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A brain circuit on ionic neurons

With the authors' help we reproduced their ionic neuron model. It works as in the paper, but it is not a suitable building block for a circuit; and a second, measured device produces no spikes at all in the circuit we tried.

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Refuted

simulation, not measurement · 2 published models · criteria written in advance · robustness checks · no chip fabricated

6/6	0.16%	1.624 s	0/37
spiking modes of the paper reproduced after the interpolation fix	width of the sustained-firing window relative to threshold, against the 10% required	memory time of the nanochannel from the model, against 1.62 s in the paper	configurations of the nanochannel circuit in which the potential oscillates

SUMMARY

After light and lasers (NR-07, NR-08) we asked the same question of **iontronic** devices, in which current is carried by ions in a liquid, as in real neurons: can a validated brain circuit run on such neurons? Before any simulation we wrote two criteria: the model must reproduce the figures of its own paper, and the neuron must be **usable**, that is respond in a graded way up to at least 40 Hz over a current range at least 10% of the threshold wide. The first model, the conical-channel circuit of the Utrecht group, initially locked after two spikes. We wrote to the authors: the cause was the **interpolation** of the conductance, which differs between Mathematica and our code exactly where it decides whether the neuron fires. With their fix the model reproduces all six spiking modes of the paper, but fires continuously only between 19.03 and 19.06 pA, 0.16% of threshold, and at most at 23.5 Hz: **not usable**, as predicted on the first day. The authors suggested a second device, a microchannel filled with silica microspheres, measured in the laboratory and never tried in a spiking circuit. Its model is reproduced well, but in the circuit built with all the ratios of the original one the potential **does not oscillate**, while the same circuit with the

conical conductance shape spikes as in the paper. Along the way we found and corrected four errors of ours in the first circuit.

1 The question

Does the D3 basal ganglia circuit keep working if its neurons become ionic neurons? The work on lasers (NR-08) taught us that what matters is the **ratio** between the time scales of the neuron and those of the circuit, not absolute speed. The usability criterion, written in advance, therefore has two parts: (1) a graded rate up to at least 40 Hz over a current range at least 10% of threshold wide; (2) a recovery time after a spike at most 0.2 times the neuron's integration time (0.1 for the neurons of the reference circuit). If the neuron fails, the circuit is not simulated.

2 The first model: bipolar conical channels

Of the three candidates found in the literature, only one had a complete model: the four-channel conical circuit of Kamsma and colleagues (Utrecht, 2023 and 2024). On 27 September our implementation reproduced each channel, but the circuit fired at most two spikes and then locked. Six hypotheses of an error on our side, written in advance, were all refuted. We closed the line as "refuted for the available models" and wrote to the authors, sending the code.

The authors replied twice within a few days. The second time they found the cause: the channel conductance is computed on a voltage grid and then **interpolated**. They use Mathematica's default interpolation, a local cubic through the four nearest points; we used SciPy's cubic spline. The two differ exactly where the conductance changes abruptly, which is where it is decided whether the neuron fires. They sent back our file with their fix, the only difference.

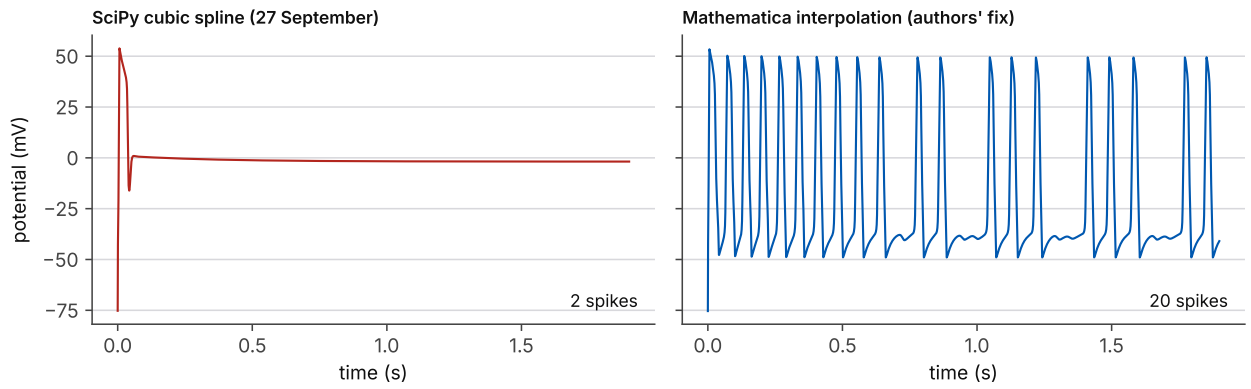


Figure 1. The same circuit, at the same current of 19.05 pA, with the two interpolations of the tabulated conductance; everything else is identical. Simulation re-run on 2 October 2026.

With the fix, and with two errors of ours corrected and declared (a script that stepped over the current of 19.05 pA; a test programmed with two positive pulses instead of a negative and a positive

one), the model reproduces all six spiking modes of Fig. 2 of the paper: 20 spikes in 1.9 s as in the figure, rest at −75.4 mV against −74, peak at +53.4 against +51. Mixed mode appears at 19.0275 pA instead of 19.02, a shift of 0.0075 pA that we declare.

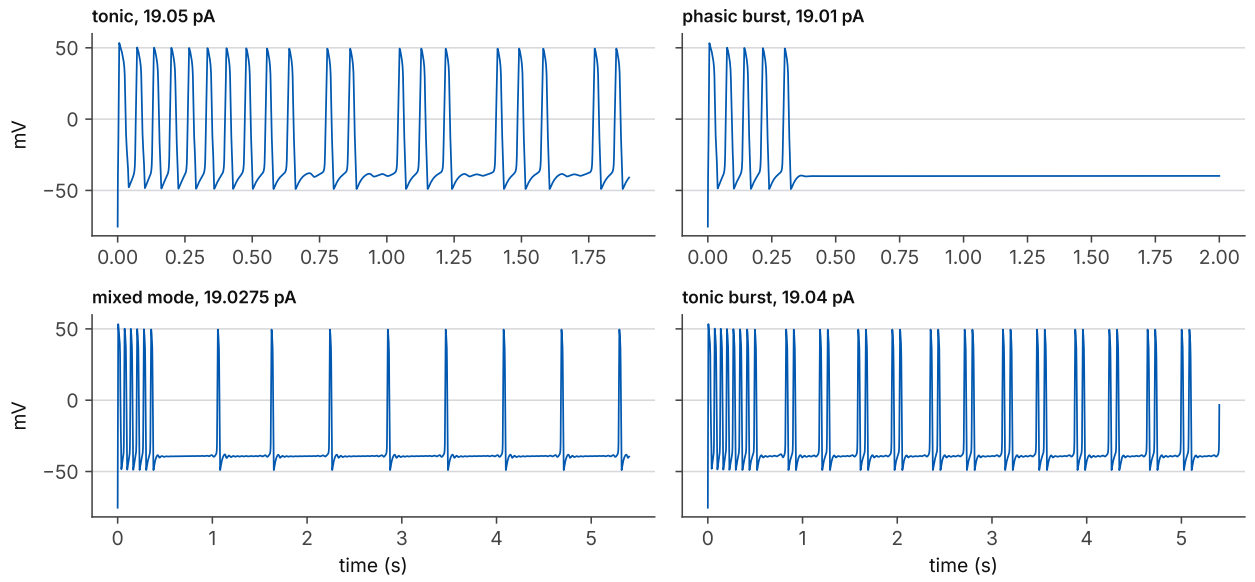


Figure 2. Four of the six spiking modes of the paper, reproduced with the corrected model: tonic spiking, phasic burst (5 spikes as in the figure), mixed mode and tonic bursting.

Is the neuron usable?

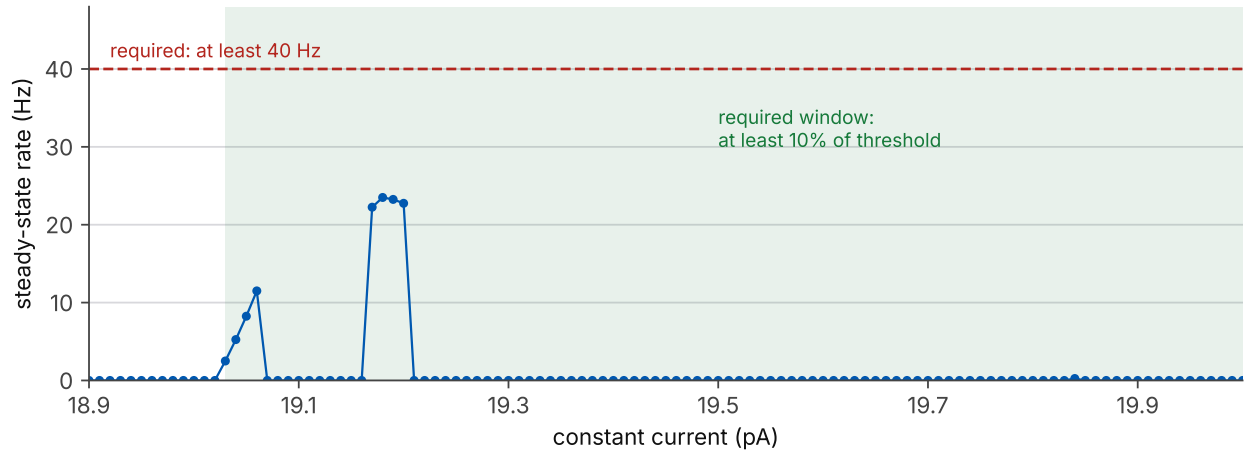


Figure 3. Steady-state firing rate as a function of current, in steps of 0.01 pA between 18.9 and 20 pA (the full curve runs from 0 to 40 pA). Sustained firing exists only between 19.03 and 19.06 pA and in a second window around 19.2 pA. The green band is the graded range the criterion requires.

part	criterion written in advance	measured	outcome
1	up to at least 40 Hz over at least 10% of threshold	window of 0.03 pA, that is 0.16% of threshold; at most 23.5 Hz	failed
2	recovery / integration at most 0.2	integration in 0.044 ms; recovery measurement not reliable (see limitations)	not assessed



Figure 4. The usability criterion compared with measurements on the reproduced model: maximum rate and width of the sustained-firing window (log scale).

This is a clean result: no longer "we cannot get it to work", but "it works as in the paper, and it is not suited to be a building block for a circuit". It is not a criticism of the model, whose authors state clearly that the spiking modes are separated by 0.01–0.1 pA.

3 The second model: measured colloid-filled nanochannels

The authors suggested a different device with stronger rectification: a microchannel filled with charged silica microspheres (Kamsma, Kim and colleagues, PNAS 2024), built and measured in the laboratory, with a complete analytical model. It had never been tried in a spiking circuit. We tried it before replying, with the same criteria.

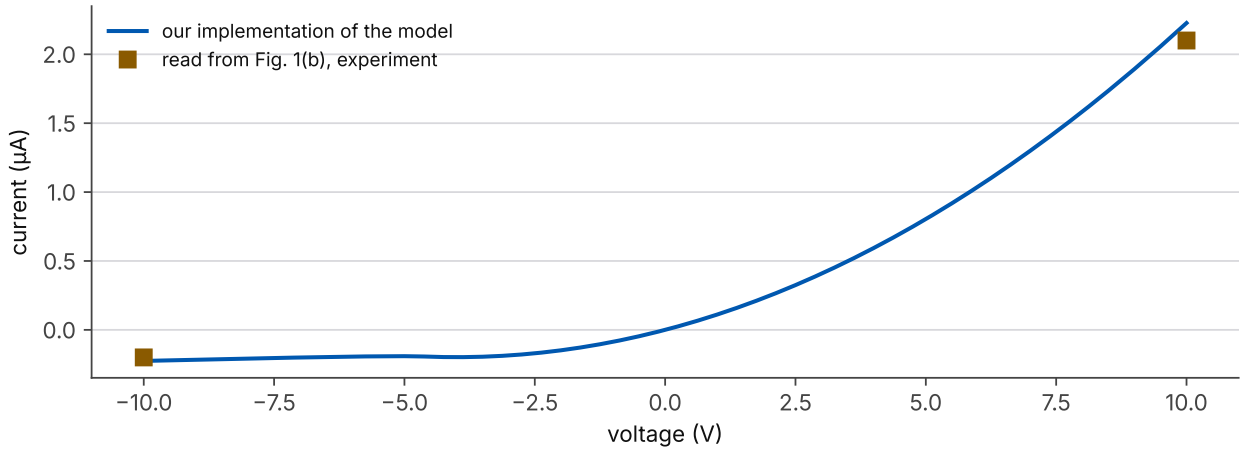


Figure 5. Steady-state current of the nanochannel computed with our implementation of the model, over the range of Fig. 1(b) of the paper; the squares are values of the experimental curve read from the figure.

The model is reproduced: the channel's memory time is **1.624 s** against 1.62 in the paper, and the rectification between +10 and −10 V is 9.9 against the measured 11. (A first check gave 4.2: we had misread the range of the figure, ±5 V instead of ±10 V. It is on record.)

The paper does not propose a spiking circuit, so the circuit is our choice, approved in advance: the same four-channel scheme as the 2024 paper, with the conical channels replaced by nanochannels, the slowest of which is the measured device. The nanochannel conductance has the **same shape** as that of the conical channels, with its knee at 1.5 V instead of 0.15 V: all voltages of the circuit are therefore multiplied by 10. Length and cross-section of each channel are chosen to respect both the time-scale and the conductance ratios of the original circuit.

The first circuit, built on 2 October, was wrong in four ways, and none of them produced an error message: the circuit simply did not oscillate. The channels were mounted the wrong way round (the two papers use opposite sign conventions); the fast channel was the weakest instead of the strongest; the capacitance was ten times too large, computed with the conductance of another channel; the currents tried did not reach the threshold. Those results are withdrawn, together with a first explanation of ours ("the nanochannel rectifies gradually"), which was false.

Before trying the nanochannel in the corrected circuit we ran a **positive control**: the same circuit, with the same scales, but with the conductance shape of the conical channels. It reproduces the paper: rest at −0.754 V (−75.4 mV times 10) and firing within a window of 0.15% of threshold, like the 0.16% of the original model. The circuit and the way we count spikes see spiking when it is there.

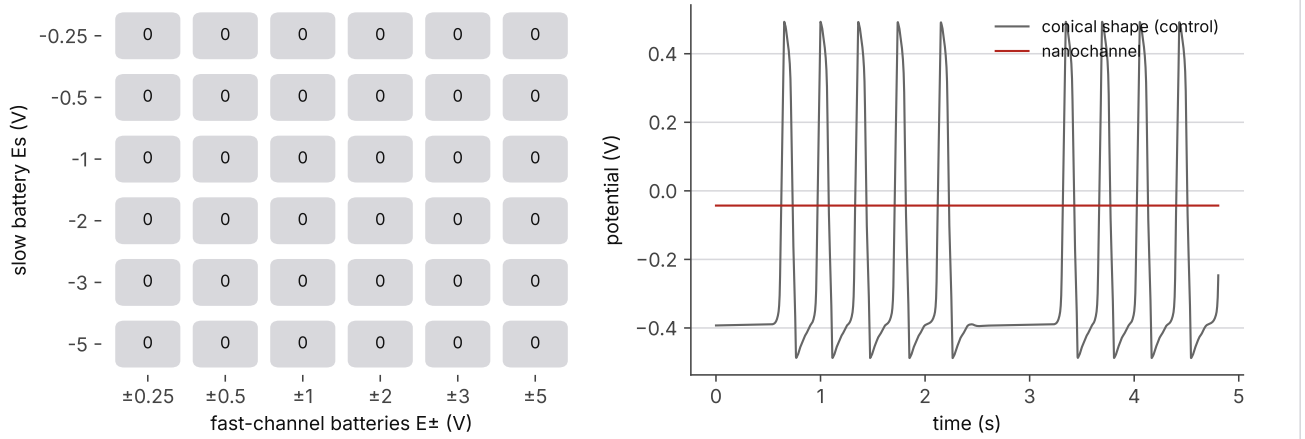


Figure 6. Left: maximum number of peaks of at least 50 mV at steady state, for each of the 36 battery combinations and 200 currents up to beyond the equivalent threshold. Right: the same circuit at the current equivalent to the 19.05 pA of the paper, with the conical shape (control) and with nanochannels.

With nanochannels, instead, the potential **does not oscillate** in any of the 37 battery configurations tried (the paper's batteries scaled and a grid of 36), 200 currents each up to beyond the equivalent threshold: 7400 simulations, not a single peak. In the fine scan around the equivalent threshold too, 401 currents in steps of 0.05%, where the control fires, the nanochannel does not oscillate; the outcome does not change with the conductance computed exactly at every step, or at 300 K instead of 293.15 K.

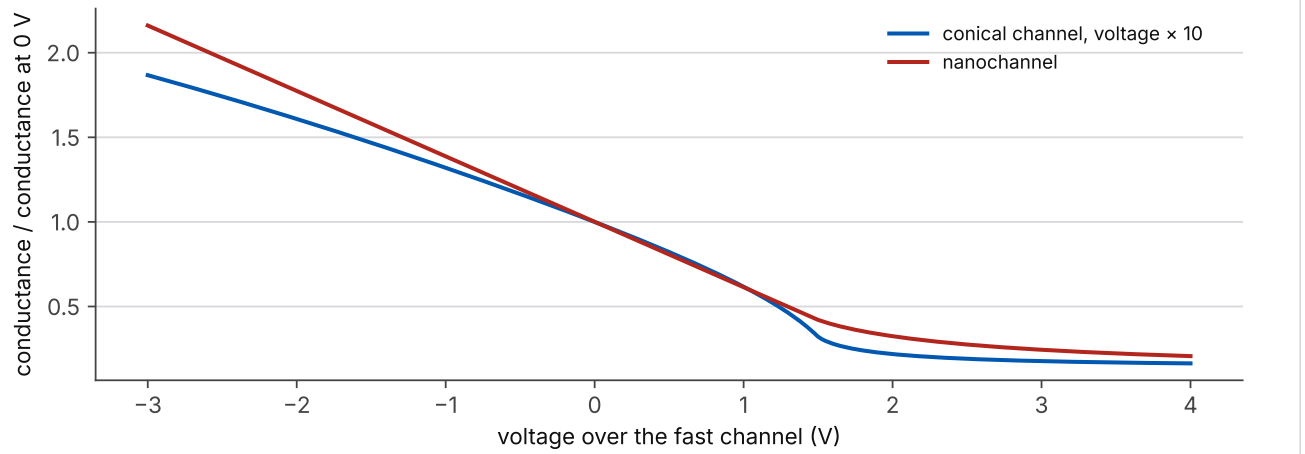


Figure 7. Conductance of the fast channel as a function of voltage: the conical channel (voltage multiplied by 10) and the nanochannel coincide up to the knee; beyond the knee the conical channel switches off further (0.22 against 0.32 of the resting conductance at 2 V).

To see which difference matters we tried, in an exploratory way, hybrid circuits. Giving the conical shape to the two fast channels alone is enough for the circuit to fire; giving it to the slow channel alone or to the slowest alone is not. The decisive point is therefore how far the fast channel **switches off** beyond the knee: the nanochannel keeps about 45% more conductance, and the spike does not

find the state that ends it. We have asked the authors whether device parameters exist that would make it switch off further.

4 What it shows and what it does not

It shows that the two complete ionic neuron models available today, reproduced with the authors' help, do not give a neuron usable as a building block of a circuit: the first fires only in a tiny window, the second, in the circuit tried, does not fire at all.

It does not show anything against the physics of ionic devices. It shows how much details that papers do not report (the interpolation) matter, that a circuit designed for one device does not automatically transfer to another, and that a negative outcome counts only if a positive control shows that the test can see a positive.

> **Limitations.** Simulation, not measurement. The nanochannel circuit is our own combination of published parts; the hybrids are an exploratory analysis, outside the protocol. The temperature (293.15 K) and base charge density (6.3 mM) of the nanochannel are our choices, to be confirmed with the authors. The recovery measurement of the conical neuron is not reliable: a second crossing of 0 mV already appears at the shortest delay tried (0.5 ms) and we did not verify that it is a full spike; part 2 of the criterion is therefore not assessed, and part 1 is enough for the outcome. No device was fabricated.

5 Acknowledgements

We thank T. M. Kamsma (Utrecht University), with his written consent of 6 October 2026, for answering our questions, for the interpolation fix and for suggesting the nanochannel model. After reading our report he wrote that the failure of the usability criterion seems completely sensible to him; he added that he has not yet looked at the nanochannels in a spiking circuit and cannot say anything meaningful about our result with them, which remains ours and has not been verified by him.

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- Internal documents: whitepapers WP-P3 and WP-P3bis; records `iontronics/registry/p3_gangli_ionici.yaml` and `p3bis_nanocanali.yaml`; logs in `iontronics/risultati/`.

How to cite

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Nadirion technical report, not peer-reviewed. The criteria of every test were written before running it; negative results are reported like positive ones. The tests measure functional roles.