

Spike synchronization in a biophysically-detailed model of the olfactory bulb

Andrew P. Davison¹ Jianfeng Feng David Brown

Laboratory of Computational Neuroscience, The Babraham Institute, Babraham, Cambridge CB2 4AT, UK.

Abstract

Stimulus-evoked synchronization of action potentials has been demonstrated in mammalian olfactory bulb and in insect antennal lobes. Abolition of synchronization has been shown to impair the ability of honeybees to perform fine olfactory discrimination. We present a biophysically-detailed computer model of the olfactory bulb which qualitatively reproduces many features seen in experimental recordings. The mitral cells of the model synchronize readily without common input due to lateral interactions with inhibitory granule cells. Weakly activated mitral cells fire more slowly than, but always synchronously with, strongly activated cells. Nearby cells synchronize more readily than widely-separated ones.

Key words: Olfactory bulb; Synchronization; Biophysical model

1 Introduction

Stimulus-evoked synchronization of action-potential firing has been demonstrated in the mitral and tufted cells of the rabbit olfactory bulb [3] and in the projection neurones of the locust and honeybee antennal lobes. It has been demonstrated in the honeybee [5] that blocking of GABA_A-mediated inhibition both abolishes synchrony and impairs discrimination among similar odorants, but does not otherwise alter the neuronal response patterns. This strongly suggests that odour-evoked synchronization is functionally relevant for olfactory fine-discrimination. It is hypothesized [4] that synchronization may serve to ‘bind’ together different features of an olfactory stimulus.

¹ Corresponding author. *E-mail address:* andrew.davison@bbsrc.ac.uk

Most previously published models of the olfactory bulb or antennal lobe have considered average firing rates rather than precise spike times, and so are not suitable for elucidating the role of action-potential (spike) synchronization in olfaction. In addition, these models are of a level of abstraction which precludes the use of detailed experimental data to constrain them.

The objective of this work was to model the olfactory bulb using biophysically-detailed, spiking neuronal models, to determine whether spike synchronization will occur in such a model and, if it does occur, to investigate its properties.

2 The model

We have previously presented a four-compartment, biophysical model of the olfactory bulb mitral cell [2], reduced from the detailed compartmental model of Bhalla and Bower [1]. The reduced model has the same ionic currents as the full model but less morphological complexity. It fits the full model closely over a broad range of input conditions, but runs 70 or more times faster. Here, we used the same strategy as in [2] to develop a three-compartment model of the granule cell, reduced from the complex granule cell model described in [1]. Again the reduced model fits the fully-detailed model closely (Figure 1) but runs much faster.

We simulated a network of thirty reduced mitral cells and three hundred reduced granule cells. The ratio of granule:mitral cells is smaller than in mammalian olfactory bulb (~ 100 – 200), but there is nevertheless a substantial excess of granule cells over mitral cells. The cells are arranged in a one-dimensional array with cyclic connections (a ring). Each mitral cell makes reciprocal connections with all the granule cells within a certain range. There are no mitral–mitral or granule–granule connections. The synapses are modeled as instantaneous rise/exponential-decay conductances (time constant 10 ms) with reversal potentials of 0 mV in the granule cells and -70 mV in the mitral cells. These correspond to fast AMPA- and GABA_A-like synapses. The granule cell is known to possess NMDA receptors, but for simplicity these are not modeled here. The synaptic delay is constant, 3 ms.

Each mitral cell receives constant current input to the glomerular compartment (primary dendrite tuft). The input to the cells is heterogeneous to mimic an odour input. The mitral cells are grouped into sets of three adjacent cells, approximating glomeruli. For each group of three a baseline current input is selected at random from a negative exponential distribution with decay constant of 1 nA. The current applied to each cell within that group is randomly selected from a uniform distribution covering 0.9-1.1 times the baseline current. Current onset time for each cell is selected randomly from a uniform distribu-

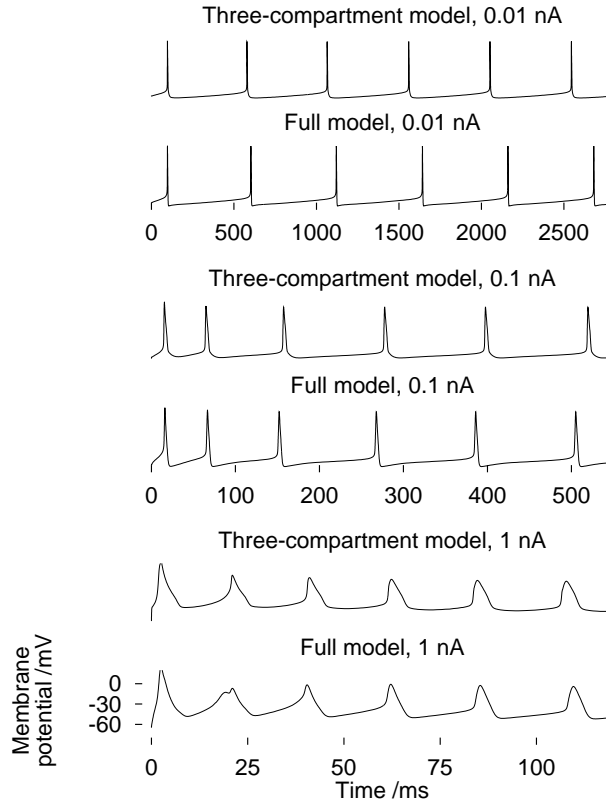


Fig. 1. Somatic membrane potential trace for full and three-compartment granule cell models with different input currents. The reduced model fits the full model well both in quantitative spike times and in qualitative features of spike shape.

tion in the range 0-100 ms. Therefore in the case of no coupling, the mitral cells fire with widely differing rates, and even the cells within a group/glomerulus do not fire in phase.

3 Results

We ran simulations with a variety of different conditions, to gain an idea of the range of behaviours which might be obtained from this network.

3.1 Synaptic weights.

The same network architecture can give different behaviours depending on the strength of the synaptic connections, including independent firing (Figure 2A) with no connections, synchronized bursting (Figure 2B) with weak excitation and strong inhibition, and global synchronization with varying degrees of suppression (Figure 2C and 2D). In general, mitral cell spikes phase-lock rapidly,

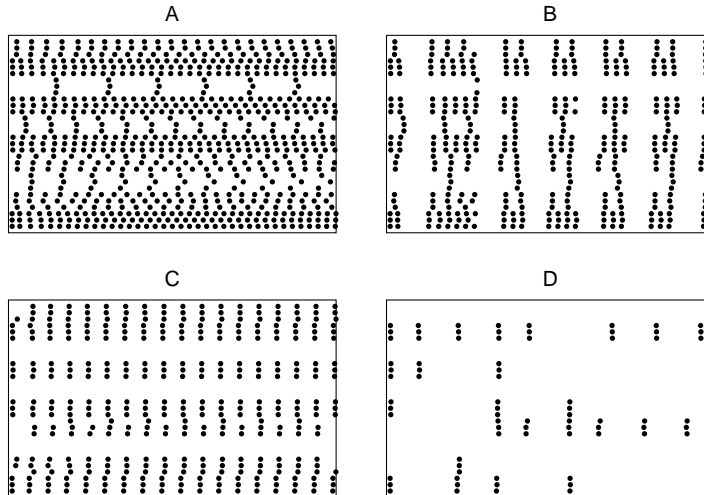


Fig. 2. Mitral cell raster plots showing effect of varying synaptic strengths. (A) No synchronization ($\bar{g}_{\text{AMPA}} = 0$, $\bar{g}_{\text{GABA}_A} = 0$); (B) Synchronized bursts ($\bar{g}_{\text{AMPA}} = 10^{-4} \mu\text{S}$, $\bar{g}_{\text{GABA}_A} = 0.1 \mu\text{S}$); (C) Global synchronization with some suppression ($\bar{g}_{\text{AMPA}} = 10^{-3} \mu\text{S}$, $\bar{g}_{\text{GABA}_A} = 5 \times 10^{-3} \mu\text{S}$); (D) Sparse synchronization with extensive suppression ($\bar{g}_{\text{AMPA}} = 0.1 \mu\text{S}$, $\bar{g}_{\text{GABA}_A} = 0.1 \mu\text{S}$). In these simulations each mitral cell was connected to all granule cells within a range of $0.24 \times$ the size of the granule cell array each side. Simulations were run for 1000 ms.

within a few inter-spike intervals, with the more weakly activated cells having a phase lag with respect to the strongly activated cells. The phase-lags are small, so the term synchronization may be used in an approximate sense. Cells do not necessarily fire together on every cycle: strongly-activated cells fire together on every cycle, weakly activated cells with lower frequency, but always synchronized with the faster cells.

3.2 Connection range.

As might be expected, global synchrony requires long range connections between mitral and granule cells (Figure 3), although the larger the synaptic weights, the smaller the range which is needed to obtain global synchrony.

With short range connections, local synchrony may be obtained (Figure 4), and independently firing domains, consisting of the most strongly activated neurones, may arise (Figure 5). Less strongly activated neurones may be suppressed entirely, or may synchronize transiently with different domains (as observed experimentally by Wehr and Laurent [6]).

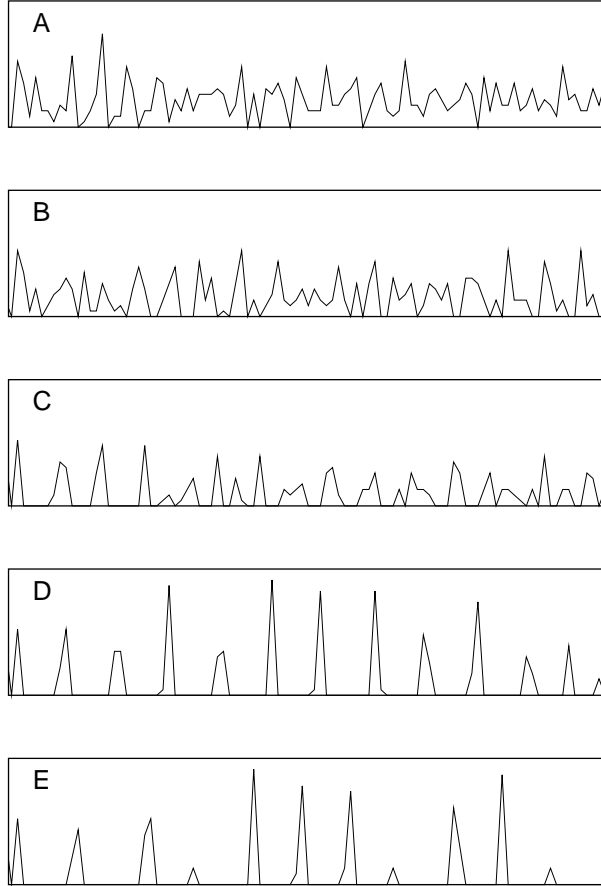


Fig. 3. Mitral cell spike time histograms for variable connection range. Connection range as a fraction of granule cell array size: (A) 0.03, (B) 0.06, (C) 0.12, (D) 0.24, (E) 0.48. Synaptic weights: $\bar{g}_{\text{AMPA}} = 10^{-2} \mu\text{S}$, $\bar{g}_{\text{GABA}_A} = 10^{-2} \mu\text{S}$.

4 Discussion

We have shown that a simple network of mitral and granule cells can qualitatively reproduce experimental findings on stimulus-evoked spike synchronization in olfactory systems. In particular, periglomerular cells, a second type of interneurone in the olfactory bulb, are not required for synchronization: their function remains to be determined. An advantage of the model is that it can be constrained with experimental data from both single-cell and network-level experiments, which will allow more quantitative predictions as the model is refined.

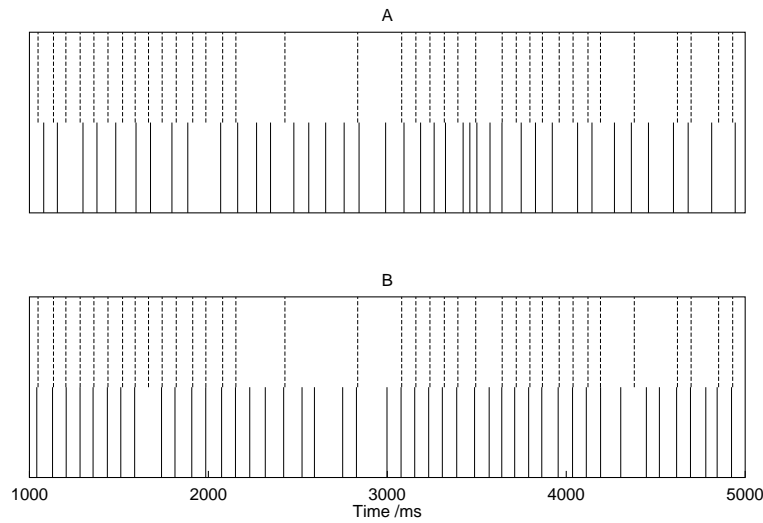


Fig. 4. (A) Spike times of two distant, weakly interacting mitral cells. Poor synchronization. The input current to the top cell is 40% of that to the bottom cell. (B). Spike times of two nearby, strongly interacting mitral cells. Good synchronization. Input same as (A).

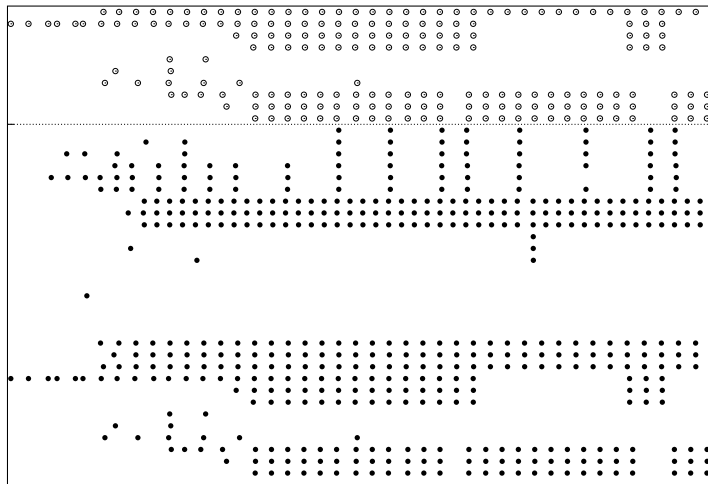


Fig. 5. Mitral cell raster plot showing local domains of synchronization. As the cells are arranged in a ring, the bottom ten cells are wrapped round and shown again at the top. There are two main domains, defined by the two groups of fast firing cells 10-12 and 21-24 (counting from bottom). Other cells synchronize sometimes with one or other groups, or occasionally with both. In this simulation each mitral cell was connected to all granule cells within a range of 0.12 x the size of the granule cell array each side. The simulation was run for 3000 ms.

Acknowledgements

This work was financially supported by the Biotechnology and Biological Sciences Research Council.

References

- [1] U.S. Bhalla and J.M. Bower. Exploring parameter space in detailed single cell models: simulations of the mitral and granule cells of the olfactory bulb. *Journal of Neurophysiology*, 69:1948–1965, 1993.
- [2] A.P. Davison, J. Feng, and D. Brown. A reduced compartmental model of the mitral cell for use in network models of the olfactory bulb. *Brain Research Bulletin*, 5:393–399, 2000.
- [3] H. Kashiwadani, Y.F. Sasaki, N. Uchida, and K. Mori. Synchronized oscillatory discharges of mitral/tufted cells with different molecular receptive ranges in the rabbit olfactory bulb. *Journal of Neurophysiology*, 82:1786–1792, 1999.
- [4] K. Mori, H. Nagao, and Y. Yoshihara. The olfactory bulb: coding and processing of odor molecule information. *Science*, 286:711–715, 1999.
- [5] M. Stopfer, S. Bhagavan, B.H. Smith, and G. Laurent. Impaired odour discrimination on desynchronisation of odour-encoding neural assemblies. *Nature*, 390:70–74, 1997.
- [6] M. Wehr and G. Laurent. Odour encoding by temporal sequences of firing in oscillating neural assemblies. *Nature*, 384:162–166, 1996.