

Chemistry

Parallel emulation of visual adaptation and memory towards biochemically mediated motion recognition in a real scene

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Abstract: Aqueous neuromorphic devices using essential biological mechanisms have recently appeared as promising candidates for high-level neurosynaptic emulation. Towards the important functionality of motion recognition, while conventional solid-state neuromorphic vision sensors have made significant progress, aqueous motion recognition based on biochemical transmission remains challenging. Taking inspiration from biology, here we report an organic photoelectrochemical transistor biosensor capable of parallel emulation of visual adaptation and memory towards biochemically mediated motion recognition in a real scene. Based on the rational design and implementation of photoelectrochemical events, two artificial Magno and Parvo pathways are emulated to produce visual adaptation and memory in aqueous conditions, respectively. Dynamic and static visual information could be correspondingly processed and applied for integrated image filtering in a real scene and recognition of moving objects by artificial neural networks.

Keywords: organic transistor, photoelectrochemical biosensor, aqueous neuromorphic devices, motion recognition, real scene

INTRODUCTION

Neuromorphic vision sensor is now experiencing a significant increase in research activity [1–4]. Taking inspiration from the biological retina, it aims to mimic the functions and structures of the retina to enable efficient neuromorphic visual perception. Among various functions, motion recognition has proven to be challenging and demands considerable research efforts in sophisticated algorithms and hardware [5–8]. Solid-state vision sensors have made significant progress [9,10] but still could not compete with nature's success, which may be due to their fundamentally different synaptic transmission. In the biological vision, motion recognition essentially necessitates biomolecular modulation that alters the states of visual synapses in an aqueous environment [11–14]. It emphasizes the importance of biomolecules and signifies that biomolecular modulation is very needed to achieve motion recognition in aqueous conditions akin to those of biological vision, which, however, is ignored by previous efforts.

Recently, neuromorphic devices capable of emulating the biological mechanisms in aqueous media have become promising contenders in the field of neuromorphic engineering [15–22]. These devices are expected

to achieve high-level biomimicry and work in close proximity to and even within biological systems because of their biocompatible nature, i.e., to directly communicate with ions and biochemicals in physiological electrolytes [19–22]. Among them, based on the fusion of organic transistors [23–33] and photoelectrochemistry [34–37], we have proposed an organic photoelectrochemical transistor (OPECT) with unique light-biochemical perception in electrolytes [38–43]. With fused photonic-electrical-biochemical transmission, its synaptic resemblance to that of biological retina has been leveraged for exploring artificial visual devices. Druet *et al.* [44] used an n-type OPECT regulated by photosensitive organic mixed ionic-electronic charge conductors for the construction of an artificial visual synapse. Corrado *et al.* [45] deployed an azobenzene-based OPECT to construct neuro-hybrid building block mimicking visual pathways. Hu *et al.* [46] exploited a hydrogel-based OPECT retinomorphous synapse capable of color perception and biomolecule-mediated synaptic plasticity. Recently, Huang *et al.* [47] explored OPECT multisensory integration by representative visual (light)-gustatory (sour) perception.

Herein, we propose a bioinspired OPECT biosensor with parallel emulation of visual adaptation and memory towards motion recognition in a real scene. As illustrated (Figure 1a), the human visual system employs visual cells to transform, filter, and process incoming visual information based on biomolecule-mediated synaptic transmission [13,14]. Different visual information (such as shape, brightness, and motion) was processed through two parallel pathways (Figure 1b) [48–50], i.e., the Magno pathway processes the dynamic visual information in parasol ganglion cells [51], while the Parvo pathway processes the static information in midget ganglion cells [52]. By this inspiration, we designed a two-pathway neuromorphic OPECT biosensor, consisting of artificial Magno and Parvo pathways, to emulate the biological visual pathways (Figure 1c). The device operated upon photogating of a poly (3,4-ethylenedioxythiophene):poly (styrene sulfonate) (PEDOT:PSS) channel by a (Cu)porphyrin metal-organic framework (denoted as Cu-MOF)/BiOBr photogate, which was connected by a salt bridge to prevent any adverse effects on the

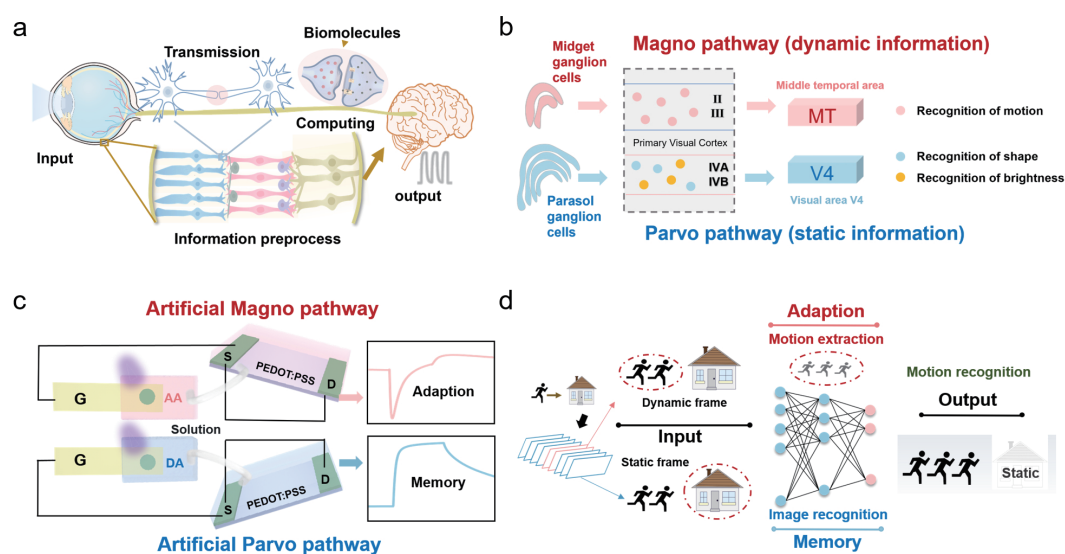


Figure 1 Aqueous neuromorphic motion recognition in a real scene. (a) Schematic illustrating the biological signal transduction in human visual system. (b) Parallel Magno pathway processing dynamic information and Parvo pathway processing static information. (c) Artificial AA-mediated Magno pathway and DA-mediated Parvo pathway. (d) Integrated workflow combining AA-mediated transient filtering for motion capture and DA-modulated weight updating for convolutional recognition.

transistor's functionality. Upon regulation by different biomolecules in aqueous electrolytes, unique dual-response characteristics of the as-developed OPECT could be produced based on the altered conductive properties of the PEDOT:PSS channel, and the parallel visual adaptation and memory could thus be on-demand generated, highly akin to that in biology [19].

Specifically, the biosensor exhibited an initial signal enhancement followed by a rapid attenuation response—adaptation—in ascorbic acid (AA) solution, while it demonstrated a monotonic signal increment to a plateau state—memory—in the dopamine (DA) solution. Such dual responses well mimicked those of biology [53,54], rendering it suitable for integrated image filtering in a real scene and recognition of moving objects by artificial neural networks (ANN) (Figure 1d). In the preprocessing stage, the adaptation function can be utilized to filter out stationary objects, capturing and outputting dynamic objects. During the next computational stage, the memory function can be employed within the backpropagation algorithm to update synaptic weights for improved image recognition. This work features the bioinspired parallel emulation of visual adaptation and memory towards biochemically mediated motion recognition in a real scene.

RESULTS

Materials characterization

The morphologies of the gate materials were characterized by scanning electron microscopy (SEM) (Figure S1). X-ray diffraction (XRD) patterns confirmed the preparation of CuMOF, BiOBr, and the CuMOF/BiOBr heterojunction (Figure 2a). The XRD pattern of CuMOF agreed with the previous report [55] (CCDC card no. 675375), while the characteristic peaks of BiOBr demonstrated the tetragonal lattice structure (JCPDS#09-0393) [56]. Besides, after being coupled with CuMOF, the primary crystal facets of BiOBr had not undergone substantial alterations, which was consistent with previous literature [57]. Ultraviolet-visible absorption spectra (Figure 2b) demonstrated the reduction of the Q-band and a red shift in the Soret band of CuMOF, verifying successful coordination between Cu and porphyrin [57]. BiOBr showed a characteristic absorption at approximately 307 nm, aligning with reported data [58]. Notably, the strong light absorption capability of CuMOF effectively extended the optical absorption range of the heterojunction. X-ray photoelectron spectroscopy (XPS) analysis further corroborated the successful synthesis of CuMOF, BiOBr and the heterojunction [58]. Distinct characteristic peaks were identified at 940 eV (Cu), 159 eV (Bi), and 69 eV (Br), in addition to the signals from C, O, and N elements (Figure 2c).

Furthermore, Tauc plots from ultraviolet-visible (UV-vis), Mott-Schottky plots, electrochemical impedance spectroscopy (EIS), Nyquist plots and photoelectrochemistry (PEC) tests were conducted to confirm the band alignment and revealed the formation of a characteristic type-II heterojunction [59] between CuMOF and BiOBr (Figures S2–S6). Subsequently, the photoelectrochemical property of the heterojunction electrode was studied. The electrode was respectively immersed in AA and DA solutions with different concentrations, followed by evaluation of the photo-responsive behaviors under intermittent irradiation ($\lambda = 450$ nm, density = 10.75 mW/cm^2) with 10 s illumination cycles. The results showed that the electrode presented increased anodic responses in AA solution of enhanced concentrations (25, 50 and 100 mM), and all of the photocurrents had obvious decay processes (Figure 2d), which were attributed to the back reduction of redox species [60,61] and rapid surface state recombination [62,63], as evidenced by the EIS measurement

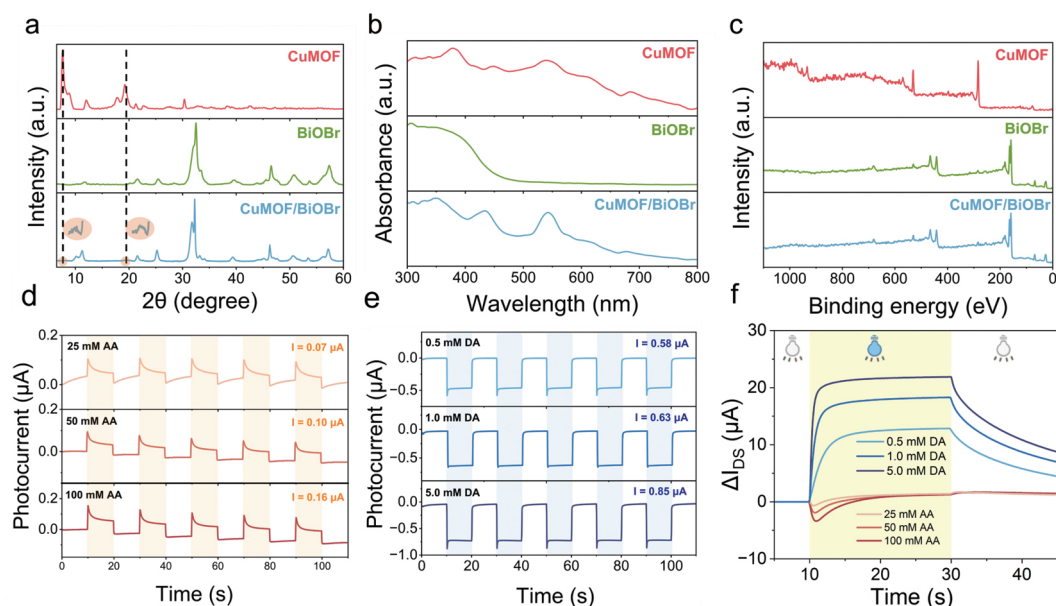


Figure 2 Materials characterization. (a) XRD patterns, (b) UV-vis absorption spectra, and (c) XPS spectra of the CuMOF, BiOBr and heterojunction. The photoelectrochemical responses of the heterojunction to (d) AA (25, 50, 100 mM) and (e) DA (0.5, 1.0, 5.0 mM). (f) The dual-directional signaling behaviors of the OPECT device, with the current change (ΔI_{bs}) corresponding to the postsynaptic current.

(Figure S4). By contrast, in the DA solution of enhanced concentrations (0.5, 1.0 and 5.0 mM), the electrode generated enhanced cathode photocurrents but with no decay during the tests (Figure 2e). Further, the electrochemical properties and stability of the PEDOT:PSS channel were tested by the Ag/AgCl gate electrode (Figure S7). Upon assembling the OPECT consisted of the heterojunction-gated PEDOT:PSS channel, analogous bipolar behaviors of the channel currents were observed (Figure 2f). As shown, the presence of AA induced inhibitory (IPSC) with obvious adaptation behaviors, while the presence of DA induced excitatory postsynaptic currents (EPSC) with clear memory. Such adaptation and memory behaviors could be attributed to the unique migration of ions between the photogate and channel in the OPECT (Figures S8 and S9). We finally used these properties in the artificial Magno and Parvo pathways to complete dynamic information filtering and image recognition, respectively. Significantly, different from previous visual adaptation [64] and memory [65] in solid-state devices, these results revealed the co-location of biologically switchable visual adaptation and memory in our aqueous neuromorphic device.

Synaptic plasticity

The synaptic weight in biological synapses was regulated by spike parameters, e.g., intensity, duration, number, and frequency, exhibiting distinct spike-dependent plasticity, including spike-intensity-dependent plasticity (SIDP), spike-number-dependent plasticity (SNDP), spike-width-dependent plasticity (SWDP) and spike-frequency-dependent plasticity (SFDP). These properties of our device were then respectively studied in the presence of AA (50 mM) and DA (1.0 mM) electrolytes.

In the presence of AA, upon increased light intensity from 4.73 to 17.53 mW/cm², the SIDP displayed an improved ΔI_{PSC} (peak values) from 1.91 to 3.67 μA (Figure 3a). The transient current consistently de-

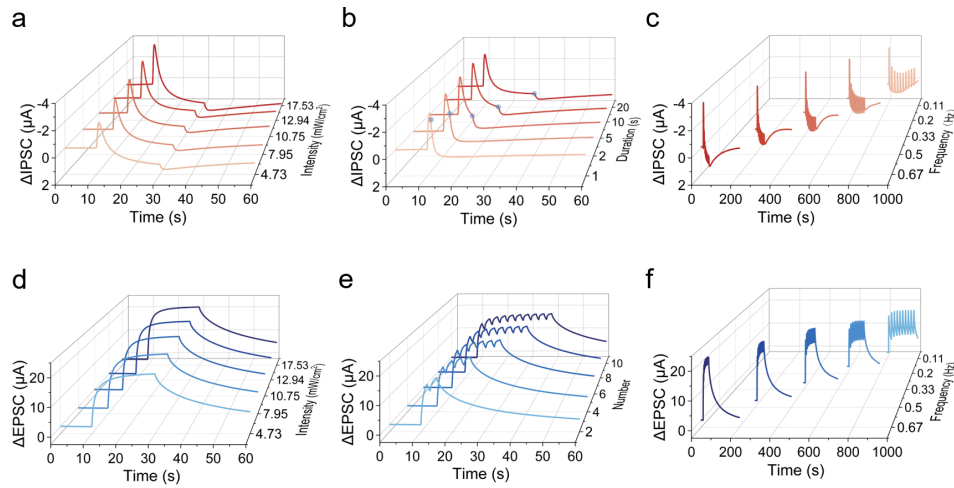


Figure 3 Synaptic plasticity. The AA-mediated (a) SIDP (4.73, 7.95, 10.75, 12.94 and 17.53 mW/cm² light pulse, 50 mM AA), (b) SWDP (10.75 mW/cm² light pulse, 50 mM AA), and (c) SFDP (10.75 mW/cm² light pulse, 50 mM AA). The DA-mediated (d) SIDP (4.73, 7.95, 10.75, 12.94 and 17.53 mW/cm² light pulse, 1.0 mM DA), (e) SNDP (10.75 mW/cm² light pulse, 1.0 mM DA), and (f) SFDP (10.75 mW/cm² light pulse, 1.0 mM DA).

monstrated a biphasic trajectory, which initially ascended to a maximum followed by a decay, eventually lower than the baseline. This phenomenon was due to the strong attenuation of the gate photocurrent in the negative direction. Upon pulse-width extension from 1 to 20 s, the SWDP induced different forms of Δ IPSC. The Δ IPSC could remain above the baseline when the pulse-width was short (1 and 2 s), while prolonged pulse-widths (5, 10 and 20 s) led to decays below baseline, as indicated by the blue dots highlighting off-state current (Figure 3b). Notably, the dependence of positive and negative Δ IPSC upon pulse-widths provided a possibility for sorting and filtering the information of different time scales. Upon increasing the frequency from 0.11 to 0.67 Hz, the SFDP demonstrated lower peak values of Δ IPSC, which was ascribed to the improved relaxation in adaptive restoration of the device (Figure 3c). The corresponding Δ IPSC gain was calculated by A_{10}/A_1 , where the A_{10} and A_1 represented the amplitude of the 10th and 1st IPSC, respectively (Figure S10a). The attenuation of Δ IPSC gain induced by increasing frequency successfully replicated the low-pass filtering characteristics of biological synapses. Besides, as the number of pulses increased from 2 to 10, the SNDP displayed multiple adaptations to achieve lower response states (Figure S10b).

In the presence of DA, with the increase of light intensity from 4.73 to 17.53 mW/cm², the SIDP displayed an expected increased Δ EPSC from 67.87 to 91.8 μ A (Figure 3d). With the pulse number increasing from 2 to 10, the SNDP exhibited saw-tooth increases in Δ EPSC, with more zigzags, slower declines, and higher peaks accompanied by gradually diminishing gains, which mimicked the biological synaptic strengthening under repeated stimuli (Figure 3e). Notably, the light-dependent updating of the conductance states provided a possibility for weight updating in image recognition. Upon increased frequency from 0.11 to 0.67 Hz, the SFDP demonstrated lower peak values of Δ EPSC, which was ascribed to longer memory decay of the device (Figure 3f). The corresponding Δ EPSC gain (Figure S11a) successfully replicated the high-pass filtering characteristics of biological synapses. Besides, as the pulse-widths increased from 1 to 20 s, the SWDP exhibited increases in Δ EPSC, which could be attributed to the continuous generation of charge carriers

(Figure S11b). The changes in currents during the overall processes followed the same trend as the variations in peak values.

Real scene motion recognition

As aforementioned, adaptation is an essential function of biological vision for filtering dynamic information. We have demonstrated that the AA-mediated SWDP could provide such a function in the artificial Magno pathway. As illustrated (Figure 4a), the information within key frames extracted from videos was represented in the pixel grid, where the residence time of dynamic information (t_d) in the same pixel grid was significantly shorter than that of static information (t_s). Besides, depending on the speed of dynamic objects, the residence times within the same pixel grid, denoted as t_d , was distinct, indicating that filtering dynamic information with varying speeds required distinct time scales. To differentiate the dynamic and static information (Figure 4b), the dynamic information corresponding to the short pulse-width was kept (i.e., the shaded parts of the Δ IPSC regions were utilized), while the static information corresponding to the prolonged pulse-width was discarded (i.e., the positive Δ IPSC regions were abandoned). At the light intensity of 4.73 mW/cm², as the AA concentration increased, the peak current ($I_{\max}$) increased from 0.91 to 4.10 μ A, while the time-to-peak ($t_{\max}$) and return-to-zero time (t_0) of the currents exhibited corresponding enhancement from 0.6 to 1.2 s and from 1.91 to 11.35 s, respectively. Such a behavior was in principle ideal to match the different t_d of dynamic objects in the motion recognition. Specifically, the t_0 served as the threshold for t_d , which determined whether the information could be retained. The $t_{\max}$ represented the optimal t_d at a certain AA concentration. When $t_d = t_{\max}$, the Δ IPSC reached the maximum value, which corresponded to the associated grayscale value. The

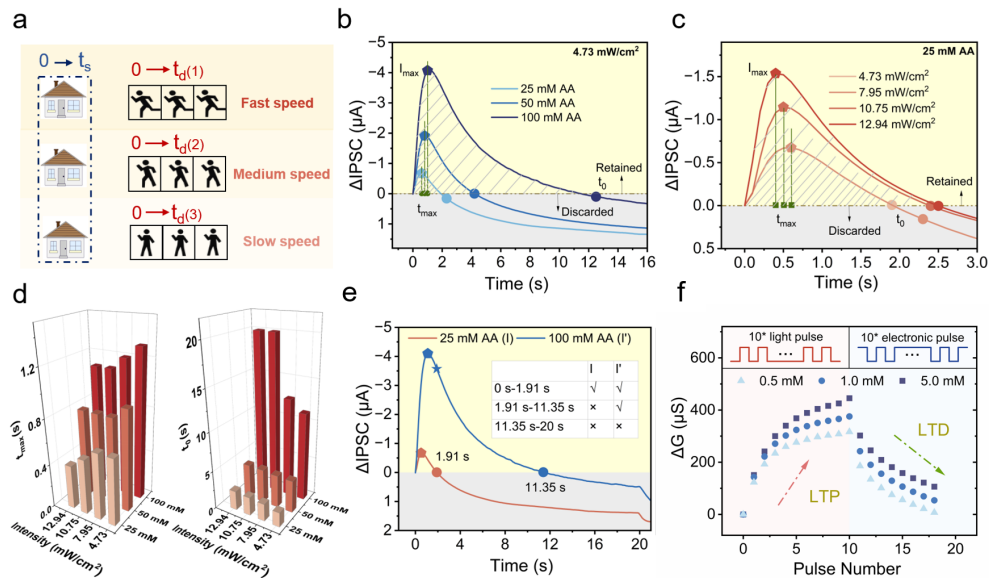


Figure 4 Prerequisite properties for motion detection. (a) Schematic diagram of frame pixel processing and time-scale of dynamic and static information at different moving speeds. Δ IPSC responses at (b) different AA concentrations (25, 50, 100 mM, 7.95 mW/cm²) and at (c) different light intensities (4.73, 7.95, 10.75, 12.94 mW/cm², 25 mM). (d) $t_{\max}$ and t_0 at different AA concentrations (25, 50, 100 mM) and different light intensities (4.73, 7.95, 10.75, 12.94 mW/cm²). (e) Schematic diagram of information filtering at different time scales (light intensity of 4.73 mW/cm², AA of 25 and 100 mM). (f) LTP and LTD curves generated by respective optical and electrical pulses in 0.5, 1.0, 5.0 mM DA solution.

greater the Δ IPSC, the higher contrast between the extracted information and the background for better clarity.

In addition to AA concentrations, the effect of light intensity on the $t_{\max}$ and t_0 was also studied. For 25 mM AA, the increasing light intensity elevated $I_{\max}$ from 1.91 to 3.67 μ A, while $t_{\max}$ showed a slight increase from 0.5 to 0.7 s, while t_0 showed a slight decrease from 2.52 to 1.91 s, respectively (Figure 4c). The values of $t_{\max}$ and t_0 under varying AA concentrations and light intensities were calculated (Figure 4d and Table S1). As shown, the $t_{\max}$ showed a positive correlation with AA concentration due to the enhanced faradaic reaction, while it showed a negative correlation with light intensity that could be attributed to the faster carrier migration upon stronger light stimulation and thus faster attainment of the $I_{\max}$. As to t_0 , the enhanced faradaic reaction similarly led to its positive correlations with both concentration and light intensity. Notably, under high concentrations and high light intensities, the enhancements of the currents were uniform, without crossover occurring in the curves.

Using the above results, different AA concentrations could be deployed to perform motion recognition tasks on different time scales (Figure 4e). When t_d was less than 1.91 s, information could be retained in cases of 25 and 100 mM AA. When t_d was at 1.91–11.35 s, the information could be retained in the case of 100 mM AA but be discarded in the case of 25 mM. When t_d was larger than 11.35 s, the information could not be retained in both cases of 25 and 100 mM AA. Except for the time scale, as a reference value for brightness normalization in a dynamic information filtering algorithm, $I_{\max}$ was positively correlated with recognition ability and information differentiation (Figure S12). In subsequent dynamic information processing, the curve with a higher $I_{\max}$ was selected if the information could be retained by different curves. Due to the aforementioned performance, we divided the current curves into two parts based on the peak values and performed function fittings. These fitted functions were then input into the algorithm, where processing results at different times corresponded to current values at those respective times, enabling us to screen dynamic and static information.

On the other hand, memory is an essential function of biological vision for image recognition. We have demonstrated that the DA-mediated SNDP could provide such a function in the artificial Parvo pathway. After extraction by the AA-mediated pathway, image recognition was achieved through the conductance updates dependent on the pulse numbers. We implemented long-term potentiation (LTP) using 10 optical pulses for conductance state updates, followed by 10 negative electrical pulses for long-term depression (LTD)-mediated state resetting in the presence of different DA concentrations (0.5, 1.0, and 5.0 mM) (Figure 4f). The adjustable synaptic weights demonstrated its memory encoding capability in write-erase operations, and the fitted function of the curve could be used in the weight updating process for image recognition (Figure S13).

Taking advantage of such properties, we explored a unique biochemically tunable artificial vision system for dynamic information filtering in a real scene and subsequent image recognition. As illustrated, the dynamic information filtration involved three key steps: extracting key frames of fixed time interval from videos (e.g., 0.5 s interval) (Figure 5a); categorizing these frames based on dual temporal scales (t_d and t_s); selecting appropriate AA concentration to discard static backgrounds to generate motion trajectories (Figure 5b). To be specific, the 25 mM AA solution was eliminated when t_d was longer than 2.52 s (25 mM, 12.94 mW/cm²), while the 50 mM solution was also excluded when t_d was longer than 4.45 s (50 mM, 12.94 mW/cm²) and 100 mM became the final selection. For the t_s , the 100 mM AA solution was eliminated

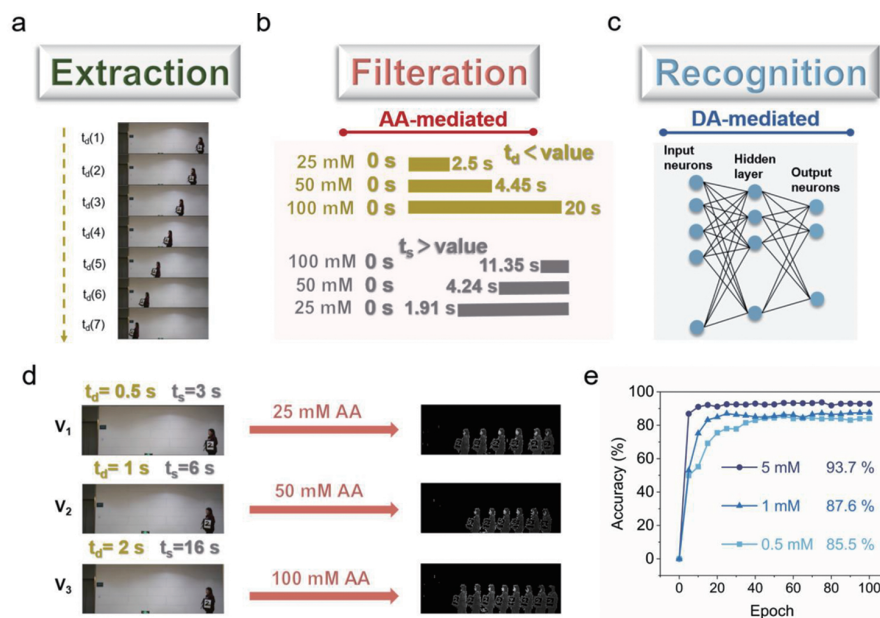


Figure 5 OPECT motion recognition in a real scene. (a) Schematic representation of extraction of keyframes from the video. (b) Temporal parameters and selection criteria for optimal AA concentrations in dynamic information filtration. (c) DA-mediated ANN architecture in image recognition. (d) Dynamic information retention profiles processed with varying AA concentrations across different temporal scales ($t_d = 0.5\text{--}2$ s; $t_s = 3\text{--}16$ s). (e) Recognition accuracy metrics with varying DA concentrations derived from ANN-based analysis of filtration outcomes.

when t_s was shorter than 11.35 s (100 mM, 4.73 mW/cm^2), while the 50 mM solution was also excluded when t_s was between 4.24 s (50 mM, 4.73 mW/cm^2) to 1.91 s and 25 mM became the final selection. These time nodes were t values measured at the corresponding concentrations and light intensities mentioned above. This time-scale adaptive filtering architecture enabled robust motion filtration across diverse tasks.

Based on the aforementioned selection criteria, three videos with diverse time scales ($t_d = 0.5, 1, 2$ s; $t_s = 3, 6, 16$ s) were systematically processed using optimal 25, 50, and 100 mM AA solutions, respectively, yielding dynamic information filtering results as demonstrated (Figure 5c). The outputs exhibited successful AA-mediated dynamic information retention as indicated by the clear moving trajectories against discarded backgrounds (e.g., left-side door), achieving non-overlapping motion tracking without any information loss. Incidentally, if the (t_d, t_s) was processed by the non-optimal AA concentration, it will lead to inferior results (Figure S14). Taking the ($t_d = 0.5$ s, $t_s = 3$ s) as an exemplar, while 50 and 100 mM solutions preserved dynamic information with higher grayscale intensity, their application resulted in partial background retention, causing data redundancy and reduced signal-to-noise ratio.

Following the AA-mediated filtering, DA-mediated information recognition was implemented on the processed images by a three-layer ANN (Figure 5d). As shown, we used a three-layered ANN consisting of input neurons, hidden neurons and output neurons, which were fully connected via synaptic weights (Figure S15). The ANN was trained via backpropagation based on the DA-mediated potentiation and depression. Compared with the randomly distributed conductance before learning, the ΔG value of pixels was substantially increased after learning. Correspondingly, upon optimization of the DA concentrations, the trained output exhibited an optimal accuracy of 93.7% in the case of 5.0 mM DA (Figure 5e). The high recognition rate demonstrated the feasibility of DA-mediated weight updating in ANN.

DISCUSSION

In summary, drawing inspiration from the architecture and functionality of the biological visual system, we designed an OPECT biosensor that emulates the parallel Magno and Parvo pathways found in human vision, characterized by the respective procession of dynamic and static visual information. Specifically, by leveraging the unique photoelectrochemical biosensing in the OPECT, the AA-mediated artificial Magno pathway can mimic the aqueous visual adaptation to capture and output dynamic objects, while the DA-mediated artificial Parvo pathway can mimic the memory function for improved image recognition in ANN. The feasibility of applying the as-prepared biosensor towards real scene motion recognition was verified. Compared with current organic transistor devices in aqueous medium, this biosensor distinguished itself from high-level biomimicry in terms of biologically mediated adaptation and memory. Overall, this work featured aqueous neuromorphic vision biosensors capable of motion recognition in a real scene, which was expected to inspire artificial biosystems that more closely resemble the aqueous processes of human vision.

MATERIALS AND METHODS

Reagents

Phosphate-buffered saline (PBS) was purchased from Jiangsu Kaiji Biotechnology Co., Ltd. PEDOT:PSS dispersion (Clevios PH1000) was obtained from Heraeus Ltd. $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$, $\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$, HNO_3 and AA were purchased from Shanghai Hutest Laboratory Equipment Co., Ltd. Polyvinyl pyrrolidone (PVP), hexadecyltrimethylammonium bromide (CTAB), trifluoroacetic acid (TFA), DA, *N,N*-dimethylformamide (DMF), and methyl sulfoxide (DMSO) were purchased from Aladdin Biochemical Technology Co., Ltd. Meso-tetra(4-carboxyphenyl)porphine (TCPP) was purchased from Shanghai Yuanye Bio-Technology Co., Ltd. Nafion was purchased from Beijing Bailingwei Technology Co., Ltd.

Fabrication of the gate electrode

CuMOF. The preparation process of CuMOF/BiOBr on indium tin oxide (ITO) was as follows. 3.6 mg $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$, 0.7 μL TFA and 10 mg PVP were dissolved in a 12 mL mixture of DMF and ethanol ($V_D: V_E=3:1$) and 4.0 mg TCPP dissolved in 4 mL solution of the same formula was added to the above solution tardily. The mixture was then heated to 80 °C for 24 h after 5 min ultrasonic. After cooling, the CuMOF nanosheets were washed in alcohol three times, centrifuged at 8000 r/min and freeze-dried overnight.

BiOBr. $\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$ (0.13 g) dissolved in 50 mL of HNO_3 (2 wt%) was dropwise added into 50 mL of CTAB solution (8×10^{-3} M), and the mixture was ultrasounded and heated in water bath at 80 °C for 3 h. The precipitate of BiOBr nanosheets was washed three times in water and ethanol, followed by ultrasonic and dried for collection.

CuMOF/BiOBr. The 100 mg BiOBr nanosheets were added to 60 mL of alcohol and the homogenized solution was ultrasounded for 30 min. Then, 3 mg CuMOF solution was added to the mixture and ultrasound treatment was performed for 15 min. The final mixture was stirred and heated in a water bath at 60 °C for 12 h. The product of CuMOF/BiOBr heterojunction was collected by ultrasound and dried overnight at

60 °C.

Gate electrode. CuMOF/BiOBr powder (2 mg) was ultrasonically dispersed in 1 mL ultra-pure water and 1% (wt%) Nafion solution was added. The mixture was dripped onto the plasma-treated ITO electrode sheet, dried and then tested.

Fabrication of the transistor

The transistor fabrication involved sequential deposition of chromium (Cr, 10 nm thickness) and gold (Au, 100 nm thickness) layers via magnetron sputtering (Kurt J. Lesker system) onto pre-cleaned glass substrates using a shadow mask with channel dimensions of 6.0 mm×0.2 mm ($L \times W$). Subsequently, a 0.1 mL aliquot of PEDOT:PSS aqueous dispersion containing 5% DMSO (v/v) was spin-coated (4000 r/min, 30 s) onto the Au/Cr electrode channel to generate a uniform polymeric thin film. Thermal annealing was then performed at 180 °C for 1 h under controlled argon atmosphere within a glovebox, followed by natural cooling to ambient temperature.

Physical characterization

The photoelectric property was investigated by a photoelectrochemical/organic transistor detector (Nandagang, Nanjing, China) and a Keithley 4200 semiconductor parameter analyzer using AA and DA as the electrolytes. The 405 nm illumination was supplied by commercially available light-emitting diodes. SEM and mapping images were characterized by a Hitachi S4800 microscope. XRD patterns were provided by Bruker D8 Advance equipment. UV-vis absorption patterns were presented by Shimadzu UV-3600. EIS data were measured out by Bio-Logic SP-150.

Data availability

The original data are available from corresponding authors upon reasonable request.

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Author contributions

W.W.Z. and Y.H.K. conceived the idea and designed the experiments. Y.H.K. and Z.L. performed the experiments and characterization. C.Y. and Z.L. helped in materials synthesis and data analysis. W.W.Z. and Y.H.K. co-wrote the manuscript and gave approval to the final version. All authors discussed the results and commented on the manuscript.

Conflict of interest

The authors declare no conflict of interest.

Supplementary information

The supporting information is available online at <https://doi.org/10.1360/nso/20250030>. The supporting materials are

published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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