APPENDIX IV

The connectivity between the locust antennal lobes and mushroom bodies: Combinatorics of a representation

"If you've made up your mind to test a theory, or you want to explain some idea, you should always decide to publish it whichever way it comes out. If we only publish results of a certain kind, we can make the argument look good. We must publish BOTH kinds of results."

Richard Feynman, Cargo Cult Science, Commencement address, California Insitute of Technology, 1974

Introduction

The connectivity pattern between locust antennal lobe (AL) projection neurons (PNs) and mushroom body (MB) Kenyon cells (KCs), as its vertebrate counterpart from olfactory bulb to piriform cortex, is characterized by massive divergence, from 830 PNs to 50,000 KCs. Furthermore, there is electrophysiological evidence that KCs have relatively high thresholds, requiring the coincidence of several input to fire a spike. Finally, PN firing rates are relatively low (less than 5 Hz across all PNs on average during odor responses). This suggests that interesting mechanisms may be in place to avoid active PNs from being "diluted out" in the sea of KCs, leading to no activity in the MB. The purpose of this exploration is to investigate the kinds of connectivity patterns between PNs and KCs that are consistent with known anatomical and physiological facts.

Notation

Let P equal the number of PNs in one AL, and K equal the number of Kenyon cells in one mushroom body that receive inputs from the AL. Let D equal the divergence ratio, the number of synapses each PN makes on average. Note that this number need not be the number of different postsynaptic neurons per PN, if there is more than one synapse to the same postsynaptic target for any given PN. Let C equal the convergence ratio, or the number of synapses that each KC receives on aver-

age. Let T be the threshold number of EPSP's caused by PNs required on average to produce an action potential in a KC. Let PS be the number of PNs spiking during the uninhibited portion of a given cycle of the local field potential (LFP) oscillations during an odor response. Let N(E) be the average number of KCs that receive E EPSPs during a given cycle of the LFP, and KS be the number of KCs that spike during a given cycle of the LFP.

Data

I will begin by giving, for each parameter, the ranges of values consistent with experimental observations:

P is very close to 830 (Leitch and Laurent, 1996).

K has a maximum of 50,000, since this is the total number of KCs in one MB. If all oscillatory activity in KCs that results from odor stimulation were the result of *direct* PN activation, K would have a minimum value of about 25,000, since this is the estimate for the number of KCs which show activity in intracellular recordings after presentation of a single odor (Laurent and Naraghi, 1994). 42% of KCs also showed extracellular responses to one or more of a panel of an average of 15 odors (Pérez-Orive et al., 2002). Imaging experiments suggest that the majority of the surface of the calyx received olfactory inputs (Wang et al., 2001).

D is about 600: 30 varicosities x 20 synapses per varicosity (Leitch and Laurent, 1996).

C can then be calculated to be:

$$C = (P \times D) / K \qquad > 830 \times 600 / 50{,}000 = 10$$

$$< 830 \times 600 / 25{,}000 = 20$$

So $10 < C < 20$.

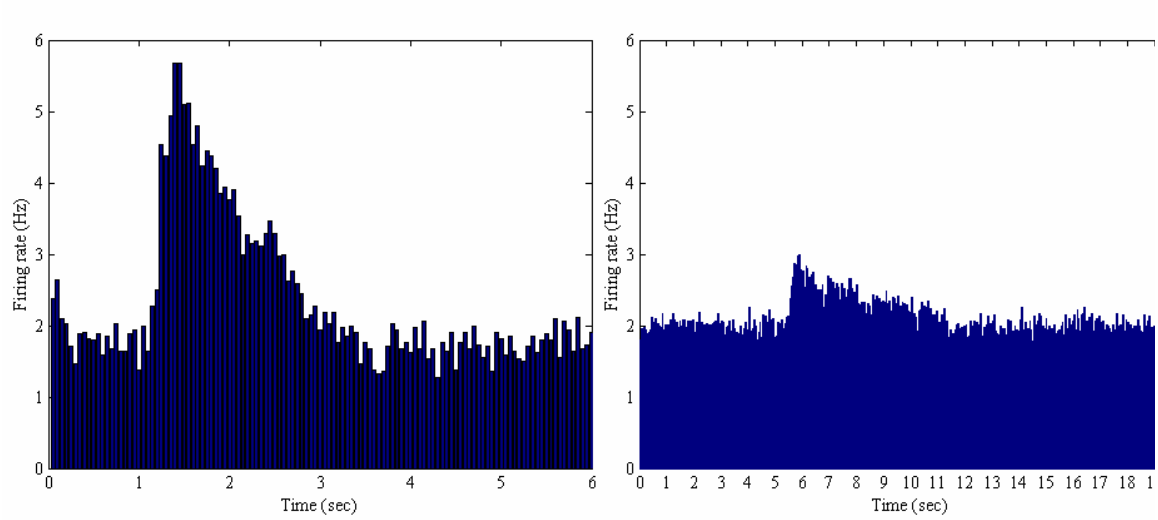

Figure IV.1. Mean PN firing rate during odor responses. Intracellular recordings (54 PNs, left) and tetrode recordings (right, 19 PNs courtesy of Stijn Cassenaer). Odors were presented at maximum concentration from t=1-2 sec at left and t=5-7.4 sec at right.

Experiments with electrical stimulation of the olfactory tract with simultaneous intracellular KC recordings independently suggest that C is at least 10, since different levels of electrical stimulation of the PN axon bundle can cause up to ~10 discrete EPSP levels in a KC (Laurent and Naraghi, 1994).

PS can be calculated as follows: The peak firing rate across all PNs (responsive and unresponsive) is 4-6 Hz (+- 8-11 Hz) (Bäcker, this thesis). That translates into 1 spike/cycle for every 4 PNs. KCs are responsive during approximately one half of the cycle only (Pérez Orive et al., 2001). Taking into account the synchronization of PNs, the fraction of of these spikes occuring during the most active 1/2 of a cycle is less than 2/3. Combining these figures, the fraction of active PNs during a half cycle is no more than 2/3 x 1/4=1/6. One sixth of 830 PNs is 138.

T is above 2-3, because subthreshold activity of KCs is regularly oscillatory, and at least that number of PNs are required to create a summated sinusoidal activity. T can also not be too low, since only 11% of KCs show suprathreshold response to any given odor (summing over the entire response period, Pérez Orive et al., 2002).

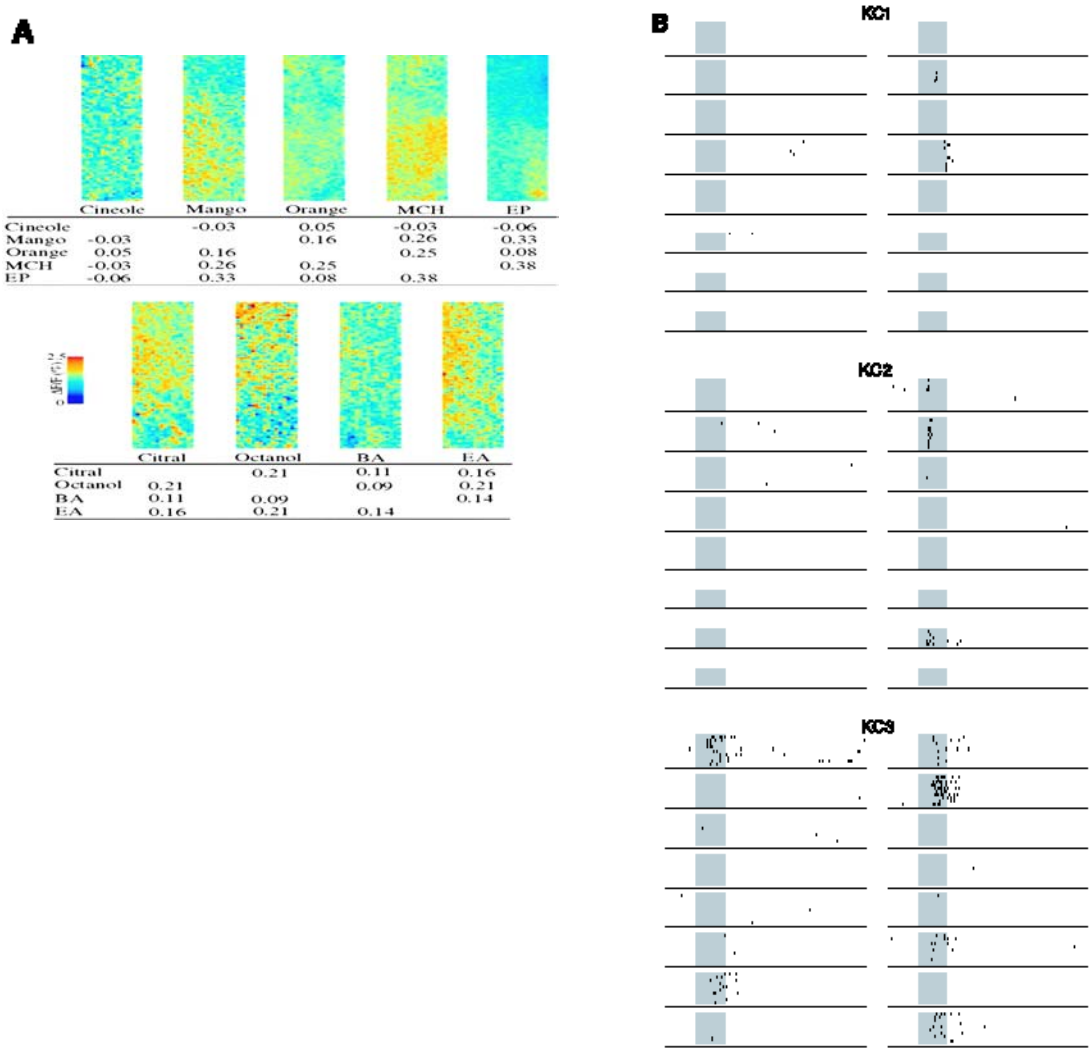

Figure IV.2. There is a striking difference between the broad nature of the inputs to KCs and the sparse nature of KC outputs. A) Spatial distribution of Ca++ signals in the mushroom body, likely to represent inputs to KCs (see Chapter 8) (from Wang et al., 2001). B) Spike trains in response to 1-sec pulses of up to 16 odors for 3 KCs (from Pérez Orive et al., 2002).

KS is on average approximately 250: 50,000 x 0.11 response probability integrated over 1-sec long odor pulses / 20 cycles per second.

Model

I assume random connectivity between PNs and KCs, and calculate the number of KCs receiving n EPSPs during the uninhibited portion of any one cycle as a function of different values for each of the parameters above. I can then compare the values obtained for KS with the experimental one to verify whether the assumption can be discarded or not. The fraction of KCs receiving i EPSPs is given by

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pr(i) = p^i * q^(C-i) * comb(C,i);
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where p=PS/P and q=1-p.

The number of KCs firing in response to an odor during a cycle is K times the fraction of KCs receiving less than the threshold number of EPSPs.

Results

The model suggests the threshold may be on the order of 8 synchronous spikes (the requirement for synchronization derives from the assumption of no decay between spikes) assuming that half the Kenyon Cells receive randomly distributed PN inputs and the parameters are as discussed above (Fig. IV.3).

Conclusions

This work suggest a range of values for KC firing thresholds that are consistent with known experimental data, assuming KCs integrate their inputs over approximately half an LFP cycle. Should the threshold be shown experimentally to diverge significantly from this value, one would conclude that a) connectivity is not uniform and/or b) integration mechanisms are very different from a one-com-

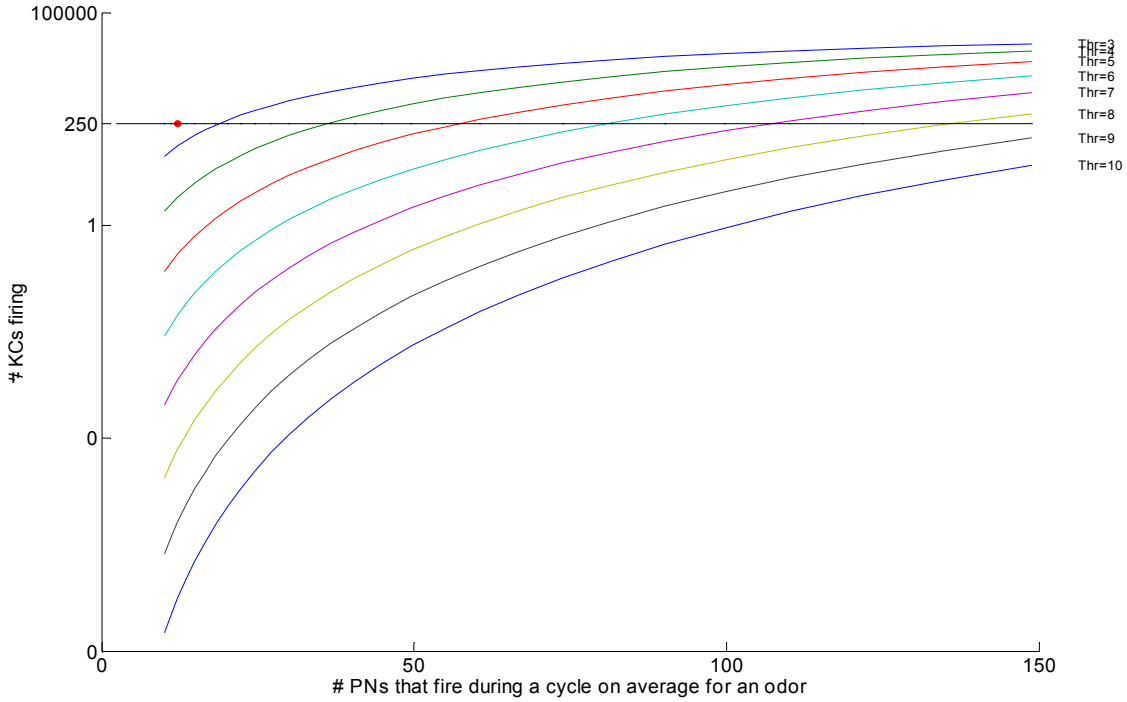

Figure IV.3. Themodel is compatible with the data for KC=25,000 and T=8.

partment coincidence detector.

Acknowledgements

The initial thrust behind this approach and the first calculations for selected parameter values are due to Gilles Laurent.