Memristive devices

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# A universal neuromorphic vision processing system

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A vision processing system that leverages reconfigurable memristive devices to implement different bioinspired neural networks can efficiently sense and process static and dynamic visual information.

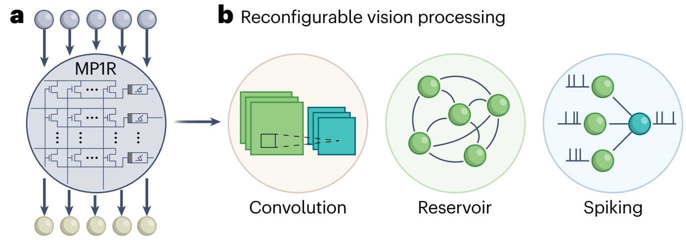


**Fig. 1 | MP1R array for reconfigurable vision processing. a**, MP1R array architecture. **b**, Vision processing algorithms implemented by the reconfigurable MP1R hardware, including convolution in an optic convolutional neural network (left), reservoir in an optic recurrent neural network (centre) and spiking in an optic spiking neural network (right).

Traditional machine vision processing relies on separate modules for sensing, processing and memory, which leads to high redundancy and low efficiency. In contrast, biological vision systems use hierarchical neural architectures and a diverse range of algorithms for effective feature extraction and interpretation, providing accurate perception with low energy cost[1,2]. Neuromorphic vision processing aims to emulate the principles and functionalities of biological optical receptors, synapses and neurons, and replicate their high efficiency and intelligence[3,4]. Biological vision systems excel, in particular, at effective local feature extraction, complex spatiotemporal processing and robust spike-based neural coding. Inspired by these capabilities, neuromorphic vision hardware has been developed to emulate these biological processing principles[4].

Since the concept of neuromorphic vision processing was introduced[5], there have been considerable developments in materials, devices, systems and algorithms. For example, two-dimensional materials have been used to create ultrafast machine vision sensors that incorporate an in-sensor artificial neural network for direct classification[6]. More recently, optoelectronic devices capable of spatiotemporal processing have been investigated for dynamic machine vision sensors[7] and an in-sensor spiking neural network[8], enhancing the ability of neuromorphic vision systems to perceive motion. However, most research has focused on specialized hardware for a single vision processing algorithm, and thus lack the versatility of general-purpose vision processing of human vision. Writing in *Nature Electronics*, Yuchao Yang and colleagues now report a multi-phototransistor–one-memristor (MP1R) array that can be reconfigured to accommodate various bioinspired vision computing principles for different tasks[9].

The researchers — who are based at Peking University and the Chinese Institute for Brain Research — created reconfigurable memristive hardware that supports the implementation of various algorithms for in-sensor vision processing tasks. The reconfigurability of the MP1R array (Fig. 1a) stems from its $Ta/TaO_x/NbO_x/W$ heterostructures, which offer a linear resistive region, volatile memory and threshold switching capabilities. Various vision computing architectures — including optic convolutional neural networks, recurrent neural networks and spiking neural networks — can be implemented using the MP1R array (Fig. 1b).

Image recognition, a fundamental task in vision computing, can be efficiently handled by convolutional neural networks[10], which extract local features using convolution kernels. This mechanism closely resembles the concept of field of view in biological vision systems. Traditionally, image capturing and recognition functions are separated into different modules. In the MP1R array (Fig. 1b, left), Yang and colleagues integrated phototransistors as optical sensors and used the linear resistive function of the $Ta/TaO_x/NbO_x/W$ memristors as convolution kernels, allowing the hardware to perform both optical sensing and convolutional processing. This integration facilitated accurate recognition of handwritten digits, illustrating the system's proficiency in spatial processing of optical information.

Spatiotemporal processing of optical information, which involves handling dynamic changes over time, poses a greater challenge for neuromorphic hardware. For this task, the volatile memory functions of the $Ta/TaO_x/NbO_x/W$ memristors were leveraged to create a dynamic reservoir for spatiotemporal processing (Fig. 1b, centre). Unlike previous reservoir systems that required extensive preprocessing and storage of images, the MP1R array-based reservoir network directly perceives and processes full images, effectively integrating spatial and temporal information. An optic recurrent neural network is created by adding an additional memristor-based readout layer, which offers an event-based dynamic vision processing accuracy of 85.3%, comparable to software-based approaches.

Optic spiking neural networks, which emulate the spike-based processing in biological systems, offer a more robust and efficient approach to vision processing. By configuring the $Ta/TaO_x/NbO_x/W$ memristors as threshold switches, the MP1R array functions as oscillation neurons, facilitating spike encoding of optical colour information (Fig. 1b, right). The resulting optic spiking neural network, coupled with a memristor-based classifier, accurately recognized images in different colours with an accuracy exceeding 91%. This system advances beyond previous memristor-based spiking systems[8], which were largely limited to single-colour or greyscale image recognition.

The reconfigurable $Ta/TaO_x/NbO_x/W$ memristor-based MP1R architecture enables the implementation of various neural networks for distinct vision processing tasks. By consolidating multiple neural processing principles within a single device, the MP1R design simplifies vision computing circuits, reduces latency and enhances energy efficiency. The crossbar structure of the MP1R also facilitates scaling for more complex real-world vision processing. In addition, the $Ta/TaO_x/NbO_x/W$ devices show low variability, which enhances the potential for practical applications of neuromorphic memristive devices.

Challenges do though remain in terms of delivering practical applications, particularly in developing reliable and stable materials for analogue neuromorphic vision hardware. In addition, efficiently implementing neural spike-based vision processing principles in hardware requires innovative design and effective integration of multiple devices. Future research should prioritize exploring and optimizing materials with low variability and high compatibility, as well as realizing and integrating high-performance memristive devices. Moreover, hardware implementation of advanced neural vision processing principles is essential for achieving universal neuromorphic vision processing. Collaborations with industry, who have access to advanced fabrication processes, will also help accelerate the development of neuromorphic vision systems.

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## Competing interests

The authors declare no competing interests.