Supporting Information for "Artificial Multisensory Neuron with Fused Haptic and Temperature Perception for Multimodal In-Sensor Computing"

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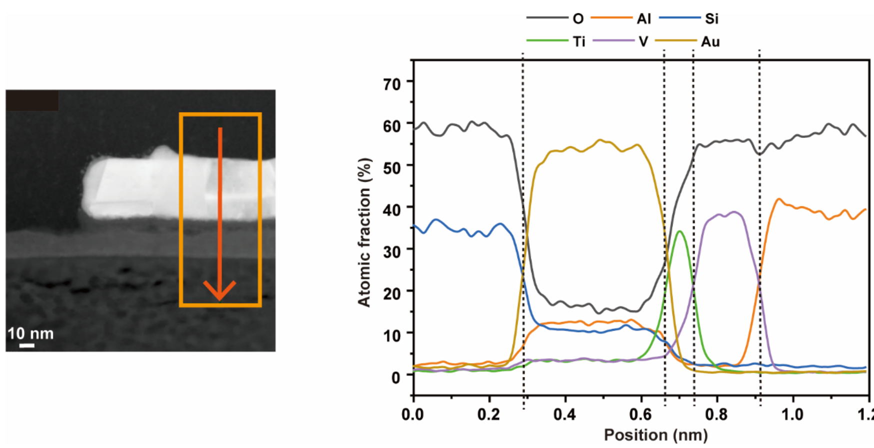

Figure S1. Chemical characterization of a VO_2memristive device. Energy-dispersive spectroscopic (EDS) elemental line-scan of a VO_2 device.

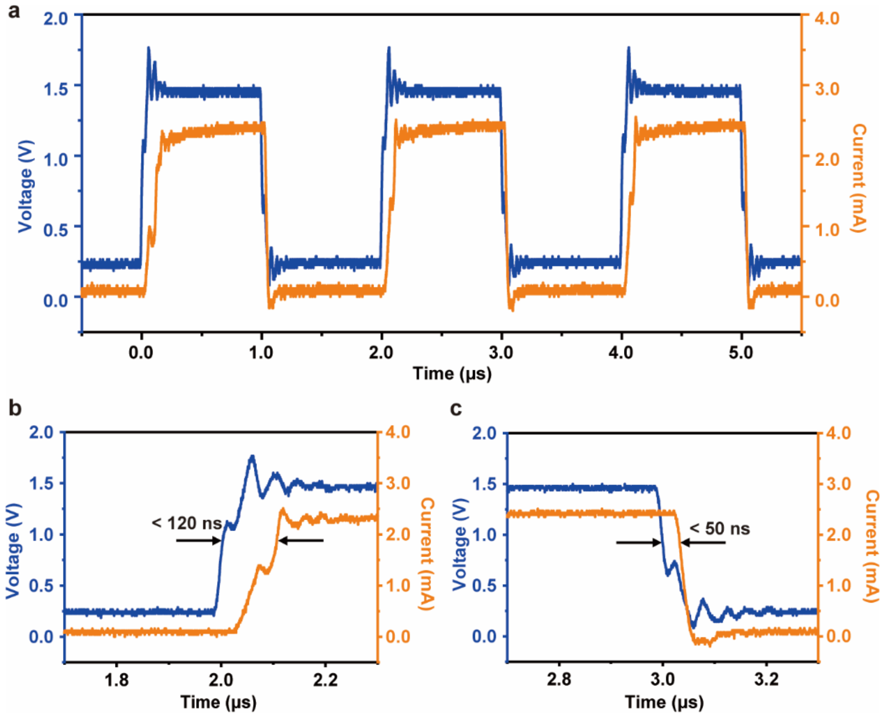

Figure S2. Transient switching response of the VO_2 memristor. a) Current waveform (orange curve) of the VO_2 memristor upon application of the voltage waveform (blue curve). b) The switching speed is <120 ns from off- to on-state. c) The switching speed is <50 ns from on to off state.

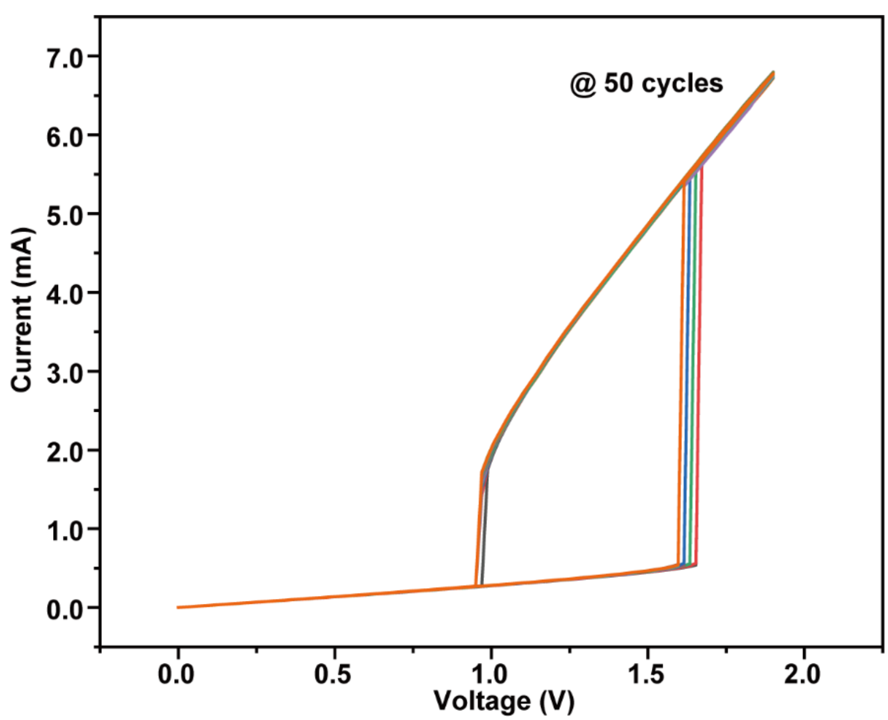

Figure S3. The I-V characteristics of VO_2 memristor without compliance current.

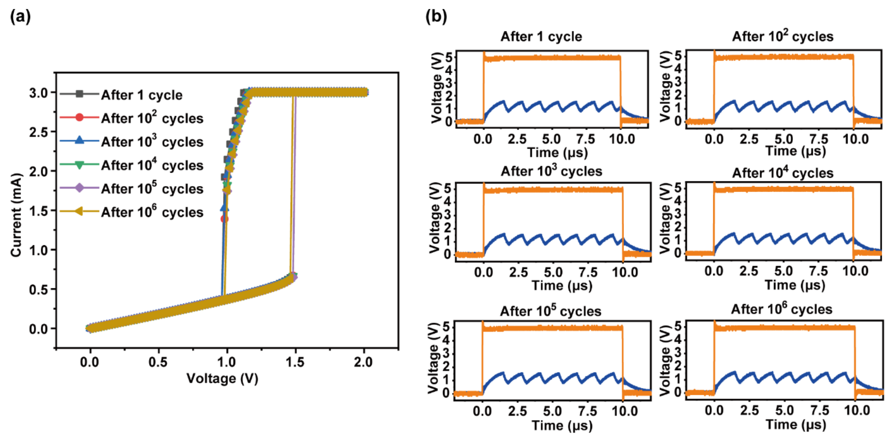

Figure S4. Endurance of the VO_2 memristor. a)I-V characteristics after 1, 10^2, 10^3, 10^4, 10^5, 10^6 cycles during endurance test. b) The endurance test results with the oscillator method after 1, 10^2, 10^3, 10^4, 10^5, 10^6 cycles.

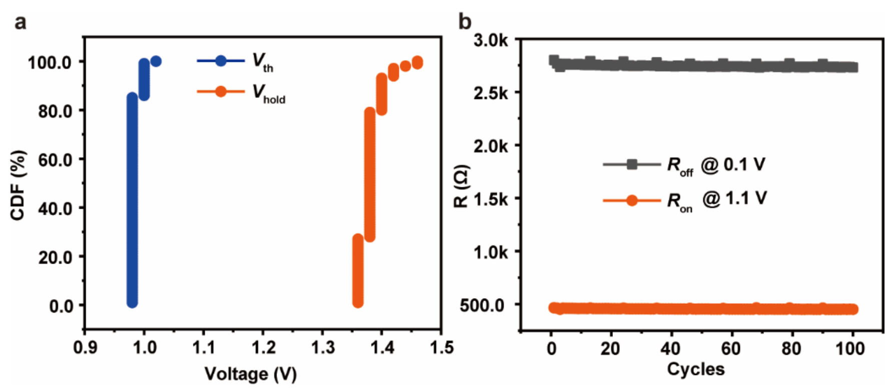

Figure S5. Cycle-to-cycle variation of the VO_2memristor . a) Cumulative plots of$V$ $_{th}$, V $_{hold}$ of I-Vcharacteristics with 100 repeated cycles in Figure 2g. b) Distributions of high and low resistance states of the VO_2 memristor with 100 repeated cycles in Figure 2g.

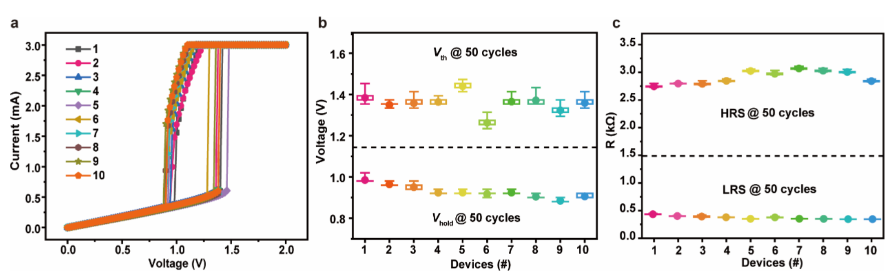

Figure S6. Device-to-device variation of the VO_2memristor . a) I-V characteristics of the device measured in 10 different VO_2 devices. b) Distributions of$V$ $_{th}$, V $_{hold}$ with 50 repeated I-V cycles in 10 VO_2 devices. c) Distributions of high and low resistance states with 50 repeated$I$-V cycles in 10 VO_2 devices.

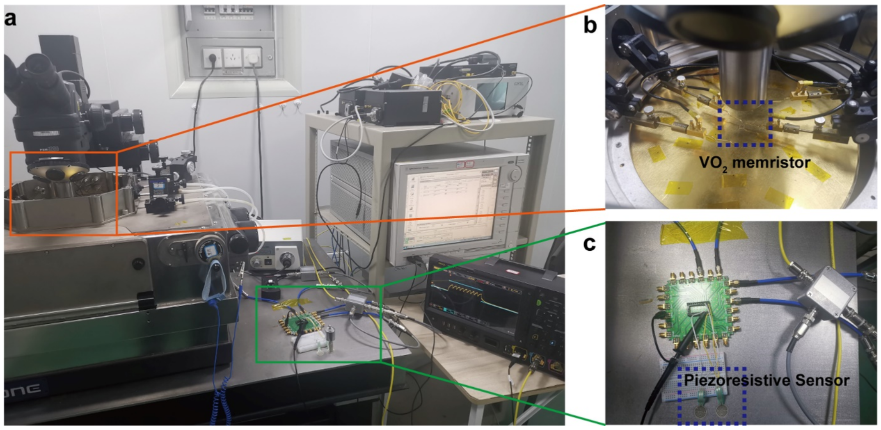

Figure S7. The experimental setup for Braille character recognition. a) The entire experimental setup. b) The probe station used for testing VO_2 memristor. c) The piezoresistive sensors connected series with the VO_2memristor.

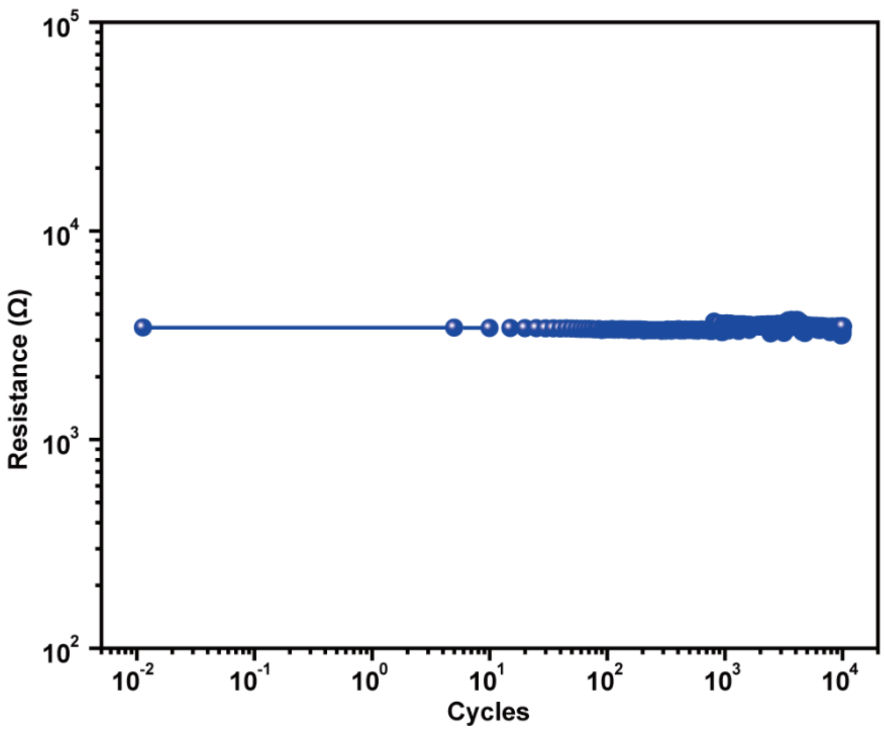

Figure S8. Stability of the piezoresistive sensor in response to 200 g weight.

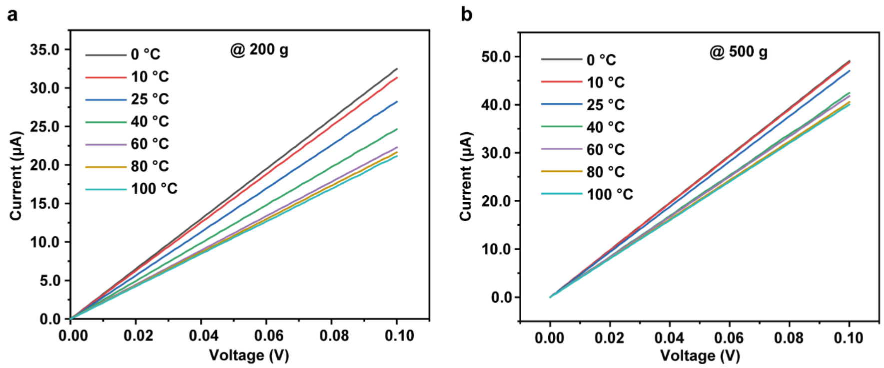

Figure S9. Temperature characteristics of the piezoresistive sensor. a) I-V curves of the sensor at different temperatures under 200 g pressure/weight. b) I-V curves of the sensor at different temperatures under 500 g pressure/weight.

Figure S9 shows the temperature characteristics of the piezoresistive sensor. It can be found that the output resistance of the piezoresistive sensor will increase when the temperature increases under fixed pressure (200 g or 500 g), implying that this sensor has a thermal shift issue. This issue may be avoided by hardware compensation circuit, such as compensation circuit of self-balancing bridge[1]and operational amplifier compensation circuit.[2]

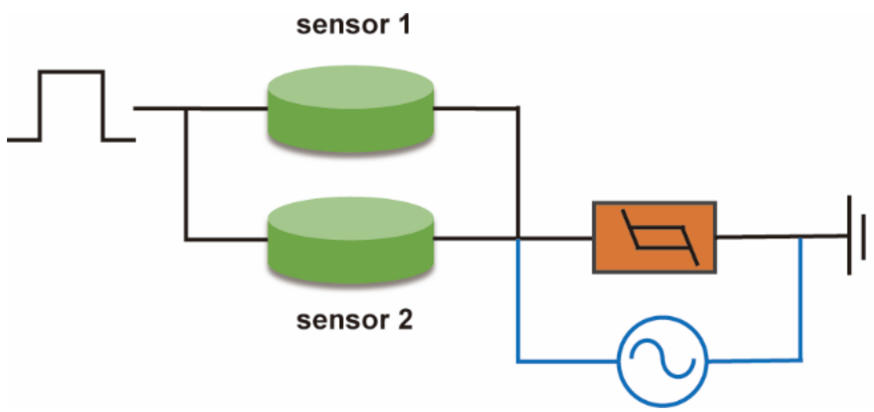

Figure S10. The circuit diagram of the recognition of braille character in Figure 4e.

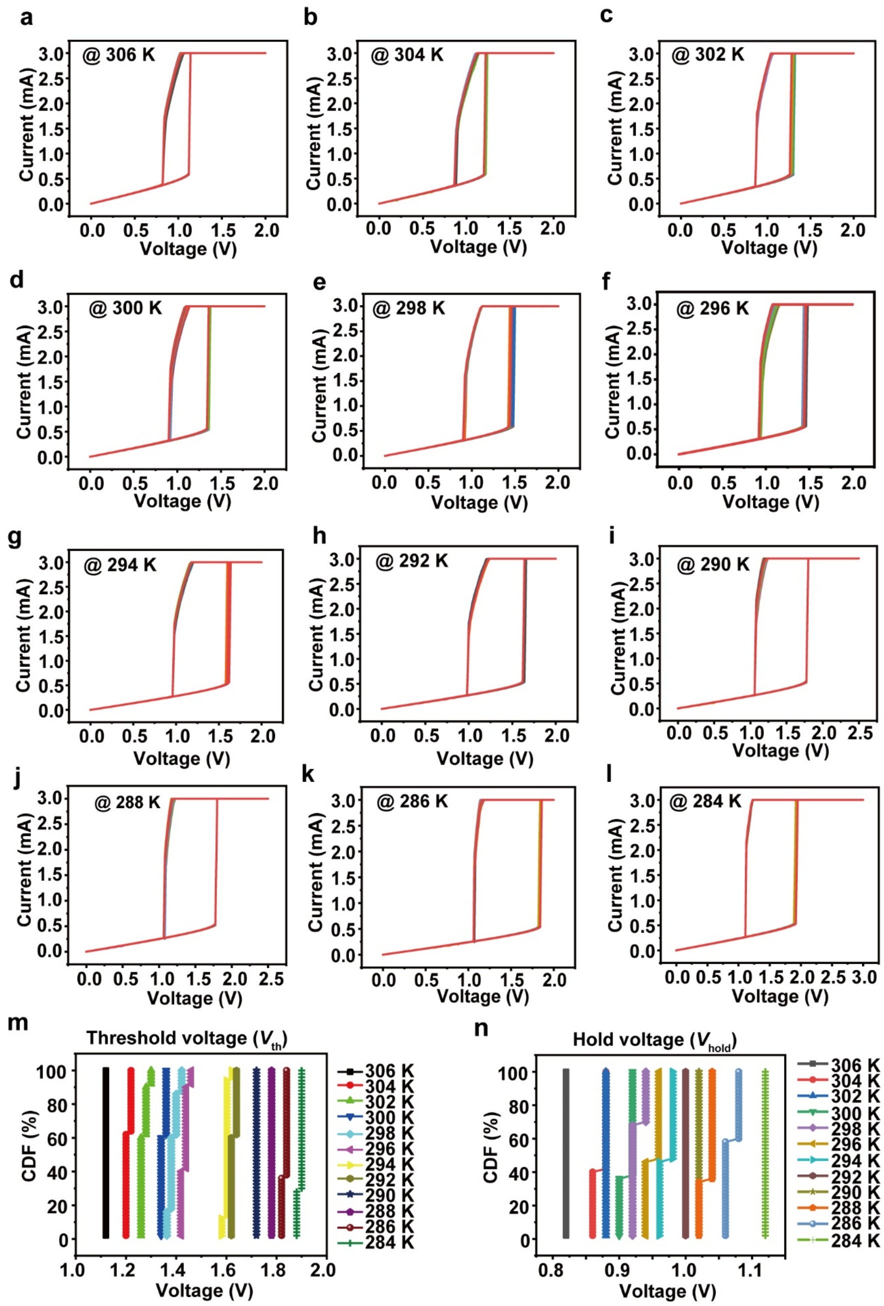

Figure S11. Cycle-to-cycle variation of the VO_2memristor under different temperatures. a-l) I-V characteristics of the VO_2 device in 50 repeated cycles under different temperatures (284-306 K). m) Cumulative plots of V_{th} in the 50 repeated cycles. n) Cumulative plots of V_{hold} in the 50 repeated cycles.

Figure S11a-l show the I-V characteristics of the VO_2 device in 50 repeated cycles under different temperatures, showing excellent cycle-to-cycle uniformity under each temperature. The cycle-to-cycle fluctuations in V_{th} and V_{hold} are further plotted in Figure S11m,n, which once again demonstrates very low cycle-to-cycle variation.

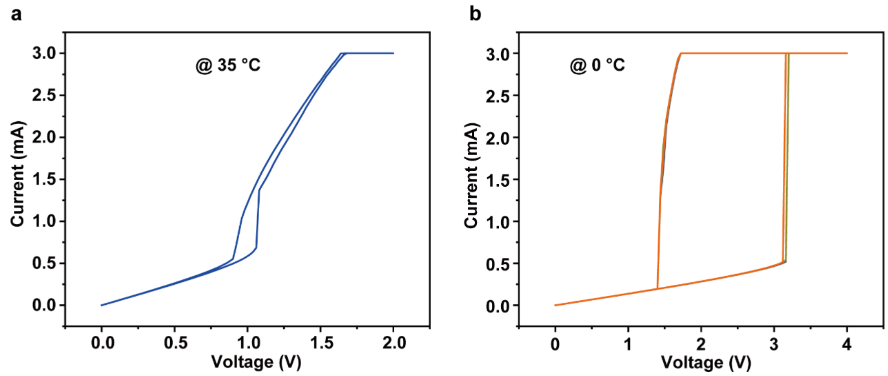

Figure S12. The I-V characteristics of VO_2memristor at 0 °C and 35 °C. a) *I-V* characteristics at 35 °C. b)*I-V* characteristics at 0 °C.

The lowest and the highest temperature that the VO_2device can operate are shown in Figure S12. When the temperature is greater than 35 °C, the device has almost no stable threshold switching (TS) characteristics (Figure S12a), so the maximum working temperature of this VO_2 device cannot exceed 35 °C. When the temperature is lower than 0 °C (the lowest temperature that the test equipment can be lowered to), the device still has stable TS characteristics (Figure S12b), so the minimum operating temperature of this device is less than 0 °C.

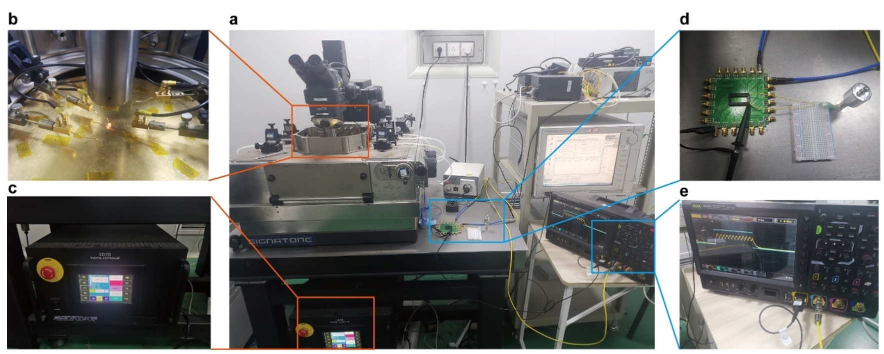

Figure S13. The entire system for testing haptic-temperature fusion. a) The entire testing system. b) The probe station used for testing VO_2 memristor with temperature control system. c) Temperature control platform. d) The piezoresistive sensors connected in series. e) The oscilloscope for measurement of the output signal.

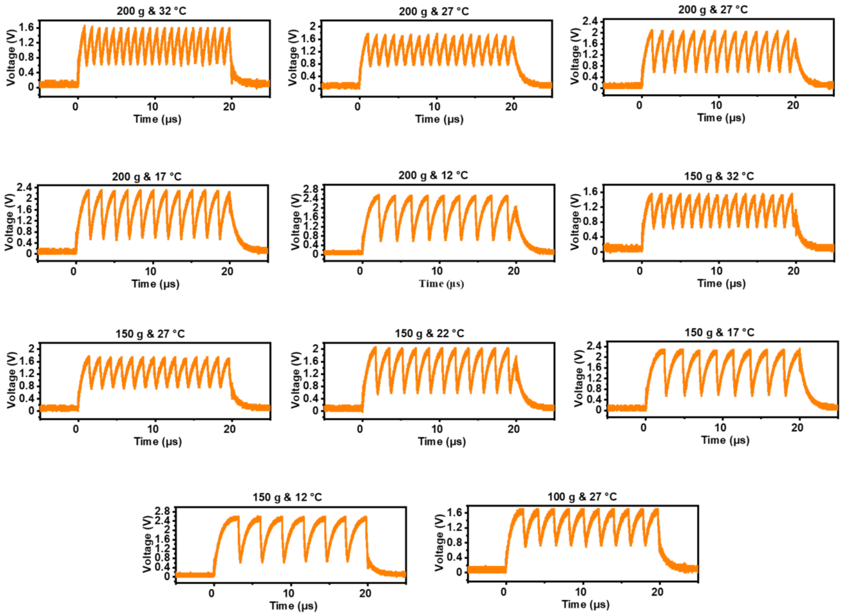

Figure S14. The neuronal response under the different pressures and temperatures.

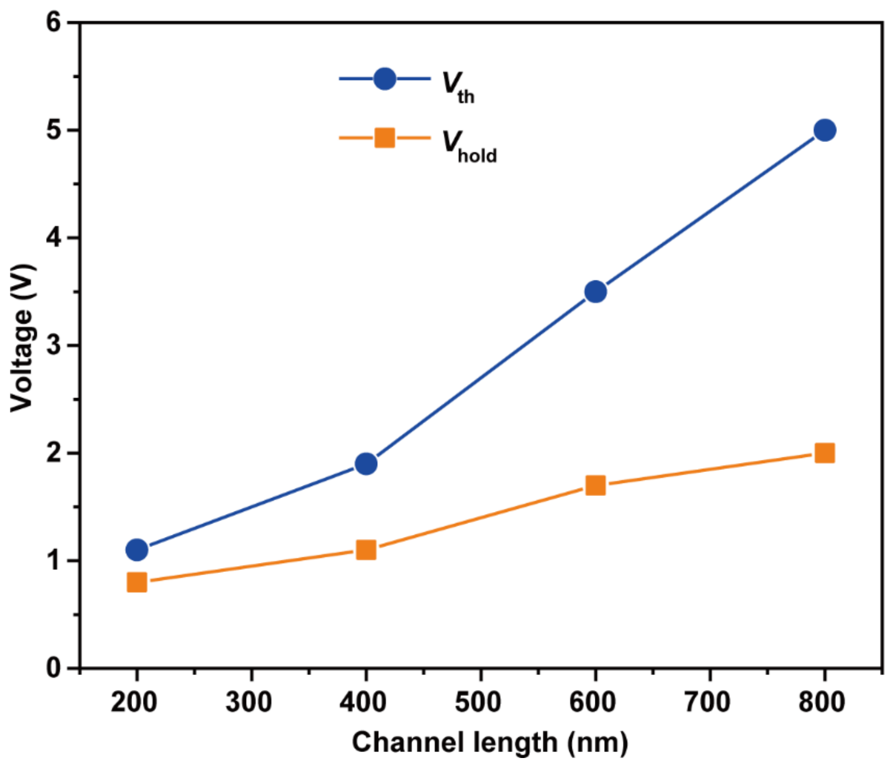

Figure S15. The V_{th} and V_{hold} of VO_2 memristor with different channel lengths.

Rich media available at https://youtu.be/4xLMAH1yJjs

Supplementary Video 1 : With convex patterns on both the left and the right (that is, both sensors have pressure by applying 100 g)

Rich media available at https://youtu.be/T8e6saQalmU

Supplementary Video 2 : With convex pattern only on the left (that is, the left sensor has pressure by applying 100 g, but the right has no pressure))

Rich media available at https://youtu.be/RhAhtFgMvMw

Supplementary Video 3 : With convex pattern only on the right (that is, the right sensor has pressure by applying 100 g, but the left has no pressure)

Rich media available at https://youtu.be/mTPXXIlp7NQ

Supplementary Video 4 : The haptic-temperature fusion under 100 g & 27 °C

Rich media available at https://youtu.be/Y3tiSgIMUJQ

Supplementary Video 5 : The haptic-temperature fusion under 200 g & 17 °C

Rich media available at https://youtu.be/YQ_rK4K_Th8

Supplementary Video 6 : The haptic-temperature fusion under 200 g & 32 °C

References:

[1] J. Bryzek, *Sens. Actuator A Phys* . **1996** , 56, 1-9.

[2] Y. Sun, X. Sun, B. Sun, Q. Meng, *Sens. Actuator A Phys.***1997** , 58, 249.