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

Roberto Fernández Galán, G. Bard Ermentrout, and Nathaniel N. Urban

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 observable 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 reframe 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) while imposing 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 would in turn represent the time scale in which neuronal 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 apodic fluctuations with different autocorrelation times, \( \tau \). The shorter \( \tau \) is, the faster are the fluctuations. Spike-time reliability was defined as the similarity between spike patterns across repetitions; in particular, the traces were convolved into binary strings where 1's represent ascended crossings of a voltage threshold at 0 mV. Then, we convolved these binary strings with a square function of width 26 and calculated reliability as the mean crosscorrelation of the resulting traces (n=6).

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) while imposing the constraint that the amplitude of the input signal (stimulus) and the background noise remain constant (fixed signal-to-noise ratio).

3. Modeling optimal reliability with stochastic theory:

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, \( \tau_{\text{opt}} \), relative to the intrinsic time constant, \( \tau_{\text{r}} \), of the neuron model (Fig. 3).

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 this case, the barrage of spatially correlated synaptic input currents will synchronize post-synaptic 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 nature adapted to optimally respond to their most natural input signal, i.e. fast synaptic currents.

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 this case, the barrage of spatially correlated synaptic input currents will synchronize post-synaptic 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 nature adapted to optimally respond to their most natural input signal, i.e. fast synaptic currents.

REFERENCES


For complimentary information visit:

http://www.andrew.cmu.edu/user/rfgalan/home.htm

This work was supported by NIDCD (RO1 DC005798-01), NIH 079504 and NSF (DMS 0513500).