

Optimal time scale for response reliability and stochastic synchronization in real neurons

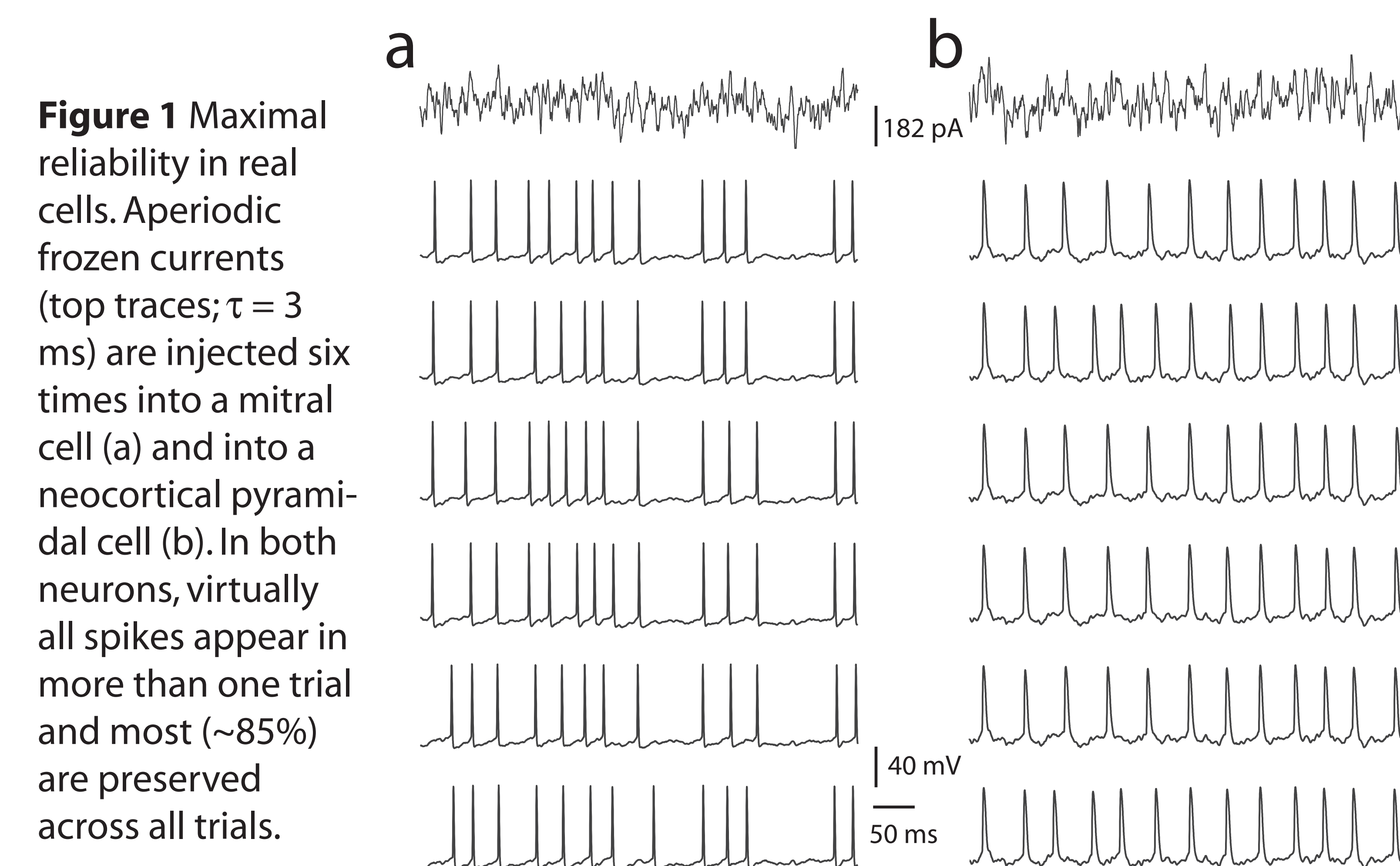
Roberto Fernández Galán^{a,b}, G. Bard Ermentrout^{b,c} and Nathaniel N. Urban^{a,b}

^aCarnegie Mellon University, Dept. of Biological Sciences, ^bCenter for the Neural Basis of Cognition, ^cUniversity of Pittsburgh, Dept. of Mathematics

1. Introduction

To understand how the brain processes information we have to elucidate the features of natural stimuli that are encoded, processed and transmitted by neurons. In sensory neurons, natural stimuli are observables from the environment like sounds and images and numerous studies have investigated what features of these stimuli are translated into neuronal activity to optimally encode sensory information. In deeper brain areas, where information is further processed, neurons communicate with each other through synaptic currents. **What are the features of these signals that permit neurons to reliably interact**, so that they can convey information with high fidelity even in the presence of background noise?

We can reformulate this question as an engineer and think of this as a design problem, in which we want to maximize the reliability of the device's response (output) given the constraint that the amplitude of the input signal (stimulus) and the background noise remain constant (fixed signal-to-noise ratio).



One feature of the input signal with respect to which it seems reasonable to optimize design is the temporal component, i.e. the rapidness of the stimulus to be detected. In fact, it has been known for a long time [1,2] that fast fluctuating currents result in highly reproducible spike times across repetitions, whereas constant (i.e. infinitely slow fluctuating) currents result in non-reproducible spike times. **Here we address the question whether, "faster is always better" and, in particular, whether there is an optimal time scale for input fluctuations to induce reliable firing.** The existence of such an optimal time scale is likely to indicate adaptation of the neuron's natural design to a preferred type of input. This in turn would represent the time scale in which neural processing most efficiently occurs.

2. Results: Experiments and Simulations

Several studies have emphasized the importance of fast input fluctuations in generating spike times that are reliable from trial to trial [1,2,3]. Here we ask whether faster is always better and in particular whether there is an optimal time scale for stimulus fluctuations to induce reliable firing. To this end, in real and simulated neurons we have repetitively presented "frozen noise" stimuli (see Fig. 1, top traces) that consisted of a constant current plus aperiodic fluctuations with different autocorrelation times, τ (the shorter τ is, the faster are the fluctuations). Spike-time reliability was defined as the similarity between spike patterns across repetitions. In particular, the traces were converted into binary strings where 1's represented ascendent crossings of a voltage threshold at 0 mV. Then, we convolved these binary strings with a square function of width 2δ and calculated reliability as the mean crosscorrelation of the resulting traces ($n=6$).

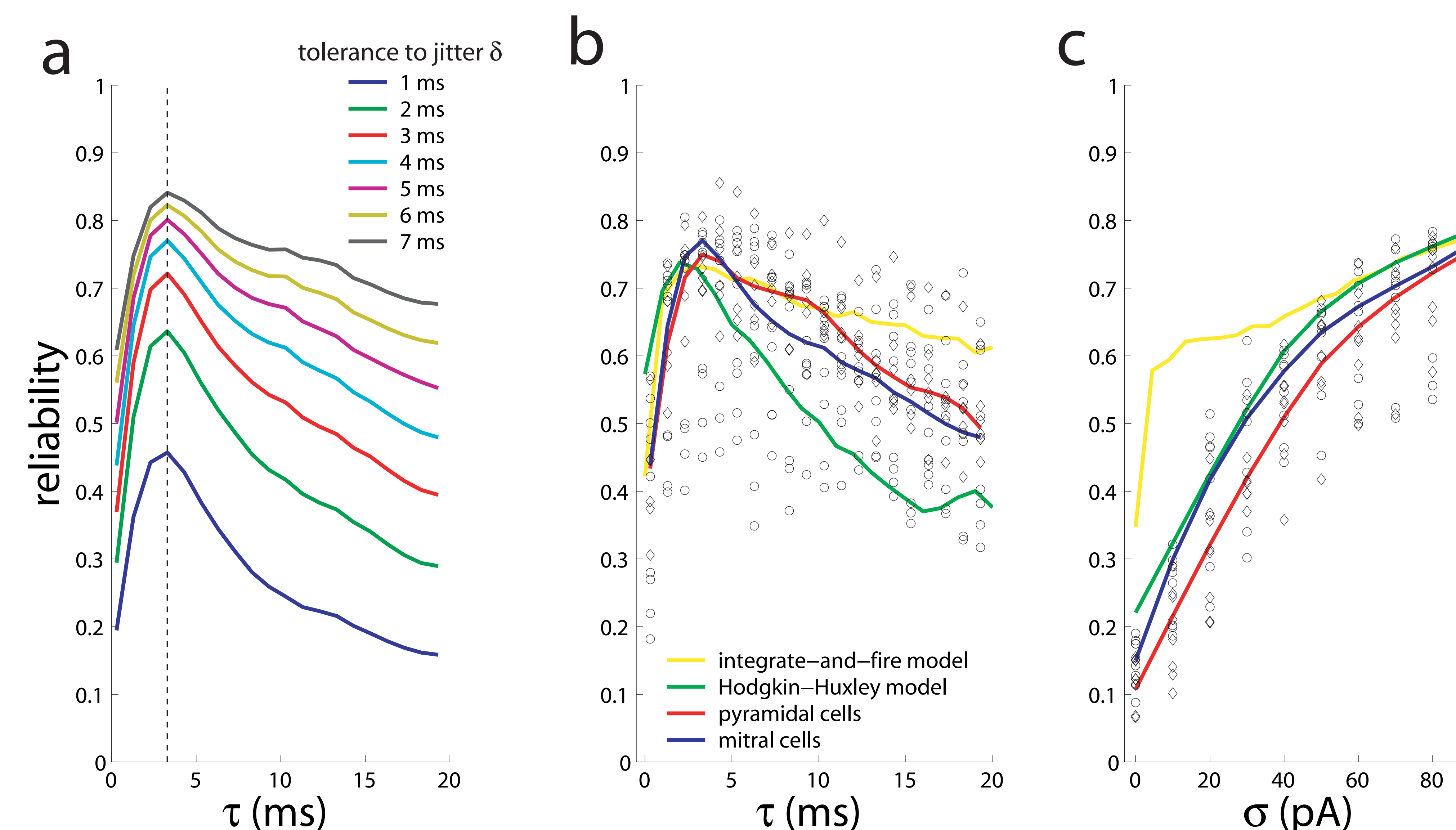


Figure 2. Optimal time scale for reliability in real and simulated neurons. **(a)** Spike-time reliability of mitral cells for several values of δ . As expected, reliability increases overall with increasing tolerance to jitter. However, the peak of reliability remains unchanged at $\tau = 3.3$ ms. The curve for $\delta = 4$ ms is the one plotted in (b). **(b)** On average, reliability is maximal between 2 and 5 ms, where ca. 80 % of the spikes are preserved across trials. Lines connect the median of the values (mitral cells: circles; pyramidal cells: diamonds) obtained in all experiments at each τ , for a tolerance to jitter, $\delta = 4$ ms. **(c)** Dependence of reliability on the amplitude of the stimulus fluctuations for $\tau = 3$ ms. Reliability monotonically increases with the fluctuations amplitude, σ . The optimal time scale for spike-time reliability is independent of our choice of tolerance to jitter, δ .

We performed the experiments (Fig. 1) on mitral cells ($n=4$) of the olfactory bulb and on neocortical pyramidal cells ($n=4$) of mice obtaining similar results: on average, **spike-time reliability is maximal for τ ca. 3 ms** (Fig. 2a, b). As shown in Fig. 2a, this result is not an artifact of our measure of reliability. For the optimal time scale, reliability monotonically increased with increasing amplitude of the fluctuations (Fig. 2c). Interestingly, already half of the spikes were reliable as soon as the input fluctuations doubled the background input noise (<10 pA). Similar curves of reliability are followed by the Hodgkin-Huxley model and even by a simple integrate-and-fire model lacking any conductances (Fig. 2b).

3. Modeling optimal reliability with stochastic theory: preliminary results

In the previous figures, the existence of an optimal time scale for neuronal reliability seems to be a general property of neurons that does not rely on specific conductances. Thus, simple integrate-and-fire models can be used to study this phenomenon with stochastic theory. By solving the Fokker-Planck equation with auto-correlated noise **we find an optimal time scale for reliability, τ relative to the intrinsic time constant, τ_x , of the neuron model** (Fig. 3).

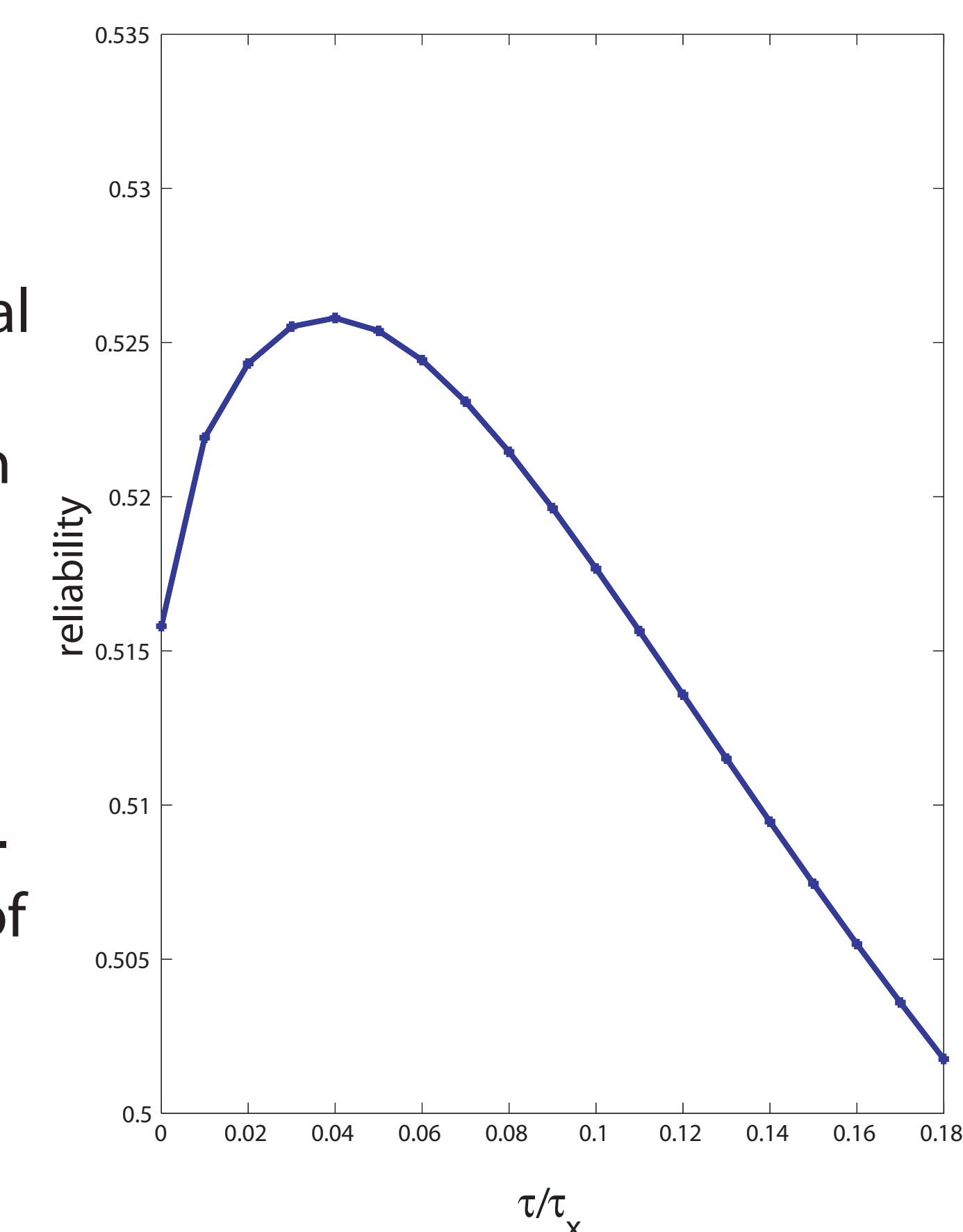


Figure 3. Optimal reliability is predicted by a simple integrate-and-fire model.

4. Conclusions

Our findings on spike-time reliability and its optimal time scale are immediately applicable to synchronization of neurons receiving random, but overlapping inputs [4,5,6], since both phenomena are closely related. In the former case the timing of the spikes is preserved in repeated trials with the same fluctuating stimulus. In the later case, identical neurons receiving similar (correlated) fluctuating stimuli trigger synchronous spikes. In particular, barrages of spatially correlated synaptic input currents will synchronize postsynaptic neurons quickly. Analogously, in the case of a single neuron, a reproducible barrage of synaptic pulses will trigger highly reliable responses.

In conclusion, we have shown that neurons have a preferred time scale in which the fidelity of the response, quantified as spike-time reliability, is maximal. In real neurons, this time scale is in the range of a few milliseconds suggesting that **neurons are adapted to optimally respond to their most natural input signal, i.e. fast synaptic currents.**

REFERENCES

- [1] H.L. Bryant, J.P. Segundo (1976) Spike initiation by transmembrane current: a white-noise analysis. *J Physiol* 260:279-314.
- [2] Z.F. Mainen, T.J. Sejnowski (1995) Reliability of spike timing in neocortical neurons. *Science* 268:1503-1506.
- [3] J.A. Movshon (2000) Reliability of neuronal responses. *Neuron* 27:412-414.
- [4] R. F. Galán, G. B. Ermentrout, and N. N. Urban (2006) Reliability, discriminability and stochastic synchronization of olfactory neurons. *Sensors and Actuators B* 116:168-173.
- [5] R. F. Galán, G. B. Ermentrout, and N. N. Urban (2006) Correlation-induced synchronization of oscillations in olfactory bulb neurons. *J Neurosci* 26:3646-3655.
- [6] R. F. Galán, G. B. Ermentrout, and N. N. Urban (2007) Reliability and stochastic synchronization in type I vs. type II neural oscillators, *Neurocomp.*, in press.

For complementary information visit:
www.andrew.cmu.edu/user/rfgalan/home.htm
This work was supported by NIDCD (R01DC005798-01), NIH 079504 and NSF (DMS 0513500).