Research · Report NR-08 · 23–24 September 2026

A brain circuit on laser neurons

The 240 neurons of the basal ganglia become excitable lasers. With weak inputs the circuit does not decide; with strong inputs it always decides, even for no reason.

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Refuted for the channel

published neuron model (SIMPEL) · 1 ns = 20 ms of membrane time · seeds 20–25 · THEORY label

0/6	6/6	~104 ms	81 fJ
decisions with input at the original scale	decisions with no input at all at scales ×5 and ×10	laser recovery in equivalent time, against ~15 ms for a neuron of the circuit	energy of one laser spike (reference in the paper: 88 fJ)

SUMMARY

The D3 basal ganglia circuit, validated with criteria written in advance, selects an action by accumulating evidence. We asked whether it keeps working when its 240 neurons become **excitable lasers**, using the published SIMPEL model (Shastri and colleagues) of a two-section laser, with the time scale fixed by physics: 1 ns of the laser corresponds to 20 ms of membrane time. Below threshold the laser is exactly an integrate-and-fire neuron, with the same time constant as the circuit; it differs in the spike and above all in its **recovery**, which lasts about 104 equivalent ms against about 15 for a neuron of the circuit. The result: the channel never decides at the original scale (0 out of 6) and, if the inputs are amplified, it always decides, even with no input (6 out of 6). No scaling factor satisfies both conditions. The refutation concerns this neuron model: a measured laser chip (Shi and colleagues, 2023) recovers about four times faster.

1 The question

This is the link between the line on physical substrates and the mission: whether a validated brain circuit works on neurons made of light, with their noise and imperfections. The photonic logic gate (NR-07) had answered no for digital logic; here the question is different, because a neuron does not have to be a logic gate.

2 Choices approved in advance

- Neuron: two-section laser, gain and saturable absorber, from the SIMPEL model (Shastri and colleagues, arXiv 1409.7030). A published model, not one written by us.
- Reference circuit: the D3 already adopted (NR-05).
- Time scale fixed by physics, not tuned: 1 ns of the laser = 20 ms of membrane time.
- Same thresholds as D3; robustness and energy descriptive only.
- "Broadcast-and-weight" connections: a shared waveguide, ring weights, balanced photodiode, 7-bit weights.

3 Checking the neuron before the circuit

At the first run, at the current given in the paper, the laser **pulsed on its own**. The diagnosis, with hypotheses written in advance, found that spontaneous emission bleaches the absorber and that in the model the self-pulsation threshold is 15.717 mA; the author chose to bias just below it. At the second run the seven qualitative test cases (including all-or-nothing response, integration, leak, inhibition and refractory period) are all passed and the spike energy is 81 fJ against the paper's 88, but the delays come out roughly halved and the threshold of one laser variant is 41% lower. An alternative model was incomplete (coefficients from a "private communication"), another too heavy: we went back to SIMPEL and **every outcome carries the THEORY label**, because the neuron model is not reproduced quantitatively.

quantity	laser neuron	D3 neuron
distance from rest to threshold	0.7% of the gain	20 mV
value after the spike	27% of rest, about −2058 equivalent mV	−60 mV
emission delay	0.67 ns = 13.3 equivalent ms	0
absolute refractory period	0.04 ns = 0.8 ms	2 ms
recovery between two spikes	about 5 ns = about 100 equivalent ms	about 15 ms

4 The circuit does not choose: it snaps

With the constants measured on the full model, without tuning, a channel of the circuit **never decides**: 0 decisions out of 20, whatever the strength of the evidence. All populations fire between 7 and 11 equivalent Hz almost regardless of the input: it is the ceiling set by the laser's slow recovery. To decide, the thalamus must reach 13.3 Hz.

The author chose a calibration with a single parameter, a common scaling factor on all inputs, and a rule written in advance: the smallest factor for which the channel decides with strong evidence in at least 5 seeds out of 6 **and** stays silent with no input.

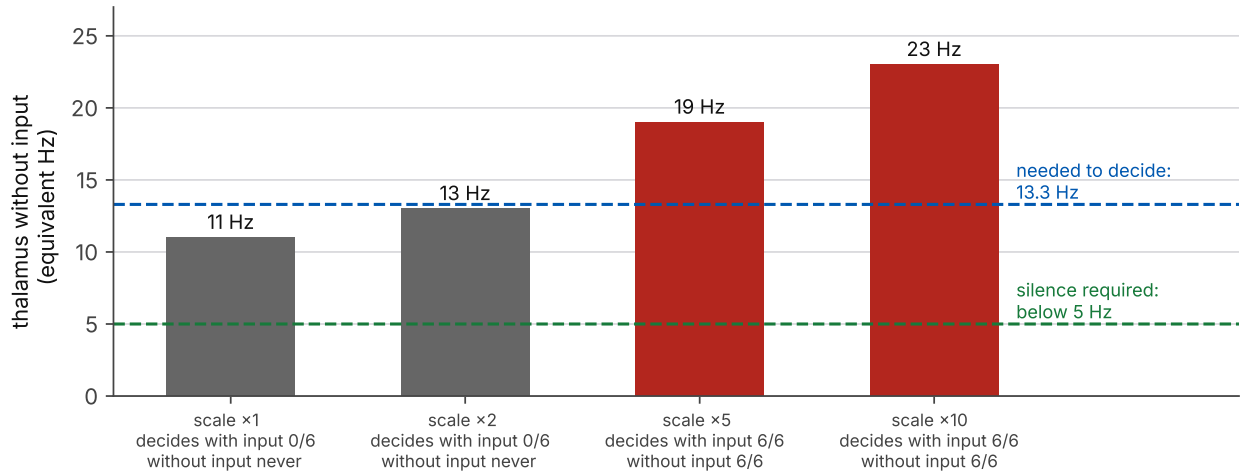


Figure 1. Thalamic rate with no input at all as the scaling factor changes, seeds 20–25, and decisions with and without input. At scales ×1 and ×2 the circuit never decides, either with or without input, and the thalamus without input is already at 11–13 Hz, above the 5 Hz required; at scales ×5 and ×10 it always decides, always at the same instant, for any input and even with none. No scale satisfies both conditions.

The reason is that the GPi, the structure that brakes the thalamus, can no longer brake it: all populations are at the laser's firing ceiling, so the balance between brake and drive, which in the biological circuit depends on the evidence, disappears.

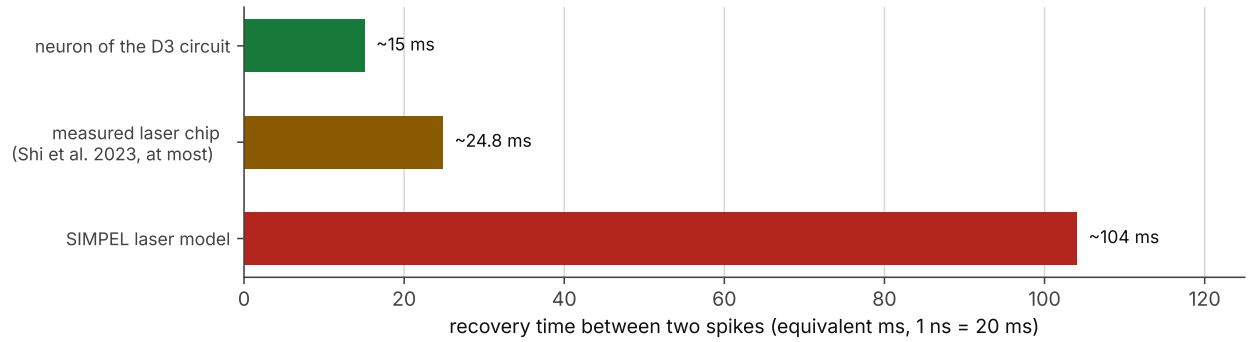


Figure 2. Recovery time between two spikes, in equivalent milliseconds. The SIMPEL model recovers in about 104 equivalent ms (5.2 ns), seven times more slowly than a neuron of the circuit. A measured laser chip (Shi and colleagues, 2023) recovers in less than 1.24 ns, that is less than about 25 equivalent ms.

5 Predictions written in advance

1. (23 September) Without device-to-device variation the circuit holds; it breaks between 2 and 5% variation. **Refuted.**
2. (updated before the code) Likely failure already at the nominal point, because of the refractory period. **Confirmed.**

6 What it shows and what it does not

It shows that the basal ganglia circuit does not work on laser neurons described by the SIMPEL model with the time scale fixed by physics, and locates the reason in the ratio between the neuron's recovery time and the time scales of the circuit.

It does not show that a brain circuit cannot run on laser neurons. The culprit is the slow gain recovery **in the model**; a real chip recovers about four times faster. Reopening the question would require a complete, published and reproduced model with fast recovery, or a measurement on a real device.

The lesson guided the later work on ionic neurons (NR-09): for a circuit, what matters is not the absolute speed of the neuron but the **ratio** between its time scales and those of the circuit.

> **Limitations.** A single channel of the circuit, a single scaling factor, no device-to-device variation; neuron model not reproduced quantitatively (halved delays, different threshold); between the two simulation levels a 13–20% difference in firing rate remains, with an open cause. The full D3 bench was not run.

References

- Shastri, B. J. and colleagues. SIMPEL: circuit model for photonic spike processing laser neurons. arXiv 1409.7030.
- Nahmias, M. A. and colleagues (2013). A leaky integrate-and-fire laser neuron for ultrafast cognitive computing. *IEEE J. Sel. Top. Quantum Electron.* 19, 1800212 (not read: paywalled).
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- Zhang and colleagues (2022). *Optica* 9, 579.
- Herculano-Houzel, S. (2011). Scaling of brain metabolism with a fixed energy budget per neuron. *PLoS ONE* 6, e17514.
- Internal documents: whitepaper WP-P2; record `photonics/registry/p2_gangli_fotonici.yaml`.

How to cite

Chiarolanza, G. (2026). A brain circuit on laser neurons. Nadirion, research report NR-08, 23–24 September 2026. https://nadirion.eu/en/research/laser-neurons/

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.