structure of the device is schematically illustrated in Fig. 3a,b. Figure 3c shows the equivalent circuit of the passive matrix-based system. As shown in Supplementary Fig. 22a–e, the ultraviolet (UV) laser precisely focuses on a specific distance, effectively removing gold only within a narrow height region (<1.5 nm) in which the line width is kept under 20 μm. Based on this precision, we fabricated devices with electrode pitches of 40 μm. This allows for the formation of the crossbar electrode pattern by repeatedly cutting a 2D pattern and adjusting the laser source height. Such a process eliminates the need for precise 3D positioning, simplifying the procedure. The entire patterning process is completed in just 15 min. Because both nanowires and electrodes can be easily integrated, the device is suitable for large-scale manufacturing and practical applications. Supplementary Fig. 22f–h shows how the device integrated with printed circuit boards (PCBs), and Supplementary Fig. 23 shows the PCB layout.

Figure 3d displays a photograph of the integrated device. The high-resolution hemispherical device, showcased in Fig. 3e, delivers advanced imaging capabilities. This device is connected to a PCB via a gold input/output (I/O) shown in Fig. 3f. The direct deposition of a gold film on both the artificial retina and the PCB board, followed by

simultaneous patterning, obviates the need for additional wire bonding, thus enhancing manufacturing reliability. Photographs of the B, G and R retinas are presented in Fig. 3g. Due to the vapour-phase nanowire synthesis and global electrode patterning methods, the device demonstrates excellent pixel uniformity, as shown in Fig. 3h and Supplementary Fig. 24. Figure 3i reveals the angle-dependent pixel density, where each layer achieves 635 ppi (calculated based on its planar projection) over a wide field of view exceeding 160°. Given the vertical integration of three layers, the device reaches an ultrahigh pixel density of 1,905 ppi. In comparison to other bionic eyes listed in Supplementary Table 2 (refs. 3,19,21–30,32,33), the THE-BRENA bionic eye represents a significant advance. Further, the state-of-the-art laser-writing method, capable of achieving submicrometre-level resolution³⁴, allows our process to potentially fabricate devices with a pixel pitch of ~1 μm and a resolution exceeding 70,000 ppi. Moreover, due to the perovskite–NiO–In₂O₃ junction blocking carrier movement across the nanowire, the device effectively suppresses crosstalk, which ensures its high-performance imaging capabilities. Supplementary Figs. 25 and 26 show the suppression of the crosstalk issue and the response of a single pixel on the hemispherical retina, respectively.

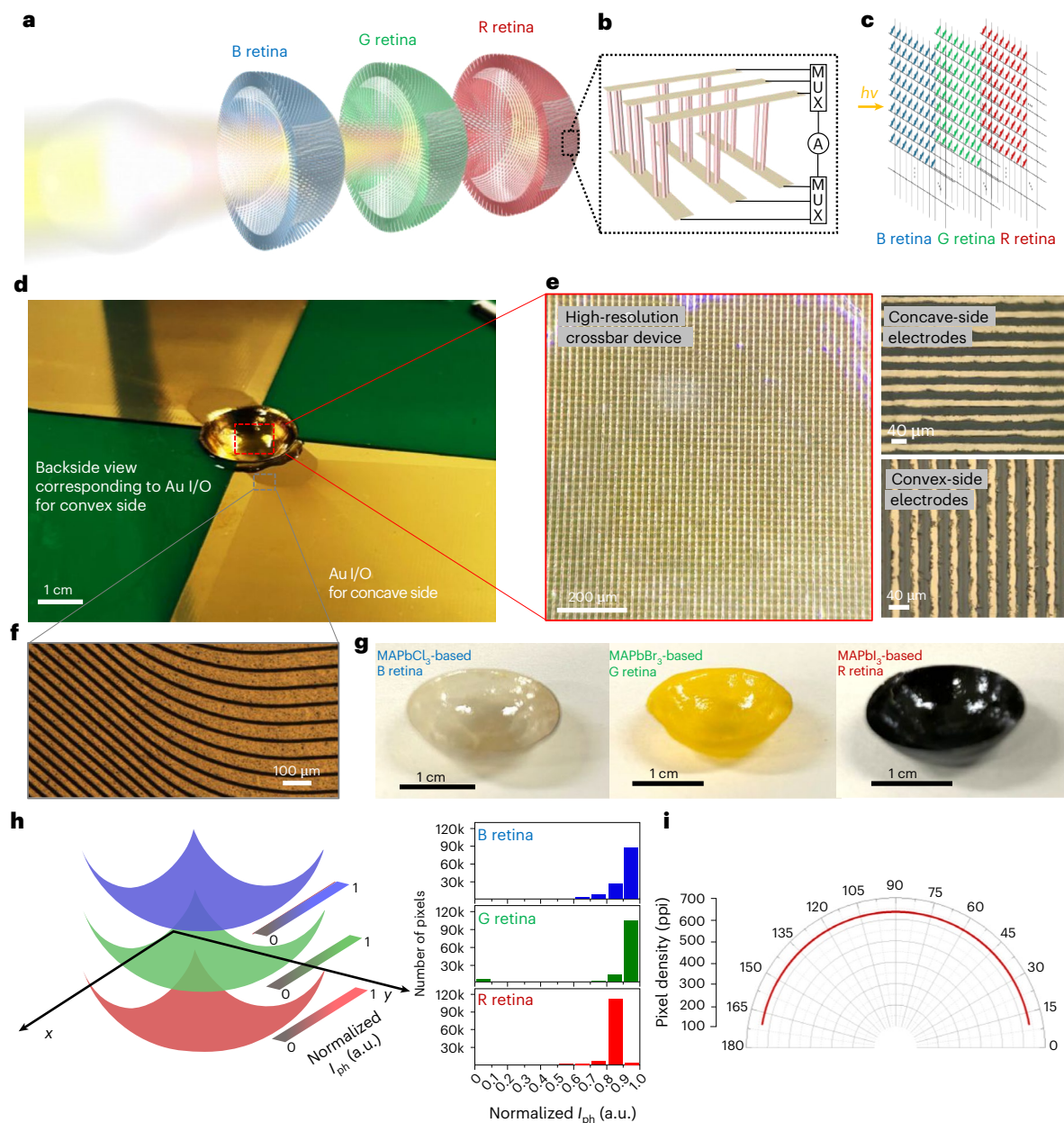


Fig. 3 | THE-BRENA-based high-resolution bionic eye device. **a**, Schematic illustration of the THE-BRENA structure. **b**, Schematic of crossbar design. **c**, Equivalent circuit diagram of the THE-BRENA structure. **d**, Photograph of the artificial retina connected to a PCB. **e**, Photographs of the crossbar electrode at

different scales. **f**, Photograph of the gold I/O contacts connecting the artificial retina to the PCB. **g**, Photographs of the B, G and R retinas. **h**, Pixel uniformity across the three layers. **i**, Angle-dependent pixel density on the hemispherical substrate.

Efficient motion detection and trajectory prediction capabilities

Figure 4 illustrates the application of the THE-BRENA bionic eye in MDR systems. Our device detects the scene of interest in Fig. 4a and produces the result shown in Fig. 4b. Because each pixel can detect the increase and decrease of light intensity, the shape of the moving objects and their moving directions can be extracted from the scene. Once the current position and moving direction of the moving objects has been detected, trajectory prediction is achieved as shown in Fig. 4c. Such real-time in-sensor motion detection and efficient trajectory prediction greatly enhance the efficiency across a broad range of applications including autonomous vehicles, smart robots and drones. Supplementary Video 2 further illustrates these motion-detection and trajectory-prediction functions via simulation.

Integrating spectrum detection with motion detection systems adds a layer of depth to data analysis, enabling more sophisticated and context-aware applications. This combination not only improves the functionality and reliability of motion detection but also opens up new possibilities across various fields by allowing systems to make more informed decisions based on visual data. Figure 4d,e shows detection by the bionic eye of both spectrum and motion information, with the R retina generating a more significant signal in response to the red object.

To further demonstrate the efficiency of the bionic eye device, we simulated motion detection and trajectory prediction, as shown in Fig. 4f. Our device performs similarly to the retinal MDR system in animals, as illustrated in Fig. 4g, which can extract motion-related features and send them to the brain for recognition. Inspired by this structure, we have developed an MDR system based on the THE-BRENA

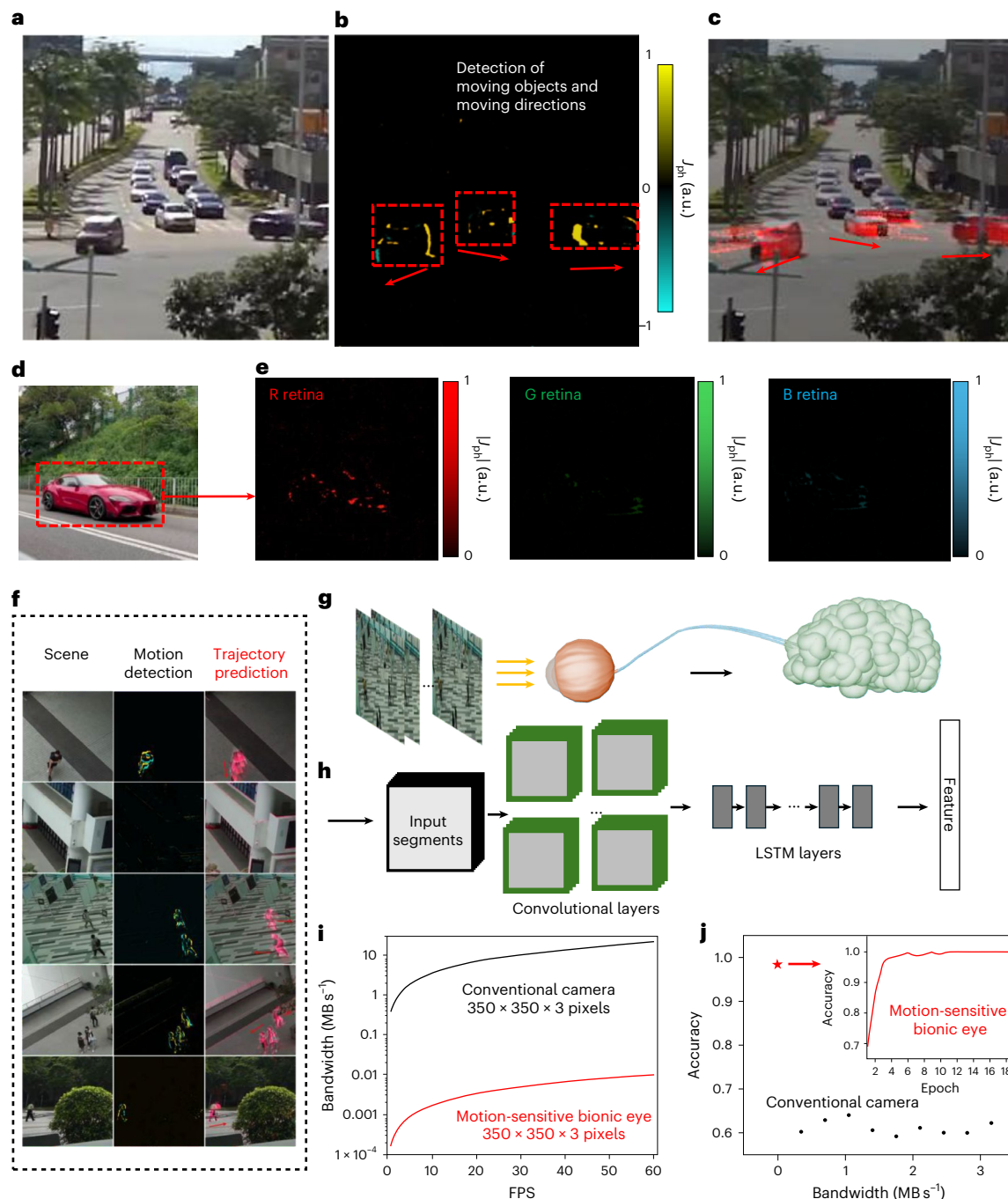


Fig. 4 | THE-BRENA-based bionic eye MDR system. **a**, The scene of interest. **b**, Scene reconstruction based on the THE-BRENA bionic eye, in which positive and negative photocurrents are normalized independently. **c**, The trajectory prediction function. **d**, The scene of interest in full-colour motion information detection demonstration. **e**, The colour-channel-dependent scene reconstruction based on the THE-BRENA device. **f**, Simulated motion detection and trajectory prediction. **g**, The schematic of an animal vision system. **h**, The architecture of the CNN-LSTM model. **i**, Comparison of bandwidth demand

between the conventional camera and the THE-BRENA bionic eye, calculated by counting activated pixel number from their respective reconstructions of the same video segment at different frames per second (FPS). **j**, Motion detection accuracy of the THE-BRENA device and conventional camera-based MDR systems after five training epochs. The input from the THE-BRENA device contains 1 frame, and the input from the conventional camera contains 1–9 frames. Inset: training accuracy of the bionic-eye-based MDR system.

bionic eye device, incorporating a CNN-LSTM architecture, as depicted in Fig. 4h. Figure 4i compares the bandwidth demand of the conventional camera and the THE-BRENA bionic eye device. Due to its specific response to features of interest, the THE-BRENA device reduces bandwidth demand by over 99.95%, significantly saving computational resources and reducing latency. The accuracy of the MDR system is displayed in Fig. 4j. Even with only one frame input to the CNN-LSTM,

the THE-BRENA bionic eye system achieves an ultrahigh accuracy of 98.57% after five epochs.

Aberration-corrected vision with ultrawide FoV

Ultrawide FoV imaging systems offer significant advantages in various applications due to their ability to monitor extensive areas. As illustrated in Supplementary Fig. 27, one single ultrawide FoV device can

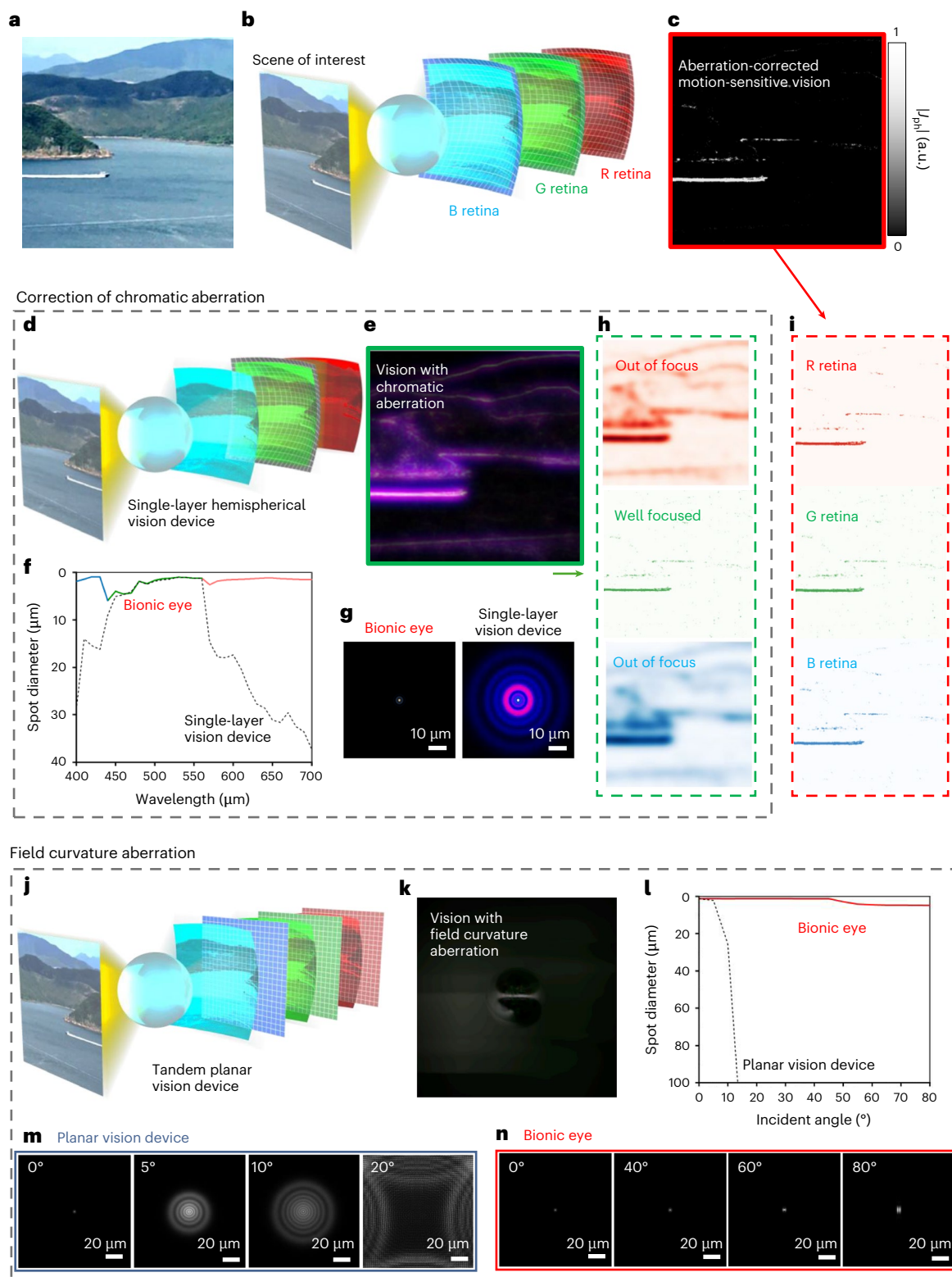


Fig. 5 | THE-BRENA bionic-eye-based aberration-corrected vision. **a**, The scene of interest. **b**, Schematic of the bionic-eye-based scene reconstruction. **c**, Scene reconstruction based on the THE-BRENA bionic eye with $350 \times 350 \times 3$ pixels. **d**, Schematic of single-layer artificial-retina-based scene reconstruction. **e**, Simulated scene reconstruction based on a single-layer artificial retina. **f**, The wavelength-dependent spot diameter focused on the THE-BRENA bionic eye and a single-layer vision device. **g**, Illustration of a white-light spot imaging based on the THE-BRENA bionic eye and the single-layer vision device, respectively.

h,i, The RGB channel output of the single-layer vision device (**h**) and the THE-BRENA bionic eye (**i**) in the scene reconstruction demonstration. **j**, Schematic of tandem planar-image-sensor-based scene reconstruction. **k**, Simulated scene reconstruction based on tandem planar image sensors. **l**, The angle-dependent spot diameter focused on the THE-BRENA bionic eye and the planar image sensor. **m,n**, Illustration of a light spot with imaging using a range of incident angles based on the tandem planar image sensor (**m**) and the THE-BRENA bionic eye (**n**).

effectively replace multiple standard cameras, eliminating blind spots and simplifying system design. However, ultrawide FoV lenses typically introduce notable optical aberrations. To address these challenges, our system uses a single spherical lens coupled with three hemispherical retinas. This design achieves low aberration with an expansive FoV exceeding 160° , as shown in Supplementary Fig. 28. The combination of a spherical lens and the THE-BRENA effectively manages field curvature and chromatic aberrations, as demonstrated in Fig. 5b,c.

Chromatic aberration is another severe issue that hampers the fidelity of imaging devices. This issue arises from the wavelength-dependent variance in a lens's refractive index: shorter wavelengths have a higher refractive index and, consequently, a shorter focal length, as depicted in Supplementary Fig. 29a. This variance results in distortions on a single-sensing-layer-based device, where different colours do not converge at the same point. A traditional solution for correcting chromatic aberration is to use a sophisticated lens set, which not only adds complexity and cost to the system but also fails to provide ideal correction across a wide spectral range⁷. In response, we have developed a tandem structure that is aligned with the lens's chromatic dispersion. For a single-layer artificial-retina-based device, while achieving well-focused imaging of green light, blue and red patterns will be focused in front of and behind the artificial retina, respectively, as illustrated in Fig. 5d. As a result, the vision will have serious colour blur, as shown in Fig. 5e–g and Supplementary Fig. 29b–e. Figure 5h,i shows imaging demonstrations based on single-layer and tandem designs, respectively, in RGB channels. When the single-layer device achieves a well-focused vision in the green light region, the blurriness in the red and blue channels is significant. Meanwhile, the bionic eye device with the tandem design achieves well-focused vision in all colour channels.

Field curvature aberration is caused by the mismatch between the curved imaging plane and the planar image sensor. As shown in Fig. 5j,k, while imaging with a tandem planar device, only a small region in the middle of the scene can be clearly detected. The use of a curved detector can geometrically correct this issue. Figure 5i–n further quantifies this performance, illustrating how the focused spot size remains under $5\ \mu\text{m}$ in diameter even with the incident light at an 80° angle. The detailed optical design is explained in Supplementary Text. In Supplementary Video 3 we further illustrate the improvement in aberration-corrected motion vision via simulation.

Discussion

Drawing inspiration from the exceptional visual acuity of cyprinid fish, we developed the THE-BRENA bionic eye, which surpasses traditional vision systems by offering excellent aberration-free imaging, full-colour vision and motion information processing.

The curved detector geometry and tandem configuration of this bionic eye correct optical imperfections such as field curvature and chromatic aberrations, resulting in an aberration-free vision device with an exceptionally wide FoV exceeding 160° , 367,500 pixels, and a pixel density of 1,905 ppi. This reaches the practical resolution level for a bionic eye device while offering the potential for large-scale manufacturing due to its simple and cost-effective fabrication method.

A key attribute of the THE-BRENA is its self-powered, full-colour, event-driven imaging capability, which performs in-sensor motion detection and efficient trajectory prediction. By focusing solely on dynamic elements, the system bypasses processing of static visual field content, eliminating over 99.95% of redundant data. This dramatically reduces computational demands and power consumption, positioning the THE-BRENA as a highly advanced tool for applications requiring rapid and accurate visual recognition and analysis.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information,

acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41563-026-02685-5>.

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Methods

Materials

All chemicals used in this experiment were obtained from Sigma-Aldrich and were used as received, without any additional purification.

Preparing PAM with lead nanoclusters

A PAM was fabricated on an aluminium substrate using a two-step hard anodization process to achieve a thickness of around 20 μm . This process involved anodizing in 0.05 M oxalic acid aqueous solutions. The voltage was gradually escalated to 120 V and maintained at this level for 2 h. Subsequently, the initial anodization layer was removed in an aqueous solution consisting of 6 wt% H_3PO_4 and 1.8 wt% CrO_3 at a temperature of 98 °C for 1 h. Then the second anodization step is conducted under the same conditions. Lead nanoclusters were then deposited at the base of the PAM channels through a process involving barrier thinning and subsequent electrochemical deposition. Barrier thinning was another anodization step that was accomplished by reducing the voltage from 120 V to 4 V to thin down the barrier layer at the bottom of the PAM nanochannels in an aqueous solution consisting of 0.2 M H_3PO_4 . Lead was electrochemically deposited via a three-electrode system with an a.c. method by using a potentiostat (SG 300, Gamry Instruments). The electrolyte is an aqueous solution consisting of 1.7 wt% PbCl_2 and 25 wt% $\text{Na}_2\text{C}_2\text{O}_4$. A 50-Hz sinusoidal voltage was applied for 10 min, and the amplitude was adjusted from 3 V to 6 V. Next, the PAM with lead nanoclusters was lifted off from the aluminium substrate via a wet etch process in 1 M FeCl_3 solution.

In_2O_3 layer deposition

On the PAM, an indium oxide (In_2O_3) layer was deposited on the sidewall of the PAM channels by atomic layer deposition (ALD). To optimize the transparency and the conductance, tin was dropped in the In_2O_3 layer with a molar ratio of 16.67%. The oxygen source, indium source and tin source are O_3 , $\text{C}_5\text{H}_5\text{In}$ and $\text{C}_8\text{H}_{24}\text{N}_4\text{Sn}$, respectively. The process was conducted at 225 °C while the $\text{C}_5\text{H}_5\text{In}$ and $\text{C}_8\text{H}_{24}\text{N}_4\text{Sn}$ sources are contained at 50 °C and 70 °C, respectively, and admitted into the ALD reactor with N_2 carrier gas (20 sccm). High-purity N_2 gas (99.9999%) was used as the carrier and purge gas. The ALD process sequence involved five cycles of $\text{C}_5\text{H}_5\text{In}$ injection (500 ms)/wait (10 s)/purge (30 s)/ O_3 injection (500 ms)/wait (10 s)/purge (30 s) steps, and one cycle of $\text{C}_8\text{H}_{24}\text{N}_4\text{Sn}$ injection (500 ms)/wait (10 s)/purge (30 s)/ O_3 injection (500 ms)/wait (10 s)/purge (30 s) steps, and the thickness was controlled by the ALD recipe. In_2O_3 was deposited in the PAM channels after six process sequences of ALD.

NiO layer deposition

On the PAM with an In_2O_3 layer, a nickel oxide (NiO) layer was deposited on the sidewall of the PAM channels by ALD. The oxygen source and nickel precursor are O_3 and $\text{C}_{14}\text{H}_{32}\text{N}_2\text{O}_2\text{Ni}$, respectively. The process was conducted at 250 °C while the $\text{C}_{14}\text{H}_{32}\text{N}_2\text{O}_2\text{Ni}$ was contained at 130 °C and admitted into the ALD reactor with N_2 carrier gas (20 sccm). High-purity N_2 gas (99.9999%) was used as the carrier and purge gas. The NiO ALD process sequence involved one cycle of $\text{C}_{14}\text{H}_{32}\text{N}_2\text{O}_2\text{Ni}$ injection (500 ms)/wait (10 s)/purge (30 s)/ O_3 injection (500 ms)/wait (10 s)/purge (30 s) steps, and the thickness was controlled by the ALD recipe. NiO was deposited in the PAM channels after 70 process sequences of ALD. After this, another process sequence of In_2O_3 ALD is processed on NiO. After the ALD process, an ion-milling process was performed to remove the oxides deposited on the top surface of the PAM to avoid crosstalk between nanowires. The Ar^+ ions are accelerated by 300 V and the etching time was 10 min. The PAM was then annealed at 400 °C for 1 h in high-purity argon gas (99.999%).

MAPbX₃ nanowire array growth

MAPbX₃ nanowire arrays were grown by a single-zone chemical vapour deposition process. The source is MAI, MABr and MACl powders. The

chemical vapour deposition process was conducted in a high-purity argon gas (99.999%) environment with an argon gas flow of 200 sccm. A 10-g source was heated to 185 °C over 20 min and the reaction then proceeded for 3 h.

Crossbar electrode fabrication

A 30-nm gold layer was deposited on the PAM by a thermal evaporation process. Following this, the crossbar electrodes were patterned by a 3D laser-engraving process using a commercial picosecond-pulsed laser system with parallel lines as laser traces (wavelength, 355 nm; pulse duration, 12 ps; beam diameter, 15 μm ; DirectLaser US2, DCT). Patterning on the hemispherical shell is achieved by adjusting the focus compensation from top to bottom (average power, 90 mW; frequency, 1,200 kHz; scanning speed, 800 mm s^{-1} ; compensation step, 500 μm ; repetitions for each step, 2).

Calibration of device performance

Supplementary Fig. 30a illustrates the measurement set-up for single-pixel performance characterization. An Edinburgh FS5 fluorescence spectrometer, equipped with a xenon lamp and monochromator, provides wavelength-selectable illumination at controlled intensity. A mechanical chopper generates periodic illumination. The light is delivered to the device via an optical fibre. Photocurrent is measured using a Keithley 2450 source meter.

Supplementary Fig. 30b shows the set-up for the scene-reconstruction demonstration. A projector displays static images and videos onto the tandem device. Each retinal layer is connected to row and column multiplexer units and a data-acquisition unit for readout.

Assembling of the THE-BRENA bionic eye

The alignment of each part is shown in Supplementary Fig. 31. The spherical lens is fixed to the B-retina PCB, which also helps block illumination with incident angles $>90^\circ$, preventing this from reaching the device. The distances from the lens centre to the B, G and R retinas are 10.42, 10.56 and 10.63 mm, respectively.

As illustrated in Supplementary Fig. 32a, a piezoelectric positioning stage (Micronix PPX-50-11200, nanometre-level accuracy) was used to achieve accurate alignment during fabrication. For each retina layer, the hemispherical detector was first placed on a planar surface, while its corresponding PCB was mounted on a piezo stage with a custom 3D-printed holder. UV-curable epoxy (NOA 81, Norland Products) was dispensed on the PCB edge, and the piezo stage was actuated to precisely bring the PCB into the desired position relative to the retina. Once aligned, the epoxy was cured by UV exposure to permanently fix the components. This process was repeated sequentially for all three layers. After assembling the three retina layers, the spherical lens was mounted on a holder, and each retina layer was aligned and bonded onto the lens in turn, again using the piezo stage and UV epoxy to ensure positional precision and repeatability. The photographs of the set-up and alignment process are shown in Supplementary Fig. 32b–f.

To evaluate the robustness of this procedure, we conducted a misalignment tolerance analysis (Supplementary Fig. 33). In simulations of light incidence at a large angle of 75° , we found that even with a lateral mismatch of up to 100 μm , the resulting unfocused spot diameter remained below 20 μm . Because this value is well below our pixel pitch of 40 μm , the imaging quality is preserved within this tolerance. These results confirm that our alignment strategy both ensures accurate stacking and provides sufficient tolerance to mitigate the impact of small misalignments.

Scene reconstruction measurement

The readout architecture used in our scene reconstruction is shown in Supplementary Fig. 34. For each side of the 350×350 crossbar electrodes, the electrodes are first connected to PCB1, which carries 350 electrodes. PCB1 then routes these 350 electrodes into six 61-pin FPC

connectors (16 pins are redundant and not used for measurement). Two of these six FPC connectors, that is, a total of 122 lines, are connected to PCB2, which converts the 122 pins into 128 pin headers (six are redundant) and then routes them to the multiplexer. The multiplexer has a 128-to-1 design, and the selected line is connected to the source meter unit (Keithley 2450). In this way, a single source meter unit can address and measure a 122×122 pixel array. The multiplexers and source meter units on both sides are connected to and controlled by a PC. Overall, these configurations fully specify the channel routing, multiplexing scheme and hardware set-up of the readout architecture used in our experiments.

We performed the measurements on a pixel-by-pixel basis to demonstrate the functionality of the bionic eye device. Specifically, for each pixel we first select it via multiplexers, then project a video pattern with dynamic changes (a switch between two frames), while continuously sampling the output current for 20 readings (~ 0.5 s). After one pixel is measured, the multiplexer switches to the next pixel, and the projector repeats the same video sequence. In this way, a 122×122 submatrix can be measured in ~ 2 h. We then manually reconfigure the FPC connections between PCB1 and PCB2 to access a different 122×122 region within the 350×350 array, while keeping the projected video position fixed. After completing the measurements for one hemispherical layer, we switch the FPC connections to the next layer and repeat the same procedure. In this way, scene reconstruction using all $350 \times 350 \times 3$ pixels can be achieved.

Simulations and data processing

Spot diagram analyses in the main text and Supplementary Information are based on Ansys Zemax Optical Studio 2024 R1; the spot diameter is determined by locating the two positions on either side of the centre of the spot where the intensity equals half of the peak intensity. Light penetration and carrier transportation simulations are based on COMSOL Multiphysics 6.3. All data and simulated videos are processed and displayed via OriginPro 2025b and python 3. For the trajectory prediction, it is achieved by first extracting the current position and motion orientation of objects via motion detection, and then extrapolating their future paths along the derived motion directions. For the motion detection and trajectory prediction demonstration in Fig. 4f, we simulated the dataset based on video segments that were acquired in the campus of the Hong Kong University of Science and Technology. For the calculation of bandwidth demand, we assume that for conventional frame-based cameras, all pixels output signals, whereas for the event-driven device, only pixels with brightness greater than 127/255 output signals.

Data availability

The data that support the findings of this study are provided in the main text, Supplementary Information and source data. Source data are provided with this paper.

Code availability

The codes used for the simulation and classification are available from the corresponding author on reasonable request.

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Author contributions

Z.L. and Z.F. conceived of the idea of this work. Z.L., K.W., S.H., X.S., Z.Y., J.L., K.S., X.Q., Y.D., F.X., Y. Zhou, S.K. and S.P. fabricated the device and performed the characterization. J.L. and Y.D. designed the PCB circuits. S.H. and Z.L. developed the 3D laser-engraving method. Z.L. developed the artificial neuron network and delivered related simulations. Z.L. and X.T. delivered the band diagram-related simulations. Z.L. and Z.F. carried out the data analysis and wrote the paper. Z.L. and Z.F. revised the paper. Y. Zi and Z.F. supervised this work. All authors discussed the results and commented on the paper.

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Competing interests

The authors declare no competing interests.

Additional information

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