

How to read a burst duration code

Adam Kepecs[†] and John Lisman^{*}

[†]*Cold Spring Harbor Laboratory, Cold Spring Harbor, NY 11724, USA; *Volen Center for Complex Systems, Brandeis University, Waltham, MA 02254, USA*

Abstract

Brief, high-frequency bursts are commonly observed in neuronal recordings and are thought to represent a special neural code. Bursts have variable durations and spike counts which can encode stimulus variables. Here we examine how a burst duration code can be read out by synapses with short-term dynamics. We find that synapses can be tuned to preferentially respond to specific burst durations and the published range of facilitation and depression time-scales matches the typical burst patterns. These findings demonstrate the decodability of a neural code based on burst duration.

Key words: bursting, neural code, short-term depression, synaptic facilitation

1 Introduction

Short-term plasticity is a prevalent property of synapses [16]. Facilitation and depression may have different strengths, time constants [15,2] and may be expressed at a distinct class of synapses [13,12,4,7] or alternatively a single synapse may express multiple forms of short-term plasticity [5,3]. Computational investigations have suggested a number of functional consequences of short-term synaptic plasticity. Synaptic depression has been proposed to serve as a gain control mechanism in cortical circuits [1,14]. Synaptic facilitation was suggested to transmit bursts but filter out single spikes [11].

We have previously shown that burst discharges carry graded information in their duration and spike count both in a biophysical model [10,8] and in thalamic relay cells recorded *in vivo* [9]. Here we show how the combination of synaptic facilitation and depression allows synapses to read this burst duration code.

¹ *E-mail:* kepecs@cshl.edu

2 Methods

We used a synaptic model developed by Tsodyks and Markram [14]. The probability of release, P , changes as the function of the inter-spike intervals ($ISI_n = t_{n+1} - t_n$) due to the interaction of depression and facilitation processes. The probability of release, $P = D \cdot F$ follows the equations

$$F_n = U + F_{n-1}(1 - U) \exp(-ISI_{n-1}/\tau_F) \quad (1)$$

$$D_n = 1 + (D_{n-1}(1 - F_{n-1}) - 1) \exp(-ISI_{n-1}/\tau_D) \quad (2)$$

where $F_0 = U$ and $D_0 = 1$. Thus, the dynamics of a synapse are determined by the parameter triplet (U, τ_F, τ_D) .

We used the model bursting neuron described in [10]. The neuron was stimulated with a random current input (white noise with a 5Hz cutoff frequency). The mean current was 1.2 nA with a standard deviation of 0.7 nA. Bursts were identified using an 8 ms inter-spike interval threshold.

3 Results

3.1 Facilitating synapses can correctly read a burst duration code

We simulated a model bursting neuron with random current injections [10] and used the resulting spike train for all of our synaptic simulations. The spike train was segmented into bursts using an 8 ms inter-spike interval threshold. As we have previously shown these bursts signal the slope of the current input in a graded manner [10]. Figure 1 shows, however, that the input-output relation is not monotonic. The mean input slope increases as a function of the number of spikes per burst. However, within a given spike count larger slopes are actually signaled by shorter bursts. Figure 1B shows that this burst duration code can be read out correctly and monotonically using a facilitating synapse. Because shorter bursts of a given spike count contain higher frequencies, facilitating synapses increase their probability of release. Thus the overall efficacy of a burst increases monotonically as a function of slope. Because the intra-burst frequency also increases as a function of slope, it is also possible to read out the code before the burst is over. Figure 1C shows that the probability of release for the second spike in a burst also increases monotonically.

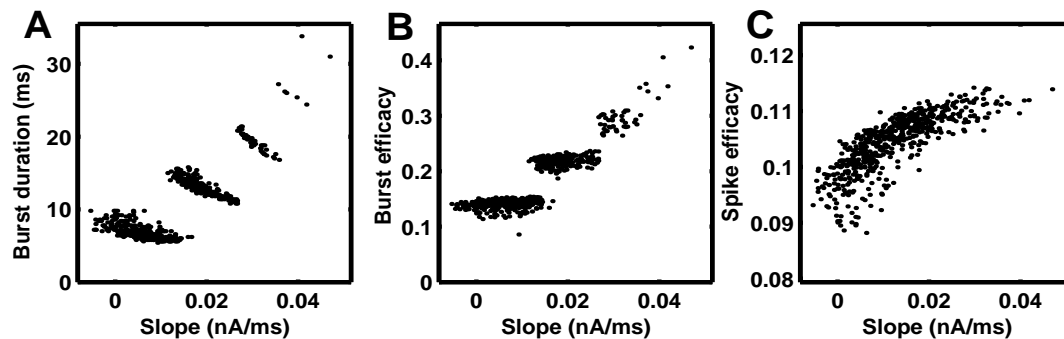


Fig. 1. **A** Burst duration signals the slope of the input current. Each cluster represents a given spike count. **B** Total burst efficacy (sum of the release probabilities for each spike in a burst) increases as a function the input slope. A facilitating synapse was used with the parameters $U = 0.05, \tau_F = 5 \text{ ms}, \tau_D = 200 \text{ ms}$. **C** Efficacy (probability of release) for the 2nd spike of each burst also increases as a function of slope.

3.2 Tuning a synapse to specific burst durations

Since different burst durations encode different stimuli it might be useful to respond to specific bursts better and other bursts less. This is possible to achieve by combining short-term synaptic facilitation and short-term depression. We passed a simulated spike train containing bursts of different durations through dynamic synapses with different parameters. Figure 2A1 shows that the mean synaptic response can either increase or decrease as a function of burst duration. Here, the synaptic response is calculated as the mean probability of release across all spikes of a burst for a given burst duration. The synaptic tuning curve is then normalized to have a maximum value of 1. Synapses can be tuned to a preferred burst duration by changing the initial probability of release (Fig 2A2). The initial probability of release determines whether depression or facilitation dominates during a burst. High-probability synapses tend to depress and their mean response decreases, while low-probability synapses facilitate and their mean response increases as a function of burst duration. Depending on the balance between facilitation and depression processes, intermediate burst durations may be preferred.

Figure 2B shows that burst duration tuning can also be achieved by adjusting the facilitation time constant of a synapse. Changing the facilitation time constant also has the effect of changing the balance between facilitation and depression.

So far we have considered only one measure of synaptic response: the relative mean release probability. Is it possible to tune a synapse to respond more overall to a shorter burst (with fewer spikes) than to a longer one? At first sight, this seems like an impossible task. Amazingly, this can be accomplished

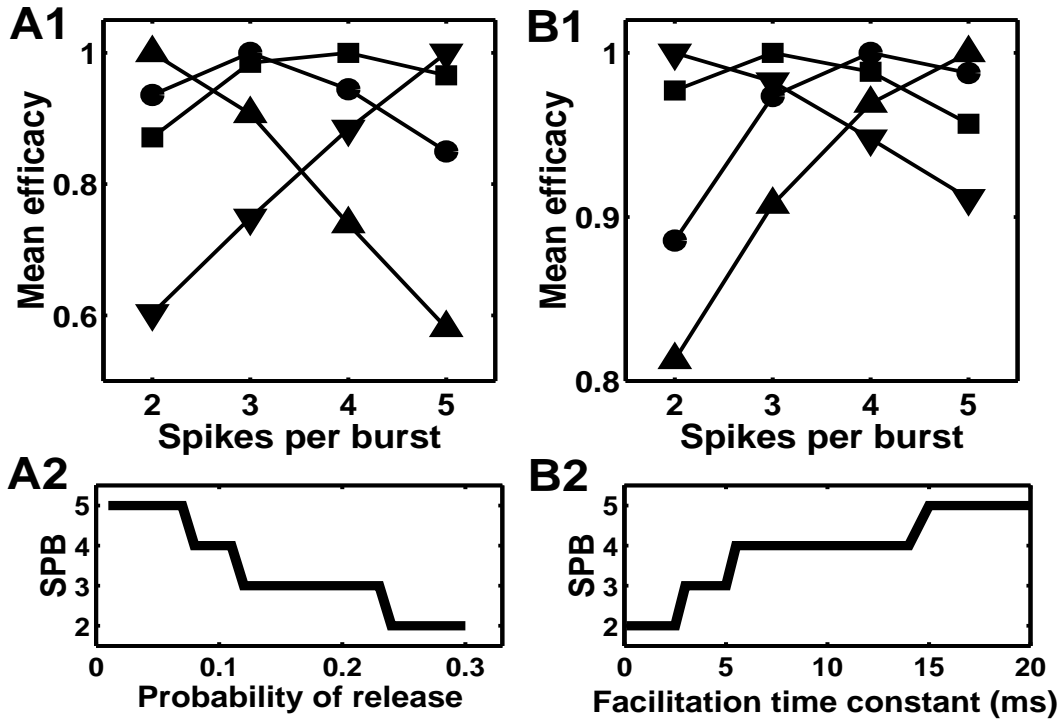


Fig. 2. **A1** Synaptic tuning curves. The mean relative release probability is plotted as a function of spike count. Each curve represents a synapse having a different initial probability of release, U . The synaptic time constants are $\tau_F = 30$ ms and $\tau_D = 200$ ms. The tuning curves are normalized to their maximum, which could be physiologically accomplished by post-synaptic scaling. **A2** Preferred burst duration is a function of the initial release probability, U . **B1** Synaptic tuning varies with the synaptic facilitation time constant, τ_F . The synaptic parameters are $U = 0.06$ and $\tau_D = 250$ ms. **B2** Preferred burst duration is a function of the facilitation time constant.

because of the correlations within intra-burst spikes. A large class bursting mechanism generates longer bursts with higher intra-burst frequencies [10,9]. Figure 3A shows that the mean first inter-spike interval decreases for longer bursts. Recall, that depressing synapses respond less to higher frequencies [1]. As a result a strongly depressing synapse can respond less to longer bursts (Fig 3B). In this case, the strength of depression determines the burst duration tuning of a synapse.

4 Discussion

Bursting neurons generate a special neural code by variations in the burst duration and spike count per burst [10,9,8]. Here we examined how a burst duration code can be decoded by synapses.

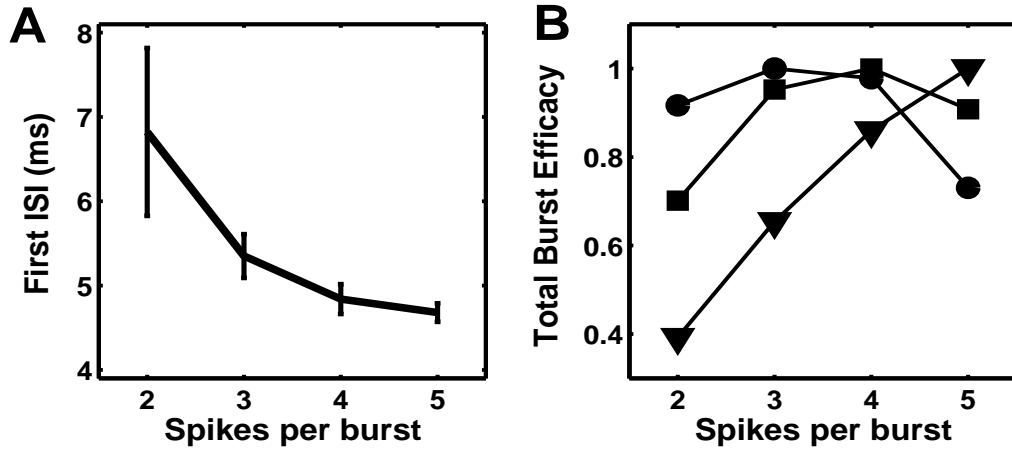


Fig. 3. **A** The mean and standard deviation of the first inter-spike interval of bursts for different burst durations. Longer bursts have shorter initial ISIs, thus higher intra-burst frequencies. **B** Total burst efficacy (relative sum of the release probabilities for each burst) for different burst durations. Synaptic parameters are $\tau_F = 20 \text{ ms}$, $\tau_D = 1 \text{ s}$ and $U = \{0.1, 0.4, 1\}$. Longer bursts result in smaller responses at strongly depressing synapses. Tuning curves are normalized to their maximum.

Our simulations demonstrate that synapses can preferentially respond to specific burst durations (Figure 2). This occurs due to a competition between facilitation and depression processes. Since synaptic facilitation has a shorter time constant, it will dominate the initial response to a burst, increasing the probability of release. However, as the burst duration increases synaptic depression tends to dominate, decreasing the probability of release. Therefore when a synapse both facilitates and depresses (as do most cortical synapses, e.g. [12,7]) a characteristic burst duration emerges for which facilitation is maximal before depression starts dominating.

We used a simple stochastic synapse model [14] and found that that burst duration tuning could be achieved using the published range of parameters [12,7]. Surprisingly, tuning was possible by changing both the time constants of synapses as well as their initial release probability. While traditional learning algorithms only tune the overall strength a synapse, our results suggest that the facilitation and depression time constants also play a significant role when reading a burst duration code. Interestingly, recent experimental observation show that synaptic time constants do change during cortical plasticity [6]. These results show that a burst duration code can be naturally decoded by the synaptic release machinery. As a consequence we propose that the observed heterogeneity in synaptic parameters is an indication that cortical synapses are tuned to specific burst durations.

Acknowledgments

We gratefully acknowledge the support of the W. M. Keck Foundation and the Sloan Foundation.

References

- [1] LF Abbott, JA Varela, K Sen, and SB Nelson. Synaptic depression and cortical gain control. *Science*, 275:220–224, 1997.
- [2] AB Ali and AM Thomson. Facilitating pyramid to horizontal oriens-alveus interneurone inputs: dual intracellular recordings in slices of rat hippocampus. *J Physiol*, 507:185–199, 1998.
- [3] MA Castro-Alamancos and BW Connors. Cellular mechanisms of the augmenting response: short-term plasticity in a thalamocortical pathway. *J Neurosci*, 16:7742–56, 1996.
- [4] MA Castro-Alamancos and BW Connors. Distinct forms of short-term plasticity at excitatory synapses of hippocampus and neocortex. *PNAS*, 94:4161–6, 1997.
- [5] LE Dobrunz and CF Stevens. Heterogeneity of release probability, facilitation, and depletion at central synapses. *Neuron*, 18:995–1008, 1997.
- [6] GT Finnerty, LS Roberts, and BW Connors. Sensory experience modifies the short-term dynamics of neocortical synapses. *Nature*, 400:367–71, 1999.
- [7] A Gupta, Y Wang, and H Markram. Organizing principles for a diversity of gabaergic interneurons and synapses in the neocortex. *Science*, 287:273–8, 2000.
- [8] A Kepecs and J Lisman. Information encoding and computation with spikes and bursts. *Network*, 14(1):103–118, 2003.
- [9] A Kepecs, SM Sherman, and JE Lisman. Burst duration coding in cat LGN. *Soc. Neurosci. Abstr.*, 31:723.20, 2001.
- [10] A Kepecs, X-J Wang, and J Lisman. Bursting neurons signal input slope. *J Neurosci*, 22(20):9053–9062, 2002.
- [11] JE Lisman. Bursts as units of neural information. *TINS*, 20:38–41, 1997.
- [12] H Markram, Y Wang, and M Tsodyks. Differential signaling via the same axon of neocortical pyramidal neurons. *PNAS*, 95:5323–8, 1998.
- [13] A Reyes, R Lujan, A Rozov, N Burnashev, P Somogyi, and B Sakmann. Target-cell-specific facilitation and depression in neocortical circuits. *Nature Neuroscience*, 1:279–85, 1998.
- [14] MV Tsodyks and H Markram. The neural code between neocortical pyramidal neurons depends on neurotransmitter release probability. *PNAS*, 94:719–723, 1997.
- [15] JA Varela, K Sen, J Gibson, J Fost, LF Abbott, and SB Nelson. A quantitative description of short-term plasticity at excitatory synapses in layer 2/3 of rat primary visual cortex. *J Neurosci*, 17:7926–40, 1997.
- [16] RS Zucker. Short-term synaptic plasticity. *Annu Rev Neurosci*, 12:13–31, 1989.