

# Theta, Gamma, and Working Memory

## Computational Models of Neural Systems Lecture 3.7

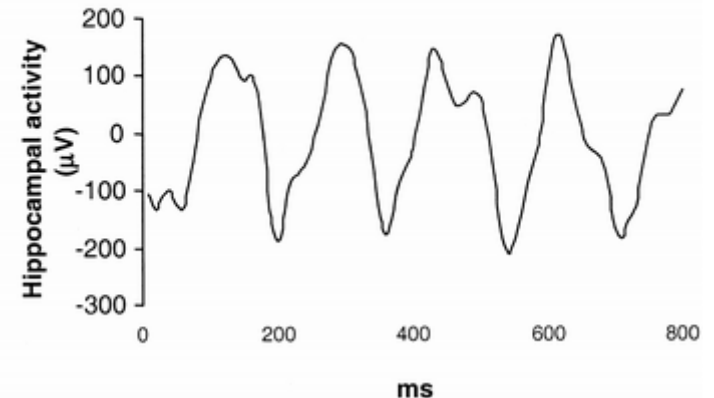
David S. Touretzky  
October, 2025

# Outline

- Theta rhythm and gamma rhythms
- Phase precession in hippocampus
- Theta and gamma in entorhinal cortex
- Lisman working memory proposal
- Hasselmo theory of EC as buffer

# Hippocampal Theta Rhythm

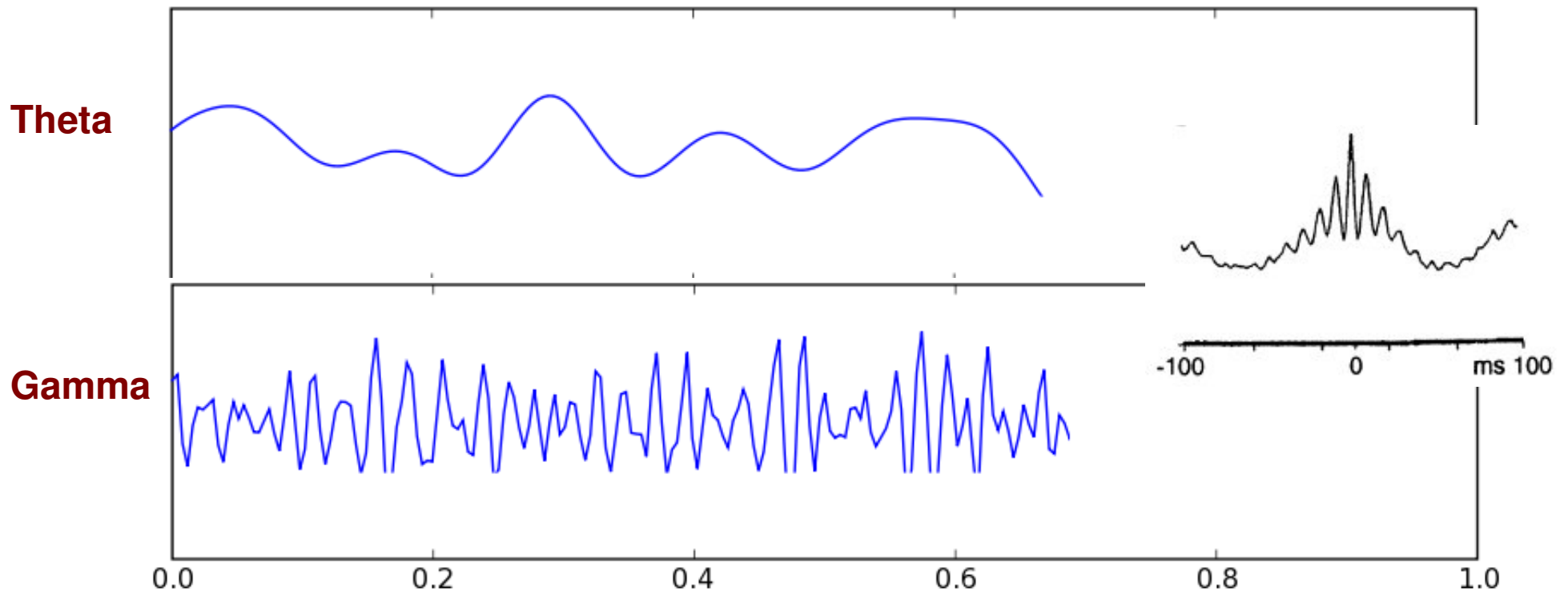
- 3-12 Hz oscillation in local field potential
  - when the animal is moving or engaged in voluntary behavior: frequency increases with running speed
  - during REM sleep



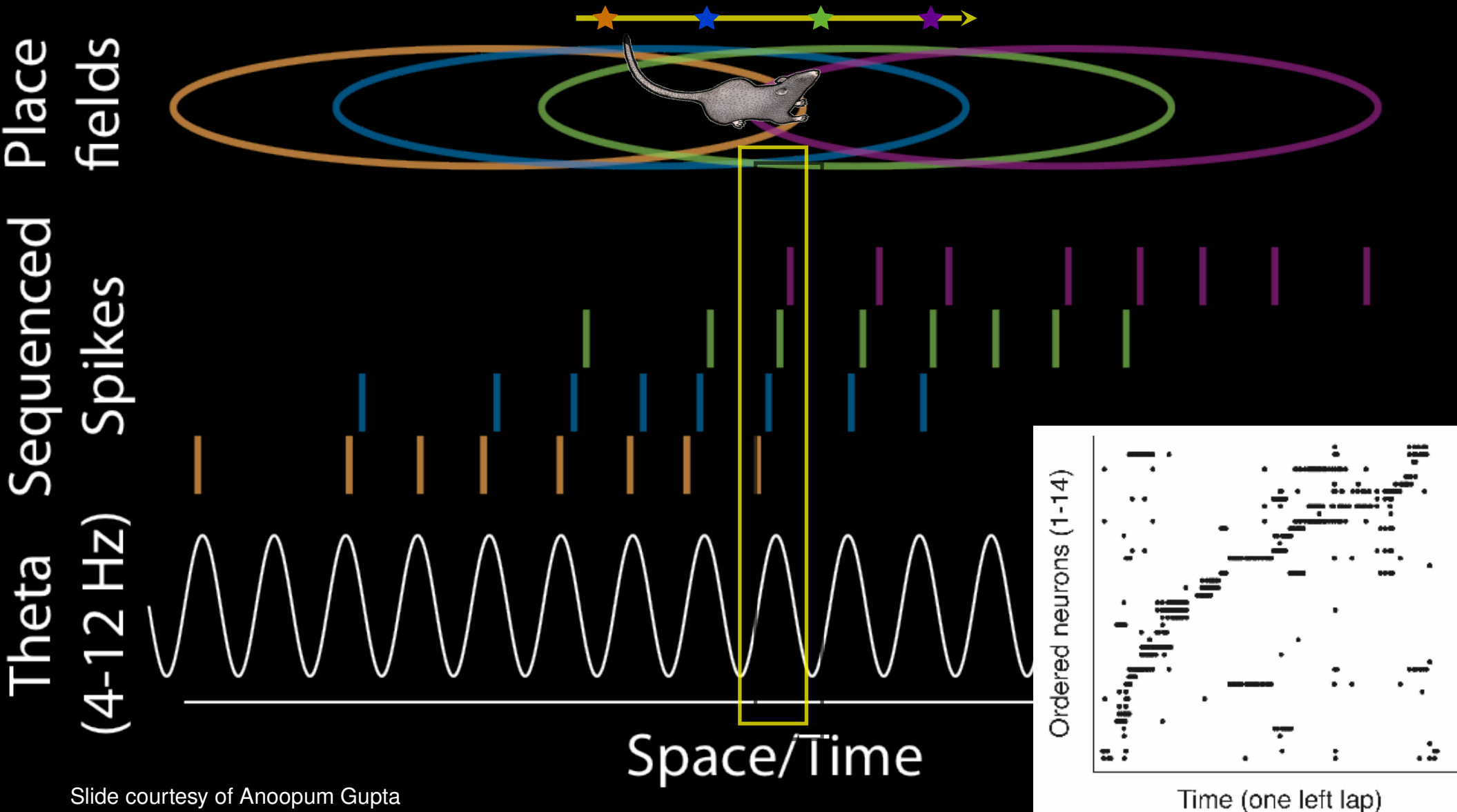
- Entorhinal cortex also exhibits theta rhythm and is the principal source of hippocampal theta.
- The theta pacemaker is the medial septal nucleus, which has a GABAergic projection to the hippocampal formation via the fornix. (Also a significant cholinergic projection.)

# Gamma Rhythm

- Roughly 40 Hz oscillation (could be from 25 to 100 Hz)
  - “Slow gamma” is 25-50 Hz; “fast gamma” is 50-90 Hz.
- Gamma is superimposed on top of theta in hippocampus.
- There is speculation that gamma rhythm synchrony may play a role in binding cortical areas together. Consciousness?

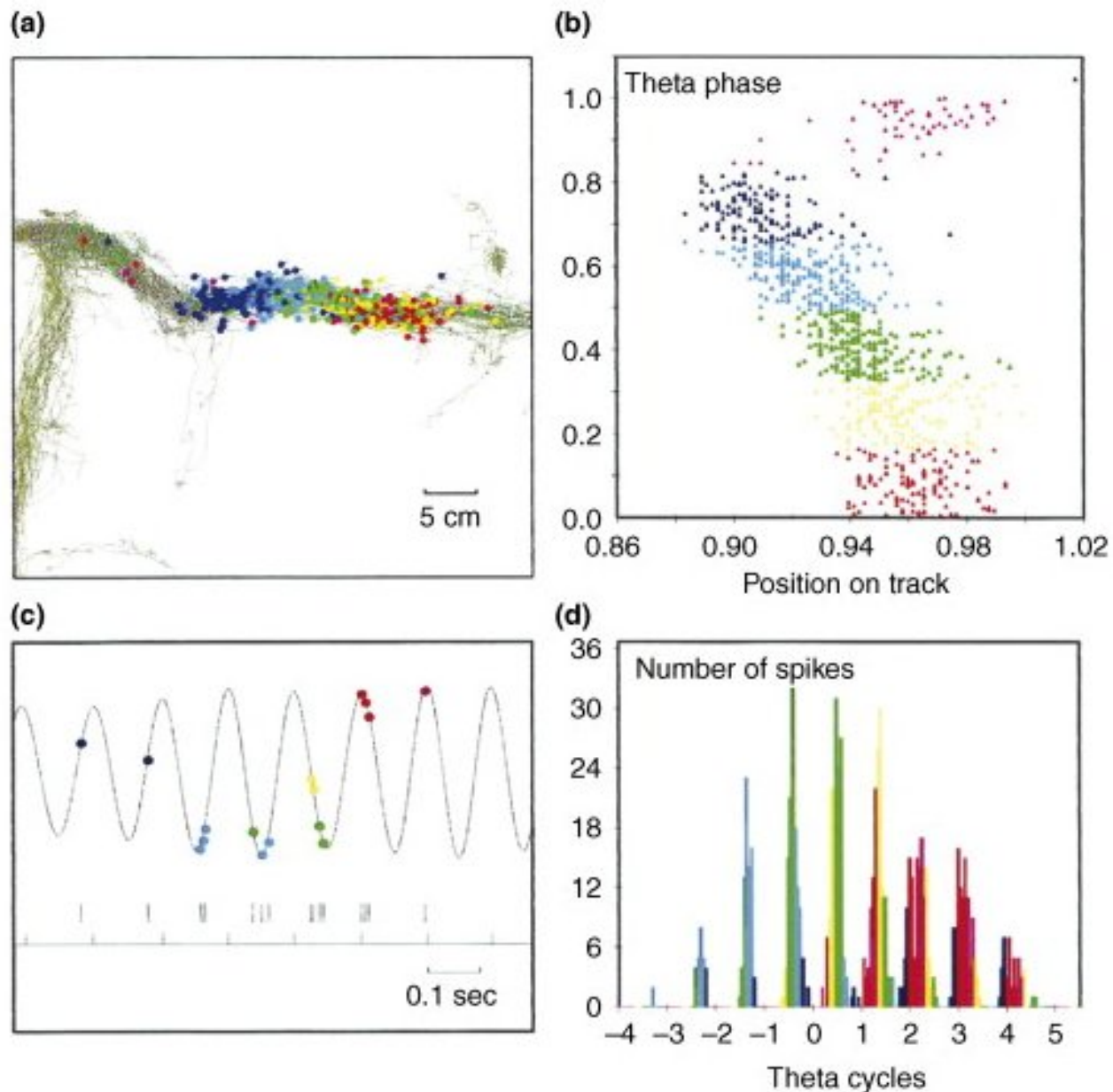


# Theta Phase Precession



Slide courtesy of Anoopum Gupta

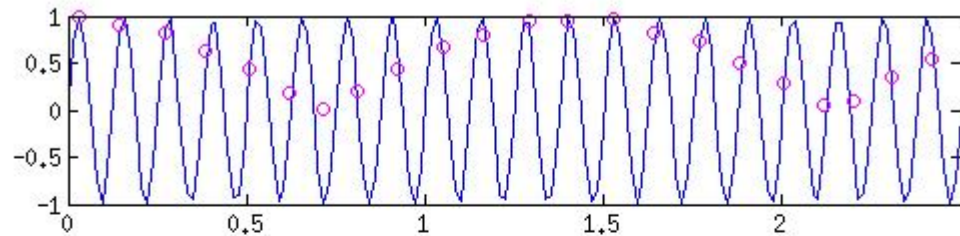
# Phase Precession In One Hippocampal Place Cell



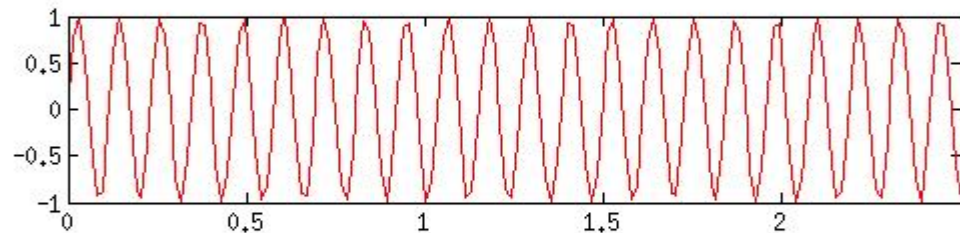
Maurer & McNaughton,  
TINS 2007

# Theories of Phase Precession

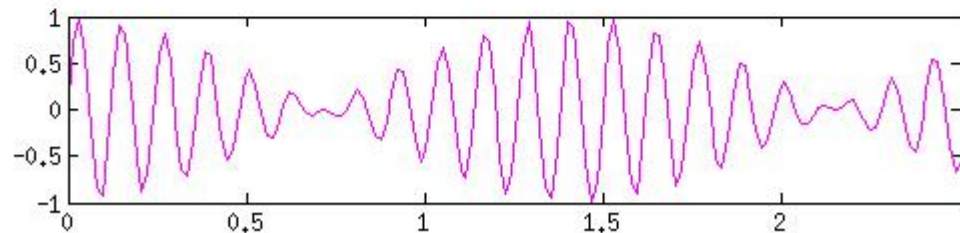
- Network theory: caused by interactions among cells; cells learn to predict firing ahead of the rat.
- Oscillator interference mechanism: slightly faster cellular oscillator beats against the theta rhythm.



soma  
8.7 Hz



theta  
8 Hz



sum

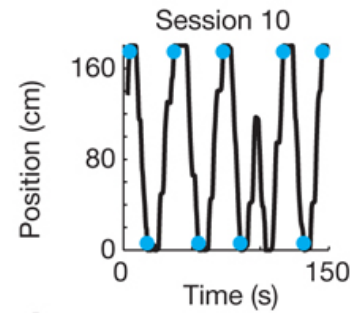
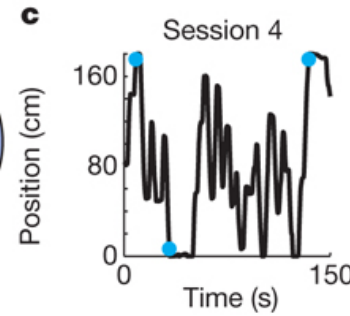
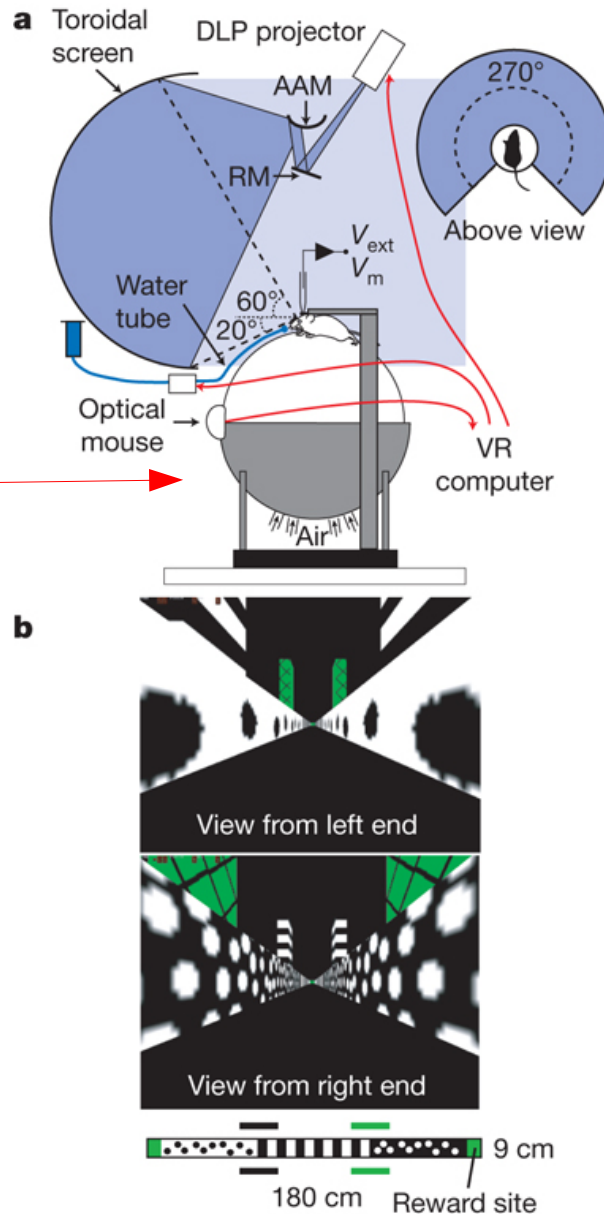
# Problems for Both Theories

- Network theory depends on learning, but phase precession has been observed on the first pass through a firing field.
- The oscillator interference model depends on a specific phase relationship between the intrinsic oscillator and the rat's location. But some cells with multiple overlapping firing fields will fire spikes at both phases of the theta cycle, which a simple oscillator couldn't do.

# Mice In a Virtual Reality Environment

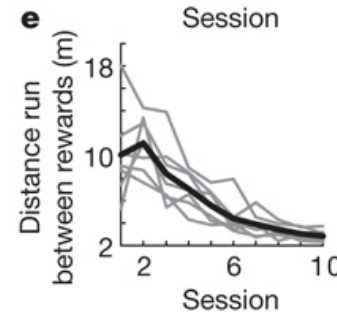
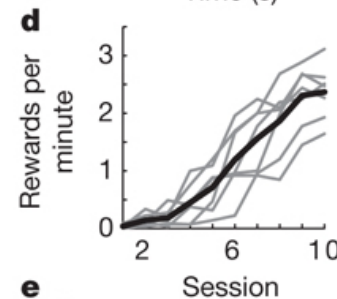
Harvey et al.  
Nature 2009

Spherical treadmill



Sample trajectories

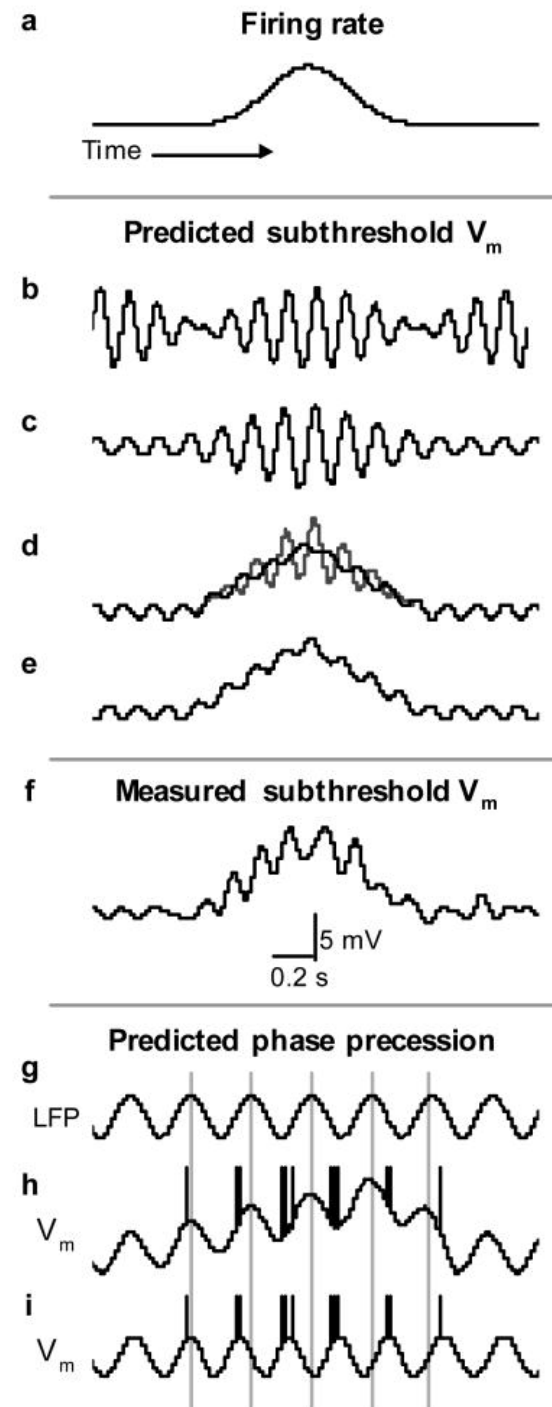
● = water reward



# Sub-Threshold Membrane Oscillations and Place cell Phase Precession

Predictions from various dual oscillator models

Measured intracellular membrane potential; spikes removed



Harvey et al.  
Nature 2009

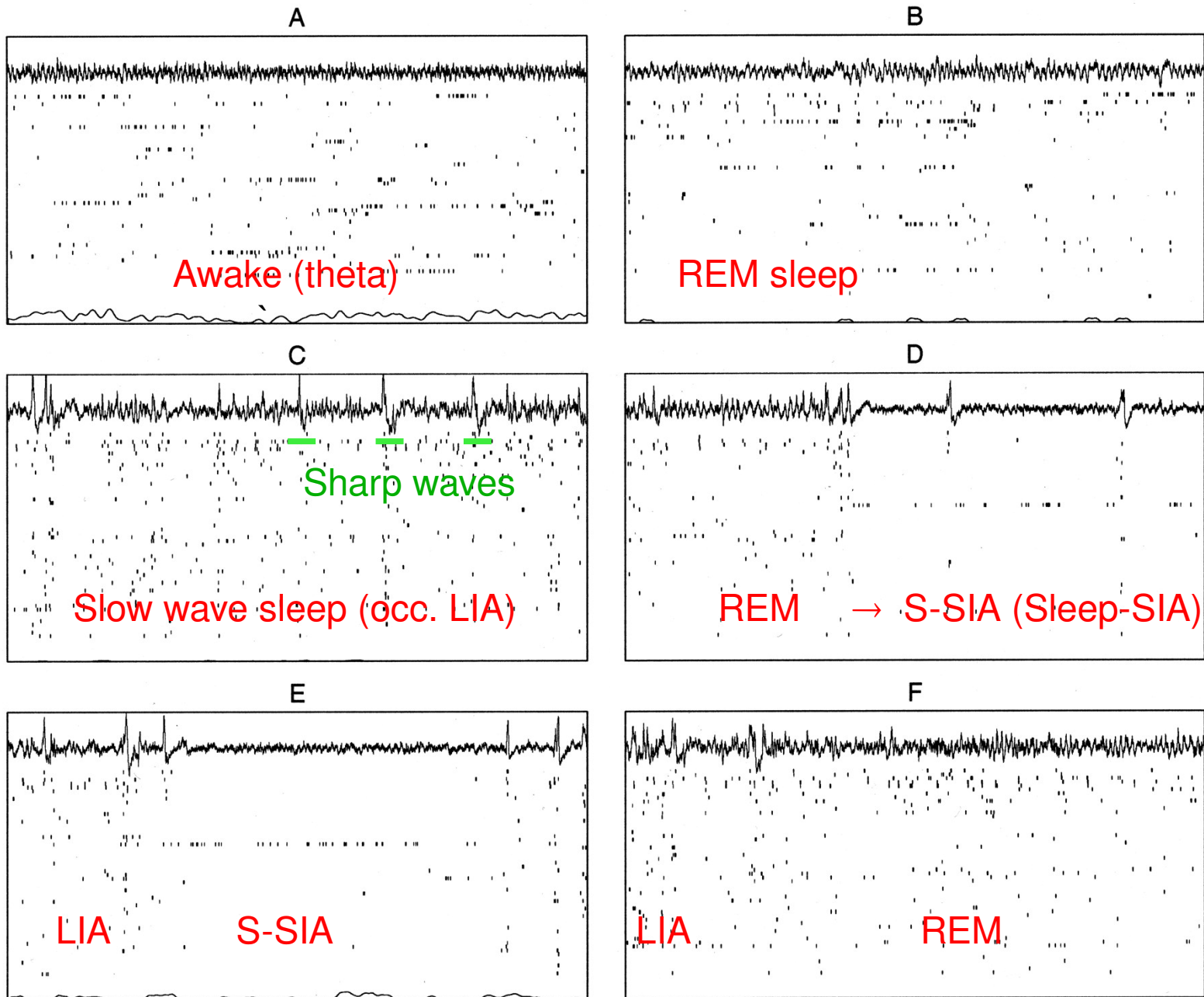
# Intracellular Oscillations

- Harvey et al. recorded *intracellularly* from place cells in mice running on a treadmill.
- Observations as the animal proceeds through the field:
  - Ramp-like depolarization of baseline membrane potential
  - Increasing amplitude of membrane potential theta
  - Phase precession of intracellular theta relative to LFP
  - Spike times advance relative to LFP but not relative to intracellular theta
- Most compatible with a somato-dendritic interference model of phase precession.

# Why Is Phase Precession Useful?

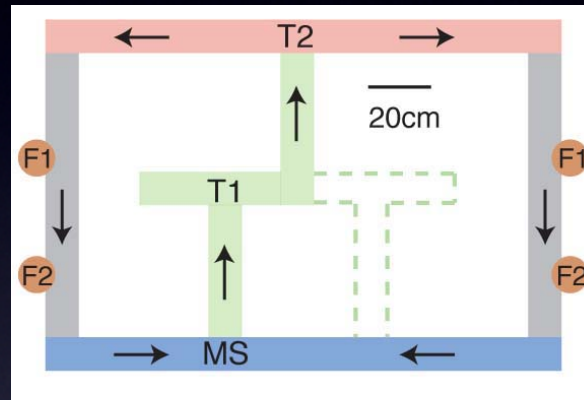
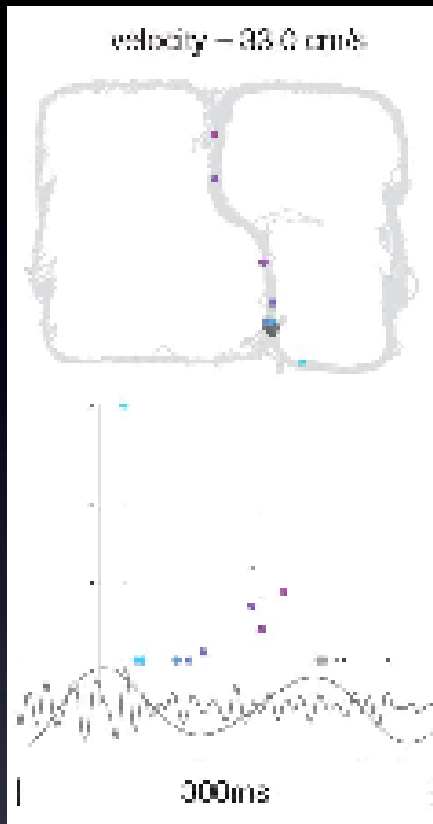
- At any given location, place cells behind the rat fire earlier in the theta cycle than place cells ahead of the rat.
- This sets up the necessary conditions for Hebbian learning: if cell A fires before cell B, strengthen the  $A \rightarrow B$  connection.
- On each theta cycle the hippocampus is playing a short *sequence* of activity representing a slice of its current trajectory.

# Hippocampal EEG

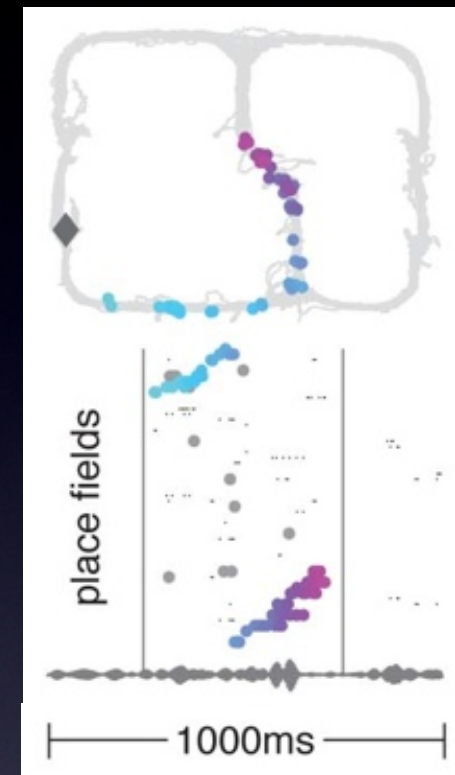


# Theta vs Replay Sequences

## Theta



## Replay



- Occur during attentive behavior
- Theta oscillation is present
- Tied to the animal's location
- Forward sequence
- Few neurons are active
- Relatively short paths represented
- Experience encoding and recall

- Occur during awake rest
- Sharp wave ripples present
- Not always tied to the animal's location
- Forward or backward sequence
- Many neurons are often active
- Highly variable path lengths represented
- Memory consolidation, learning of cognitive maps

# Lisman & Idiart (1995): Working Memory

- Hippocampal cells undergo a gradually increasing afterdepolarization (ADP) that re-excites the cell after firing.

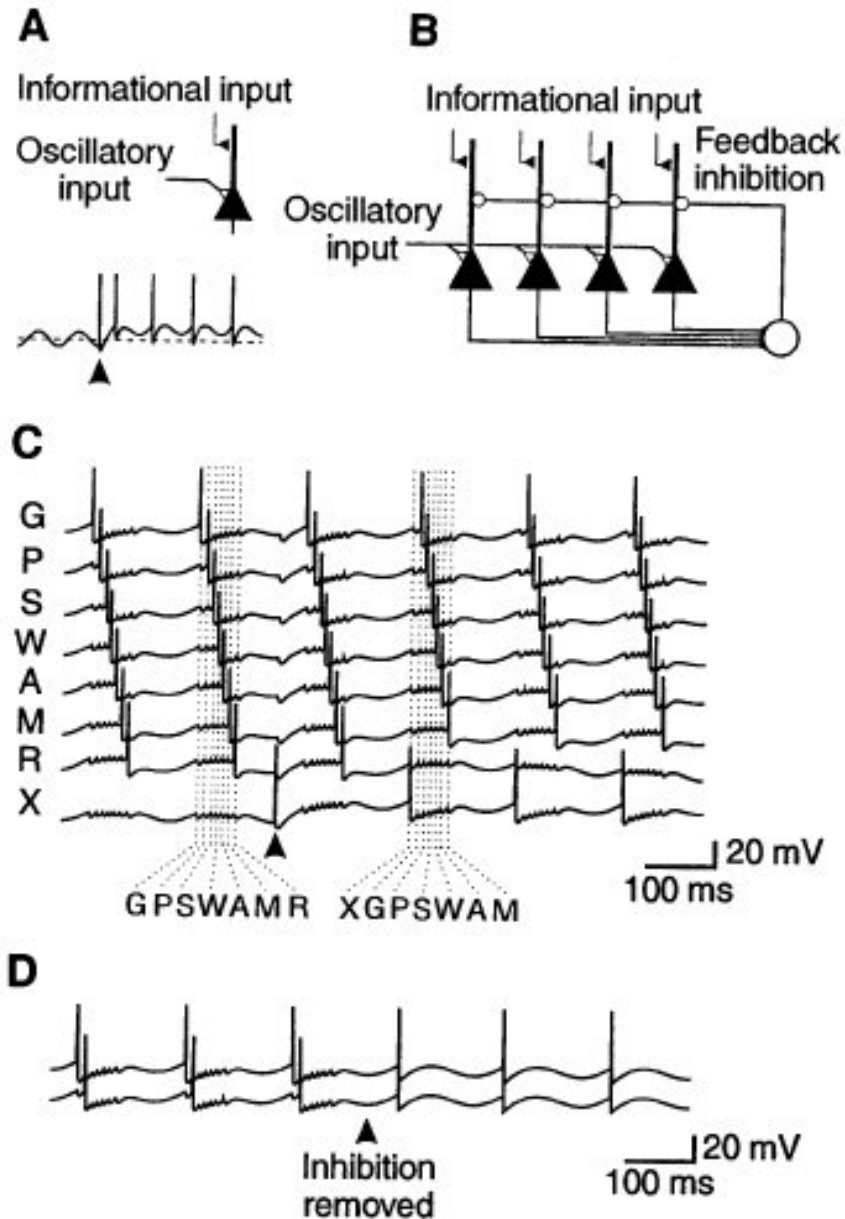


- Could this be the basis of a working memory mechanism?
- Sternberg: reaction time on list search task goes up by 38 ms per list item; hypothesize serial scan process.
- Assume true scan time is 25 ms/item (plus 13 ms/item for other “costs”, yielding observed 38 ms/item). Can fit seven 25 ms gamma cycles into one theta cycle.

# How It Works

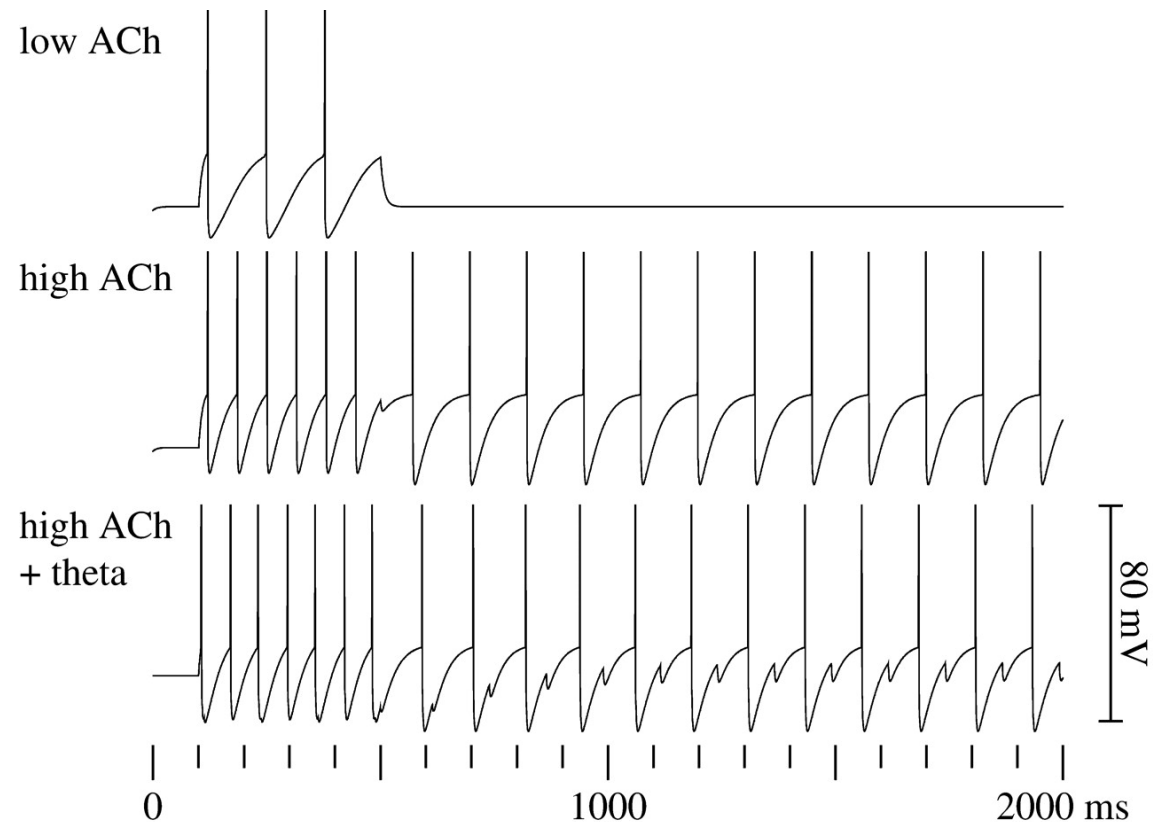
- Each cell receives sub-threshold oscillatory input at the theta frequency.
- Cells that are above threshold due to oscillator plus ADP fire.
- Rapid inhibitory feedback prevents less active cells from firing right afterward; divides up the theta cycle into a set of discrete gamma slots.
- 7 gamma cycles = 175 ms = 5.7 Hz = time for one theta cycle
- So memory capacity is 7 items.

# Lisman & Idiart Working Memory Model



# Persistent Activity in EC Neurons

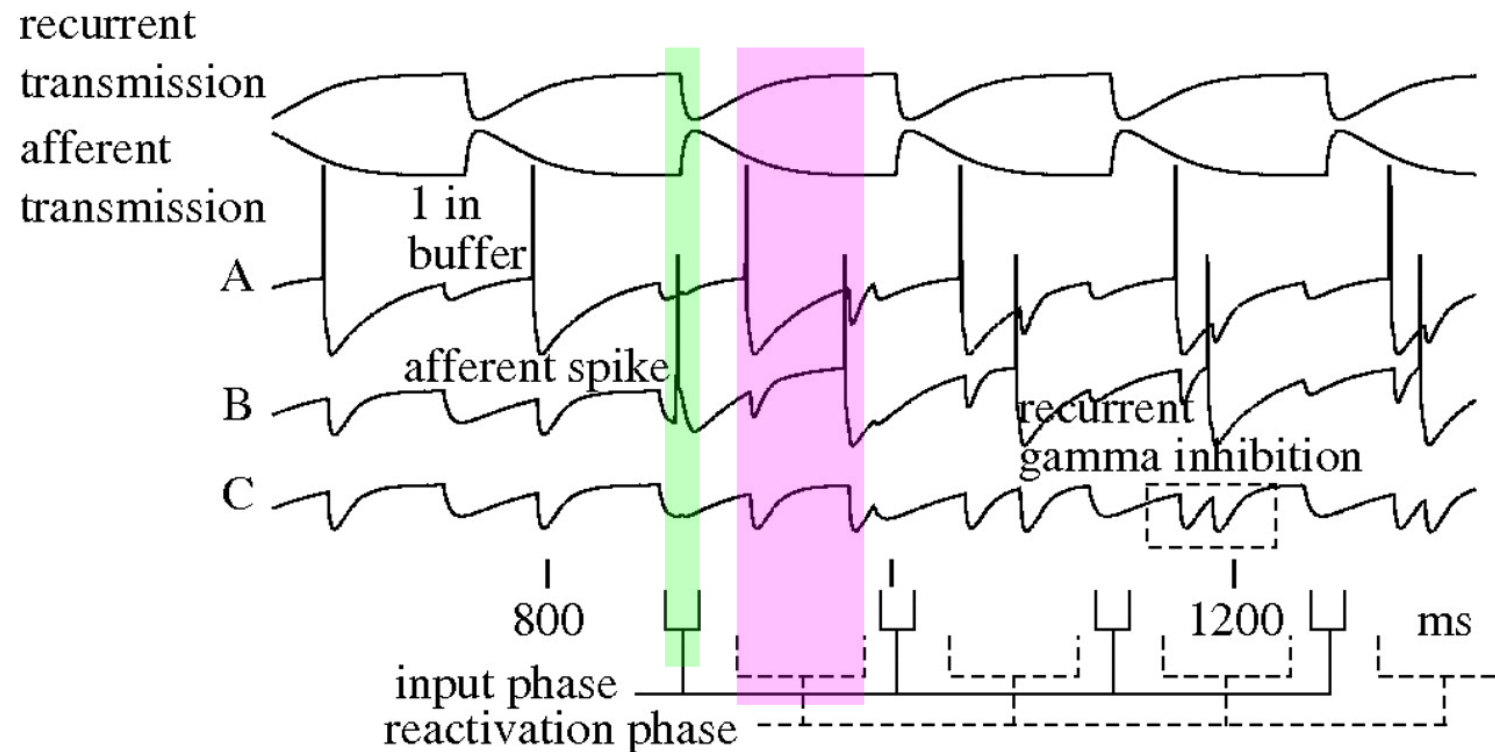
- Pyramidal cells in EC layer II exhibit ADP and persistent firing in the presence of the neuromodulator ACh.



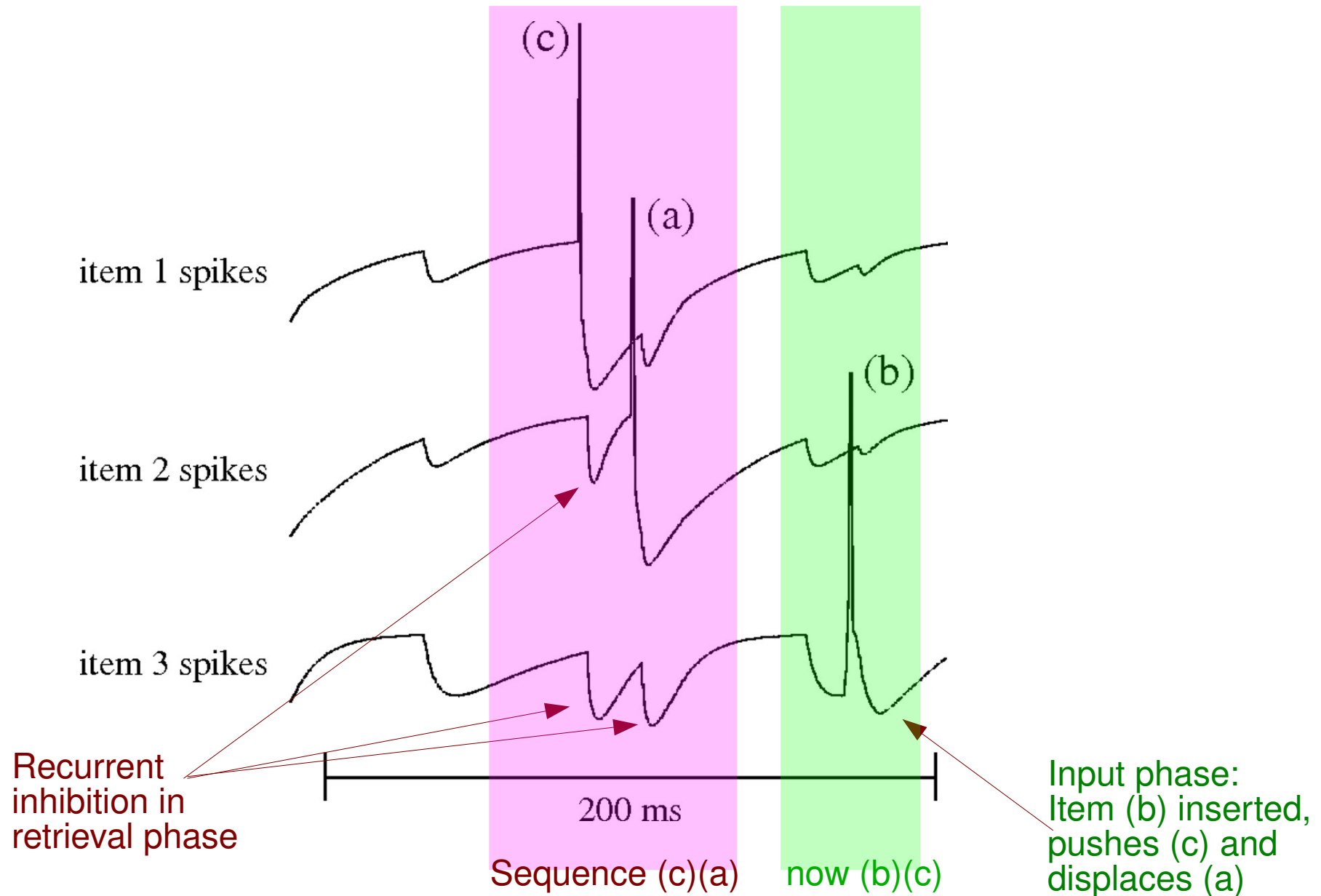
Koene & Hasselmo  
Cerebral Cortex 2007

# Koene & Hasselmo Buffer Model

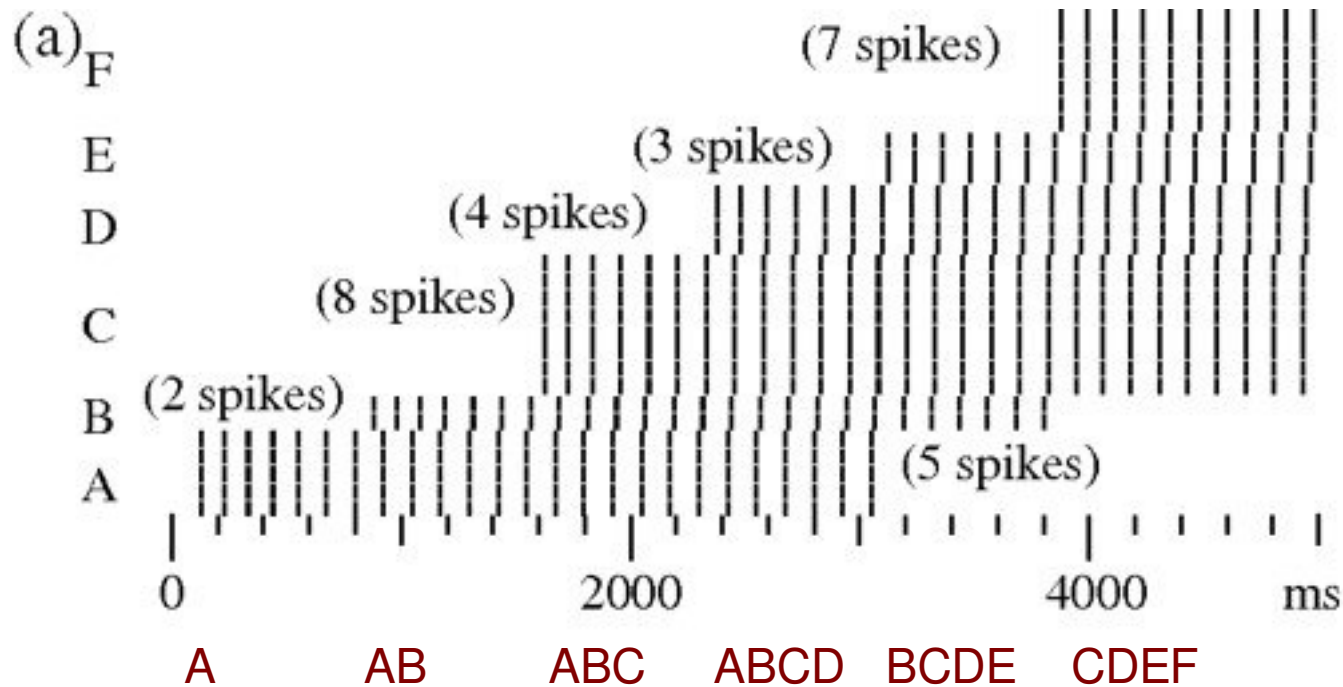
- Input phase plus reactivation phase of theta cycle



# Limited Number of Memory Slots (e.g., 2)

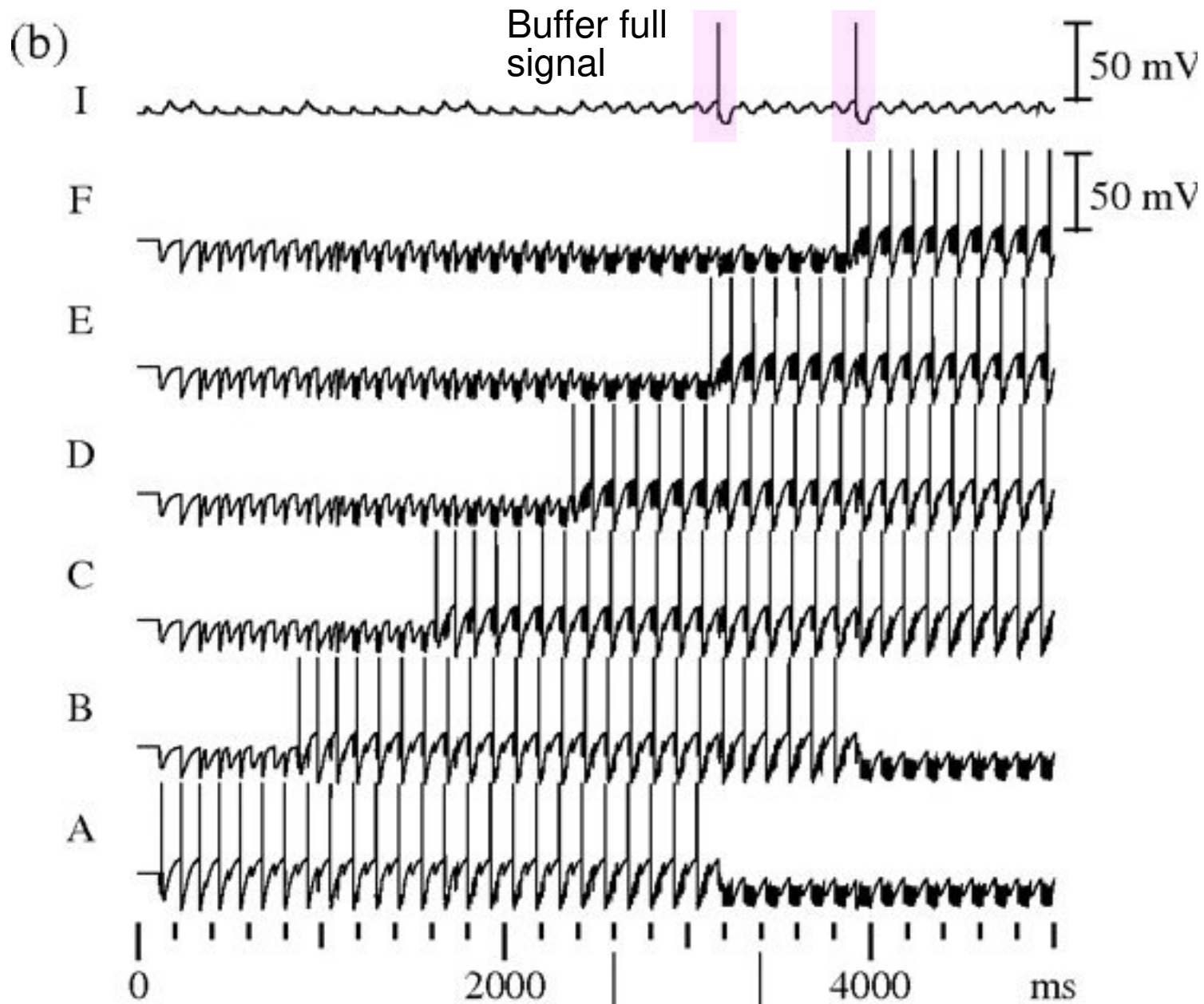


# FIFO Replacement; Capacity = 4 Items Variable Item Size

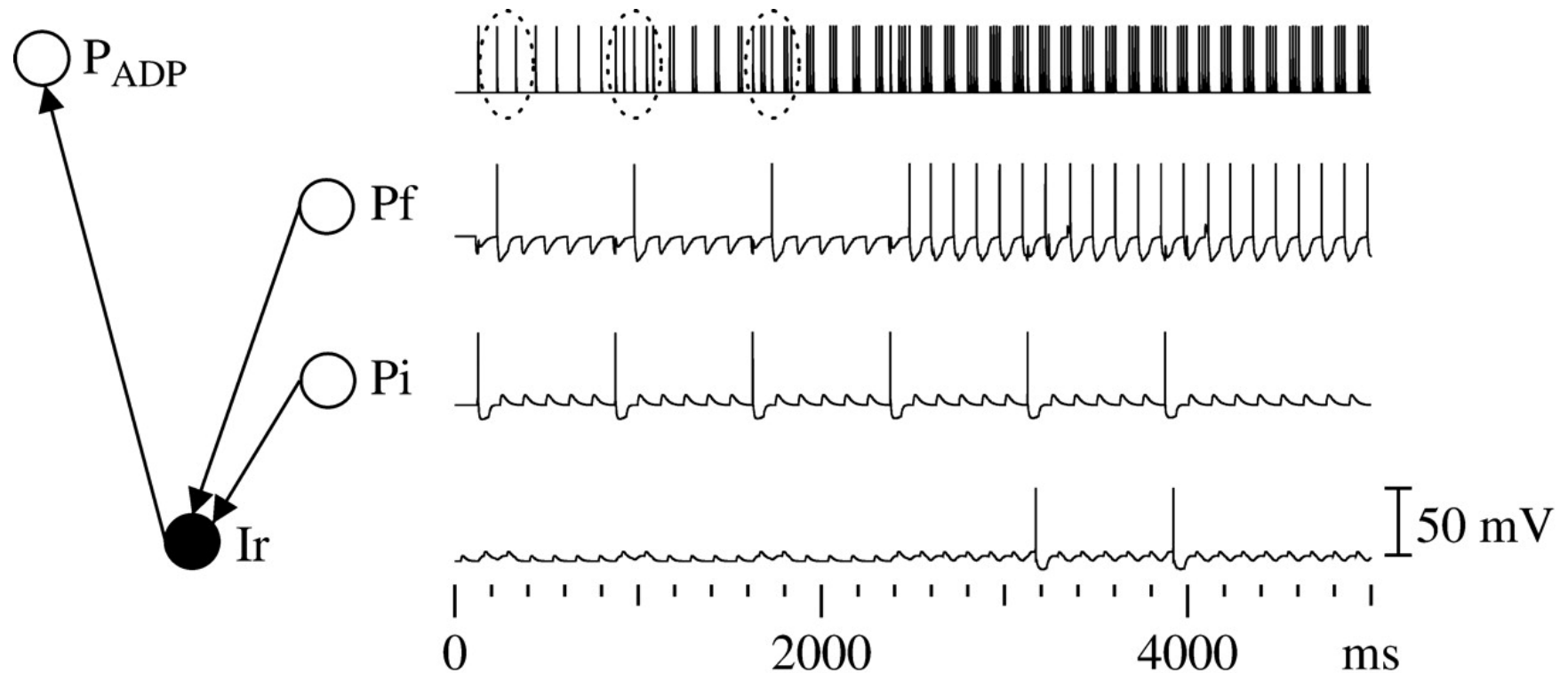


**FIFO = First In, First Out**  
**LIFO = Last In, First Out**

# Membrane Potential

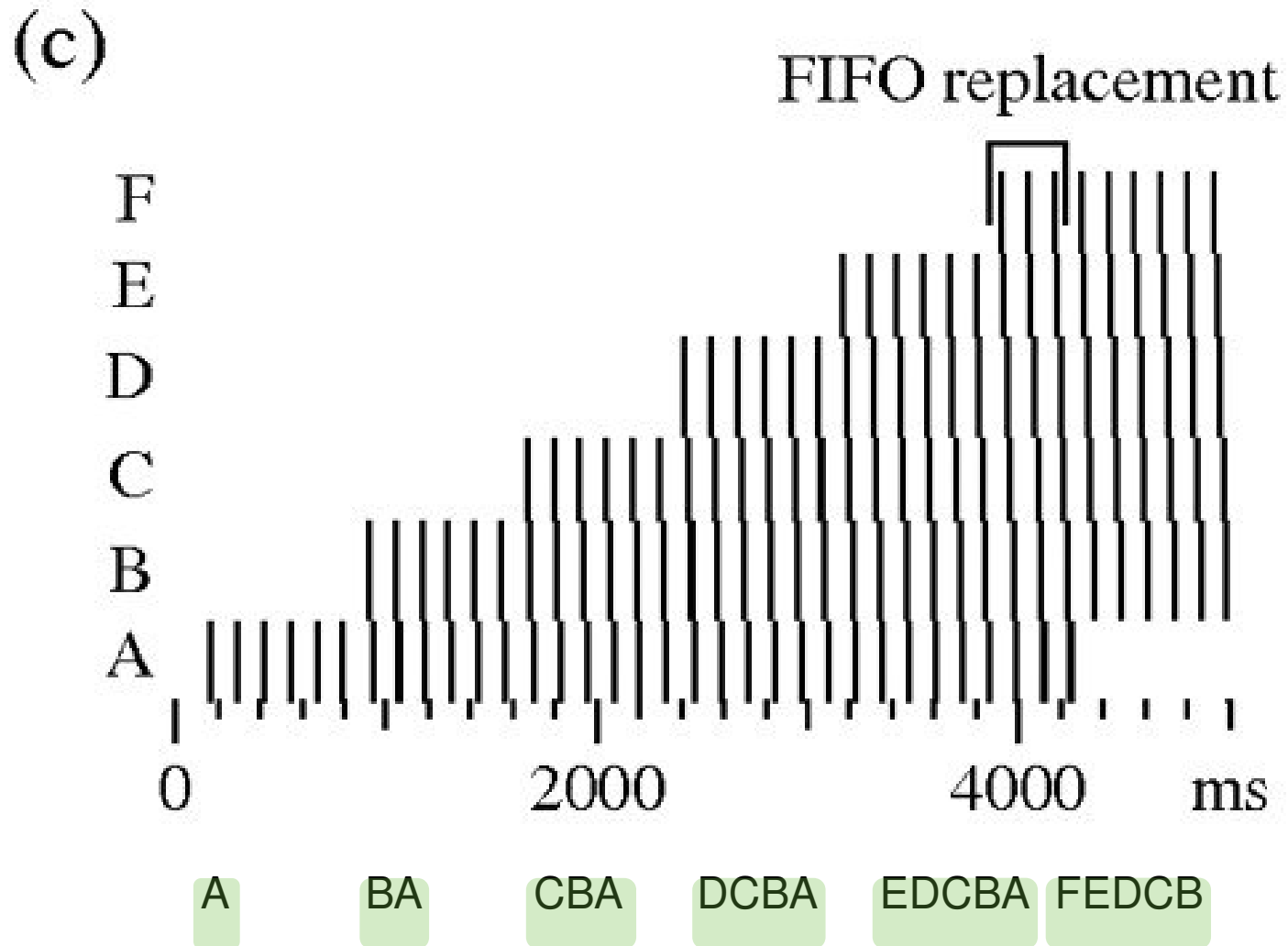


# Inhibitory Interneuron Deletes First Item Before Inserting New Item Into a Full Buffer

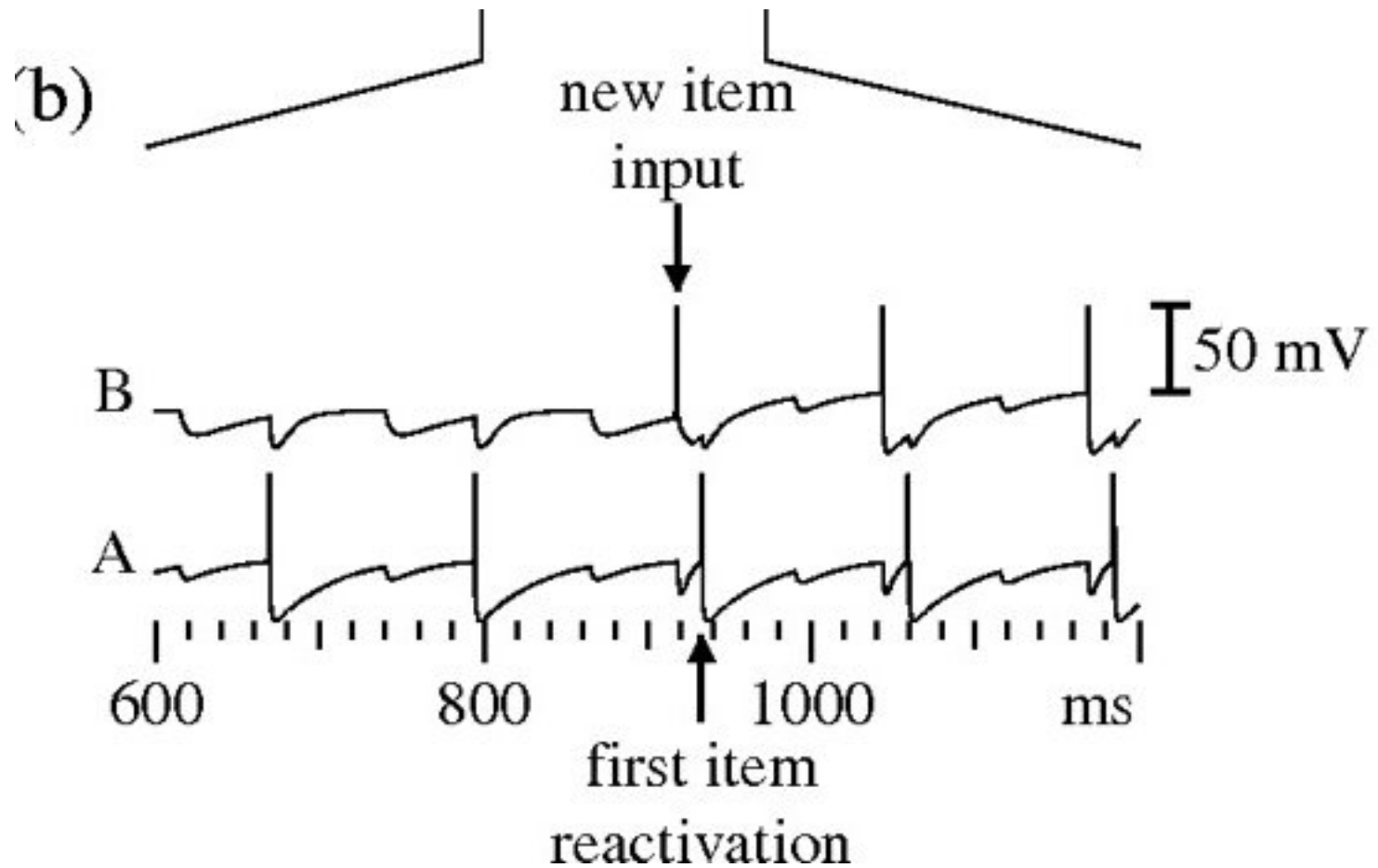


$P_f$  = buffer full  
 $P_i$  = input arriving  
 $I_r$  = inhibition for replacement

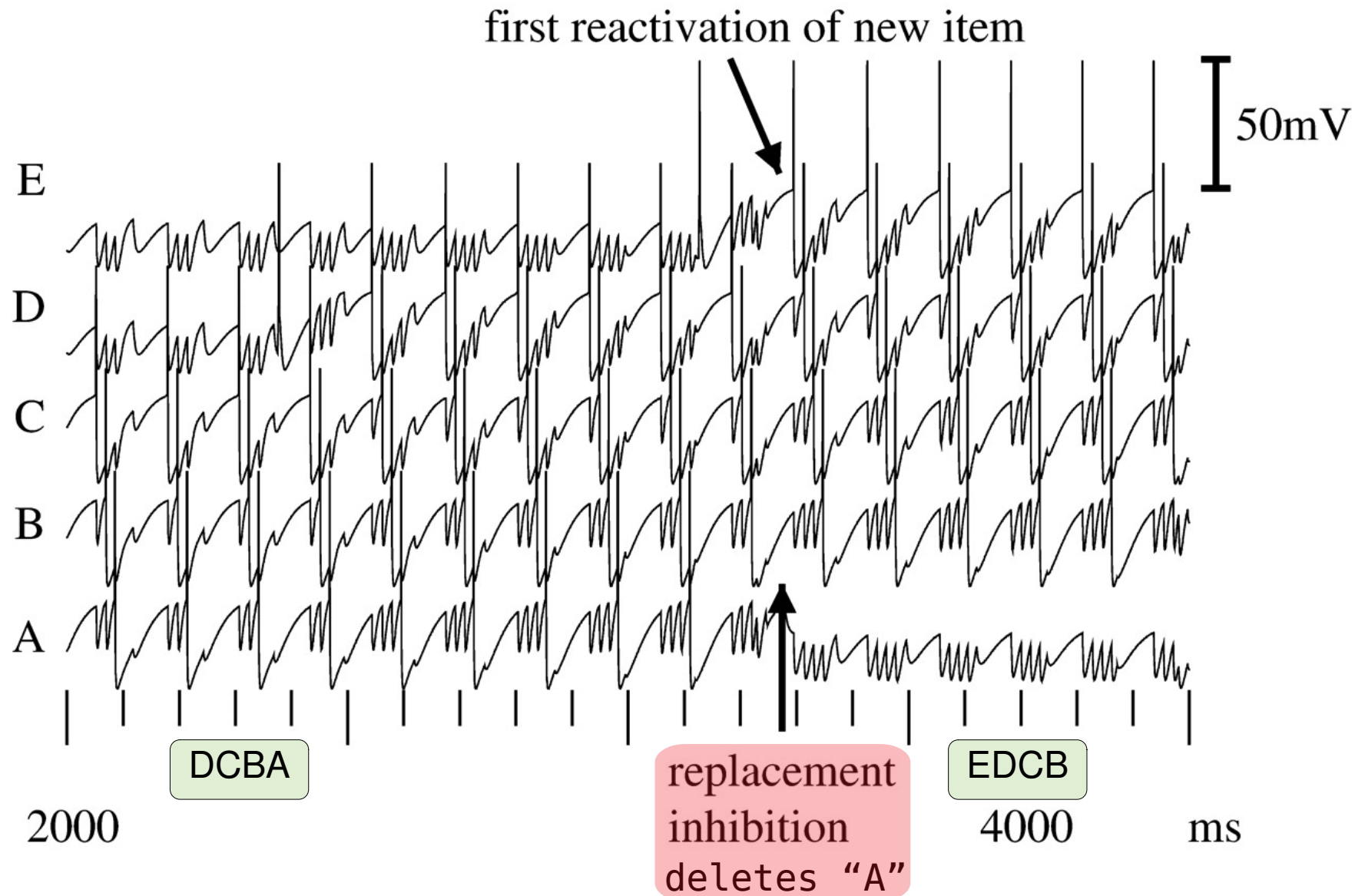
# A Reverse-Order (LIFO) Readout Buffer Inserts at the Beginning of the Theta Cycle



# Inserting At the Front of the Buffer



# Reverse FIFO Buffer With Replacement



# Summary

- The theta rhythm introduces temporal structure to hippocampal activity patterns.
- Theta phase precession of place cell firing encodes spatial information in the temporal pattern.
- ADP could allow cells in hippocampus or EC to serve a working memory function.
- The Koene & Hasselmo model can store items with different numbers of active units; only phase matters.
- Is the gamma cycle really a discretization of theta into multiple working memory “slots” for storing discrete items?
- Is the somato-dendritic interference model compatible with the theta/gamma working memory model?