Computational Neurodynamics

Topic 10
Synchronous Oscillation
Sources

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Overview

- Brain rhythms
- Communication through coherence
- Synchrony
- Generating gamma
- Coupled populations

Detecting Brain Rhythms

- Evidence of rhythmic activity in the brain can be obtained by various methods
  - EEG (electroencephalography) gathers data from electrodes attached either to the scalp, or (in pre-operative neurosurgery patients) placed directly onto the cortical surface
  - Data can also be obtained from microelectrodes inserted into cortex. This method can detect individual spike trains
  - MEG (megnetoencephalography) uses super-cooled detectors to measure the brain's magnetic field in a similar way
  - MEG is a more complex technology than (surface) EEG, but gives better spatial resolution (and is better suited to some tasks than others)
  - Both EEG and MEG give higher temporal resolution than MRI

Bands of Rhythm

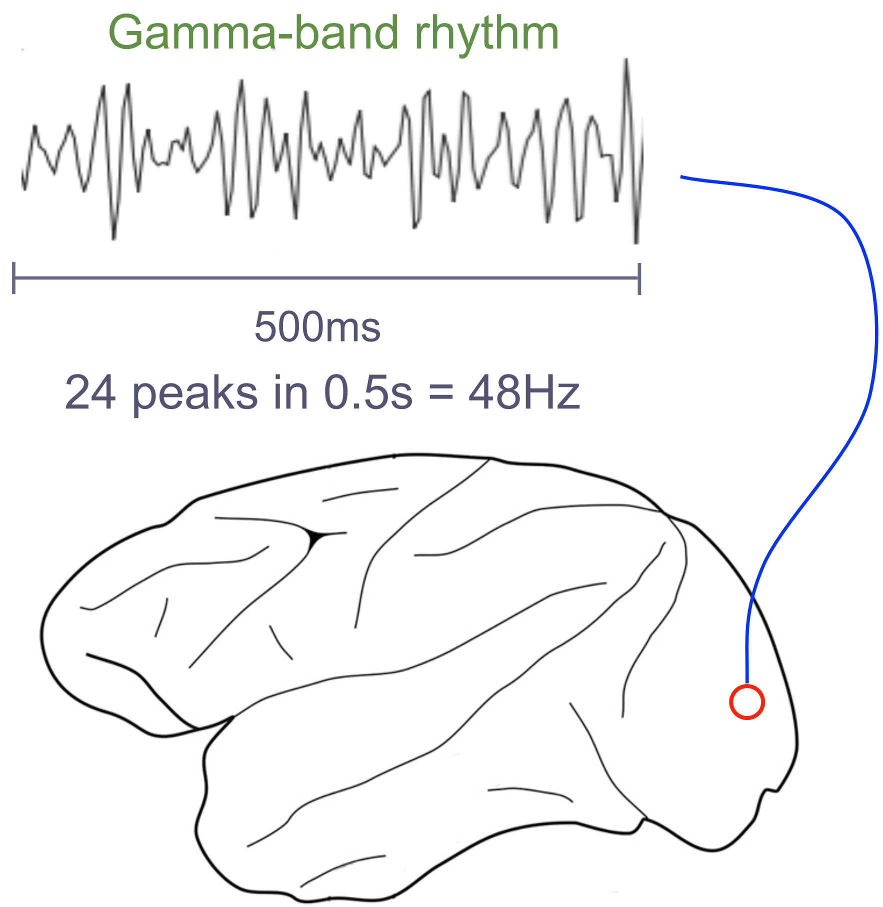
- The various kinds of rhythmic activity evident in EEG and MEG are conventionally grouped in bands according to frequency

Theta	4-8 Hz
Alpha	8-15 Hz
Beta	15-30 Hz
Gamma	30-80 Hz

- The end-points of the bands differ slightly from one author to another

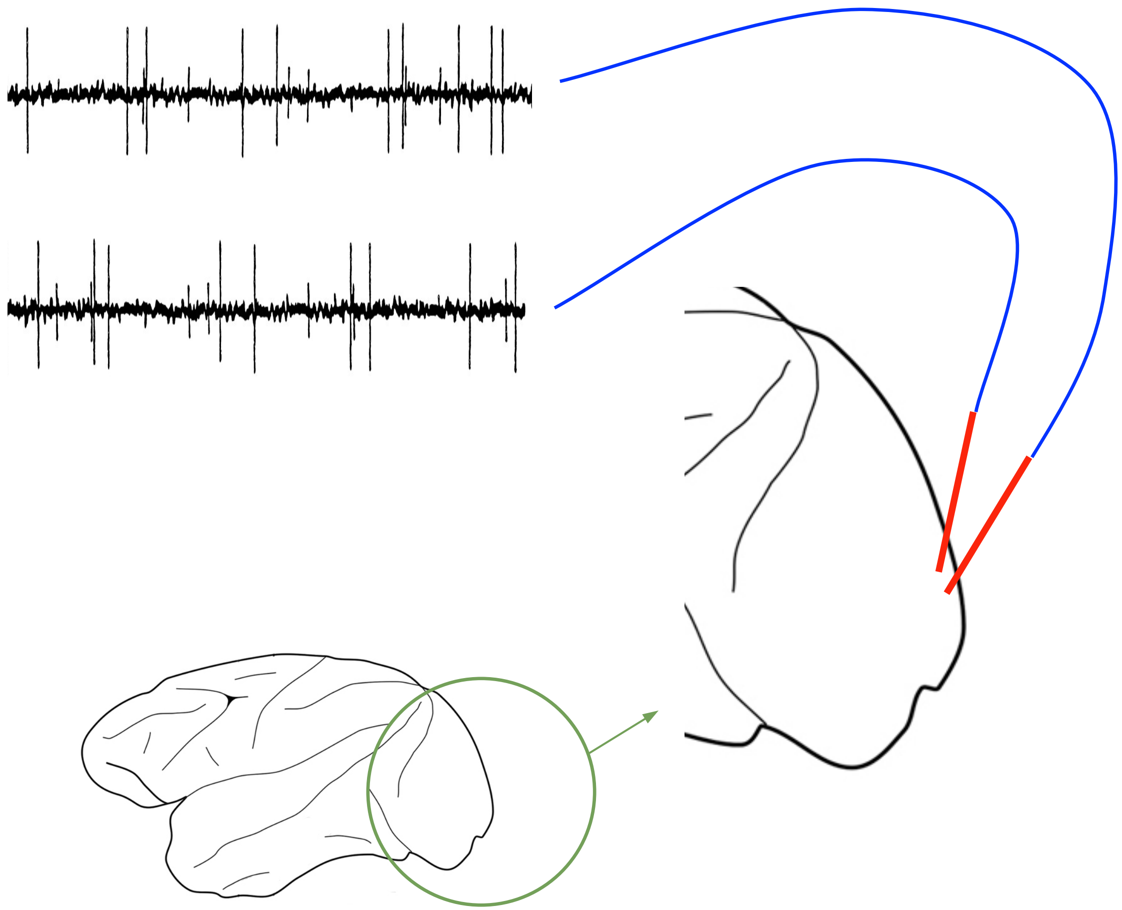
Synchronous Oscillation 1

- Because the signal on a *single surface* electrode or detector aggregates the activity of many thousands of neurons, EEG and MEG rhythms obtained this way are evidence of *synchronous* neuronal activity
- The overall level of activity of a large group of neurons is waxing and waning



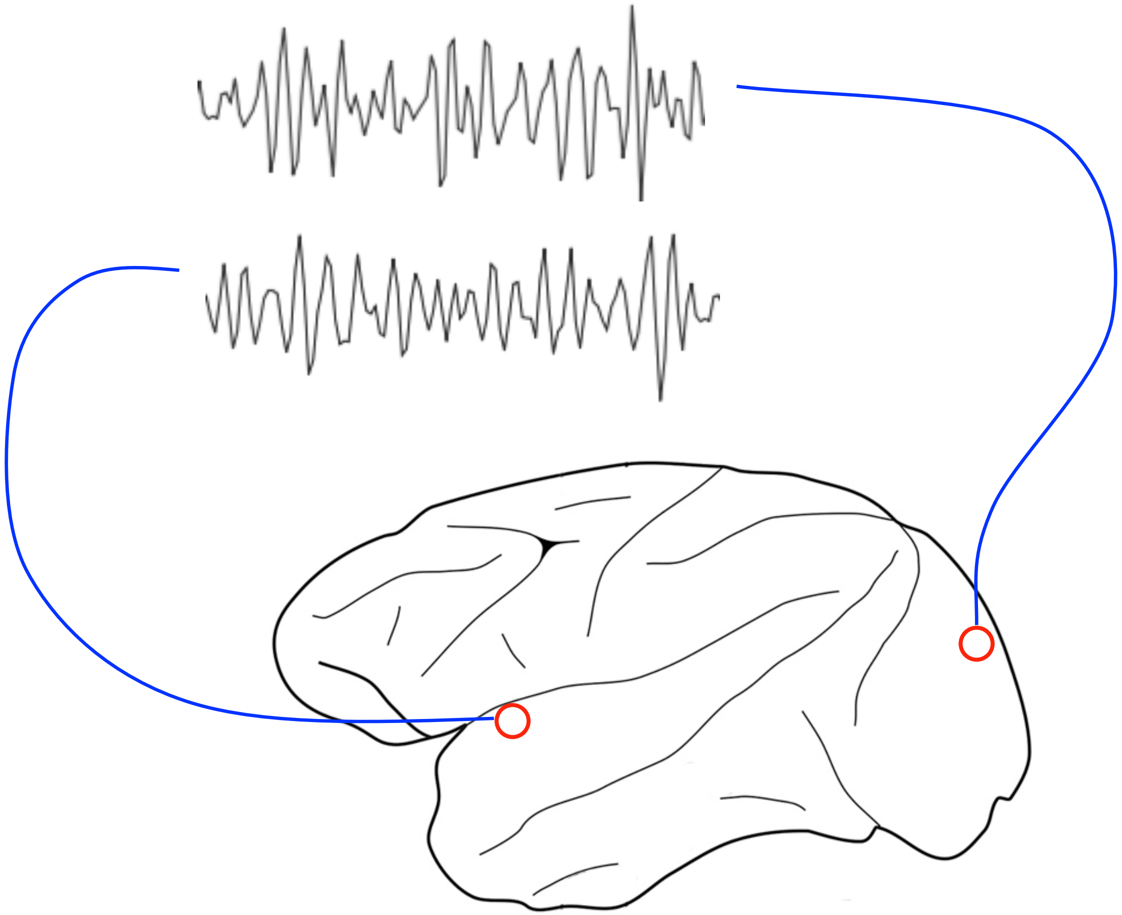
Synchronous Oscillation 2

- More precise data gathered using electrodes *inserted* into the brain at multiple nearby sites reveals synchronous activity more directly
- The data takes the form of spike trains whose firing rates fluctuate in time with each other

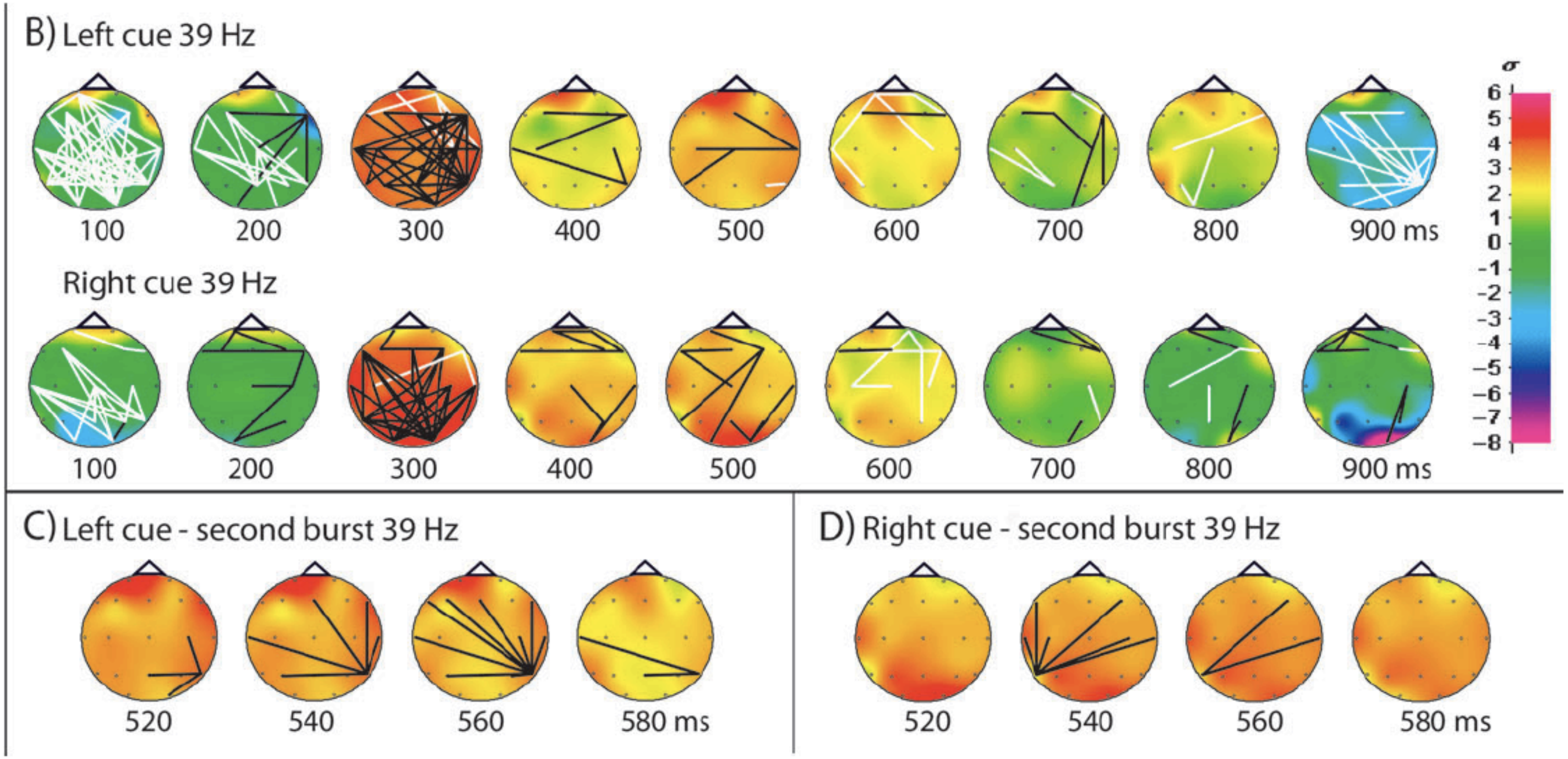


Synchronous Oscillation 3

- Using *multiple surface* electrodes and detectors, long-range synchrony can be revealed
- "Long-range" synchrony means synchronised activity at sites that are remote from each other

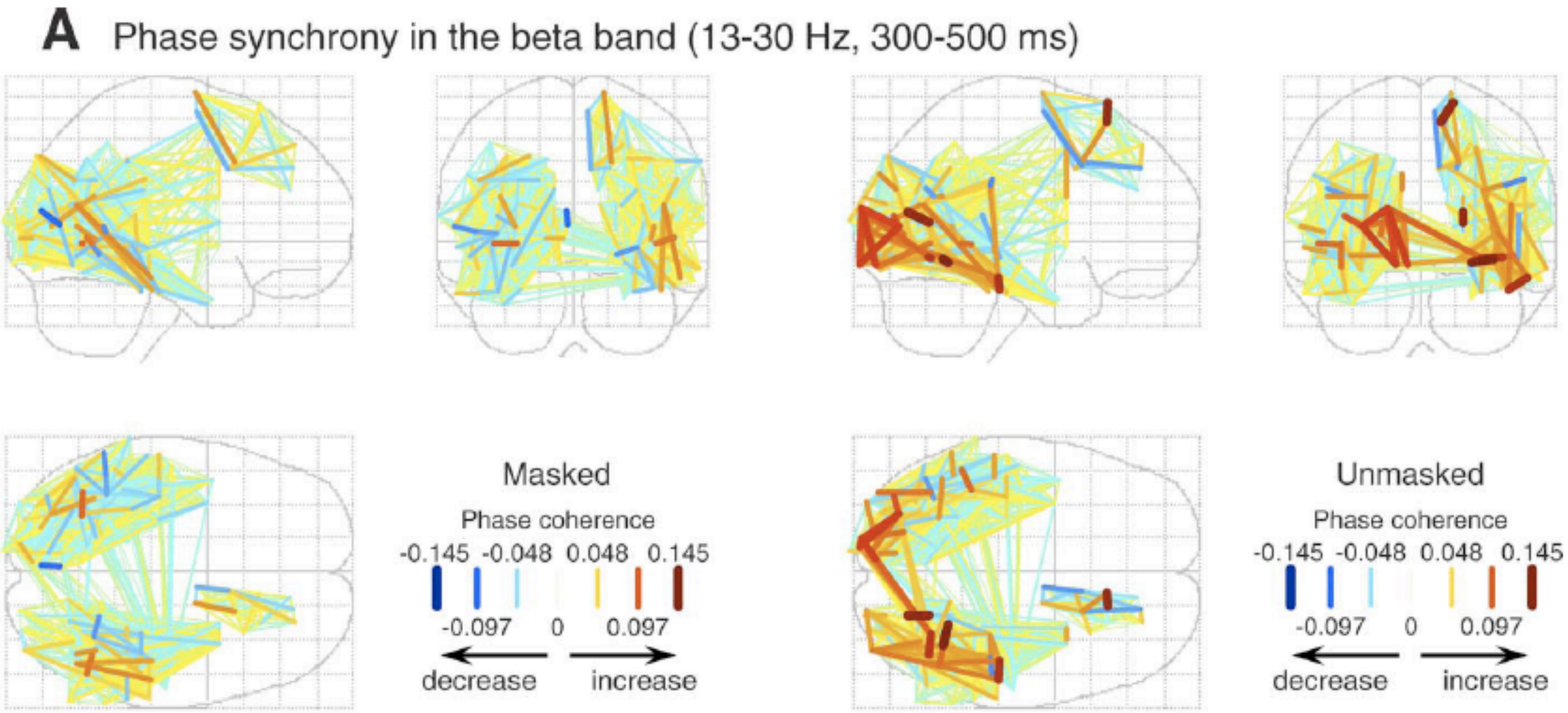


Evidence 1



Theta-modulated long-range gamma synchrony
(Doesburg, *et al.*, 2008)

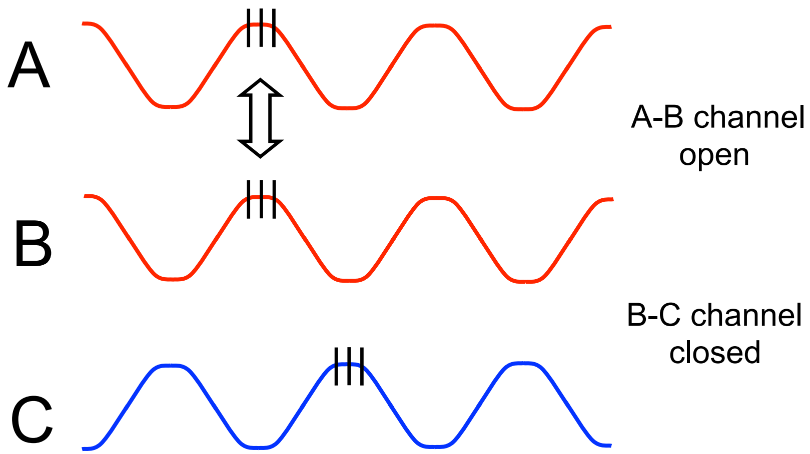
Evidence 2



Theta-modulated long-range beta synchrony
(Gaillard, *et al*., 2009)

Communication Through Coherence

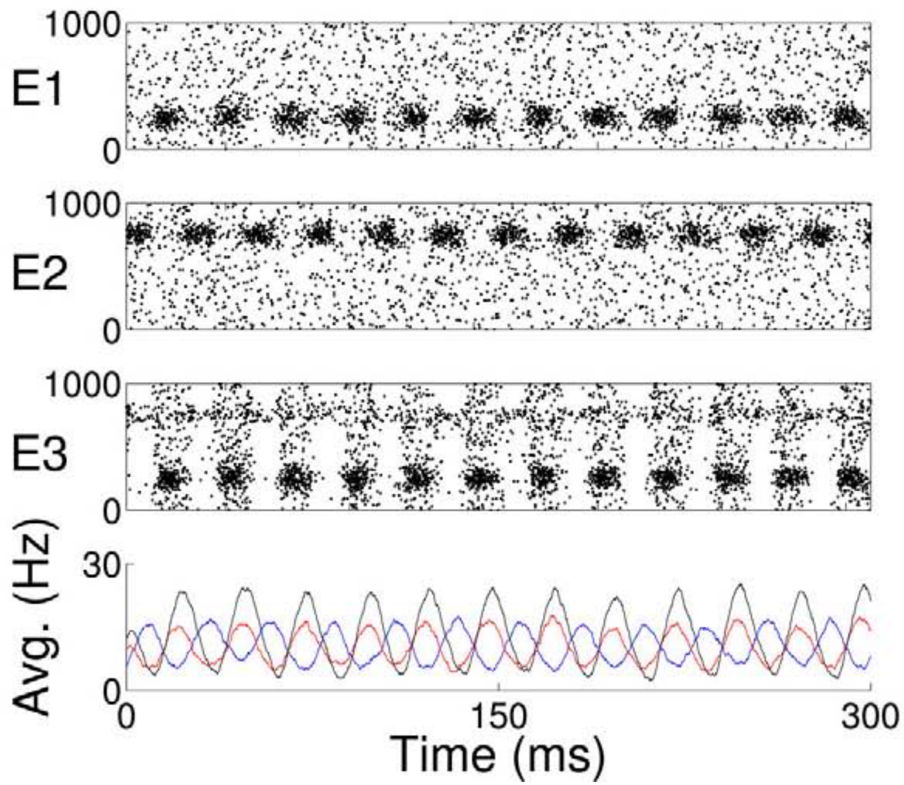
- What, if anything, is the functional role of synchronous oscillation?
- According to the *communication through coherence* hypothesis (Fries), synchronous activity allows the opening and closing of channels of communication between populations



- When two populations oscillate synchronously, they can exchange spikes, while populations that have the wrong phase relationship cannot talk to each other

Competitive Entrainment

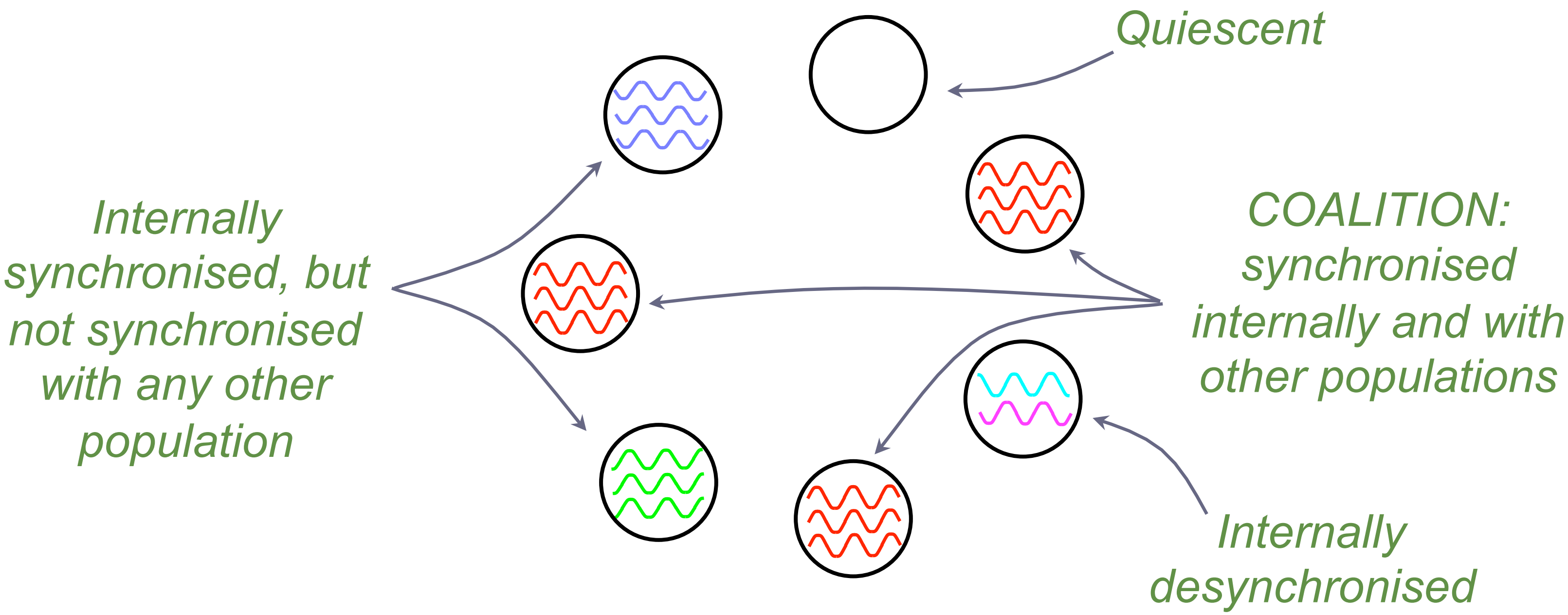
- Here we see a computer model of the communication through coherence phenomenon
- Both E1 and E2 are connected to E3
- Population E1 entrains population E3 to oscillate in synchrony with it
- This enables the pattern from E1 to be communicated to E3, to the exclusion of E2



(Wildie & Shanahan, 2012)

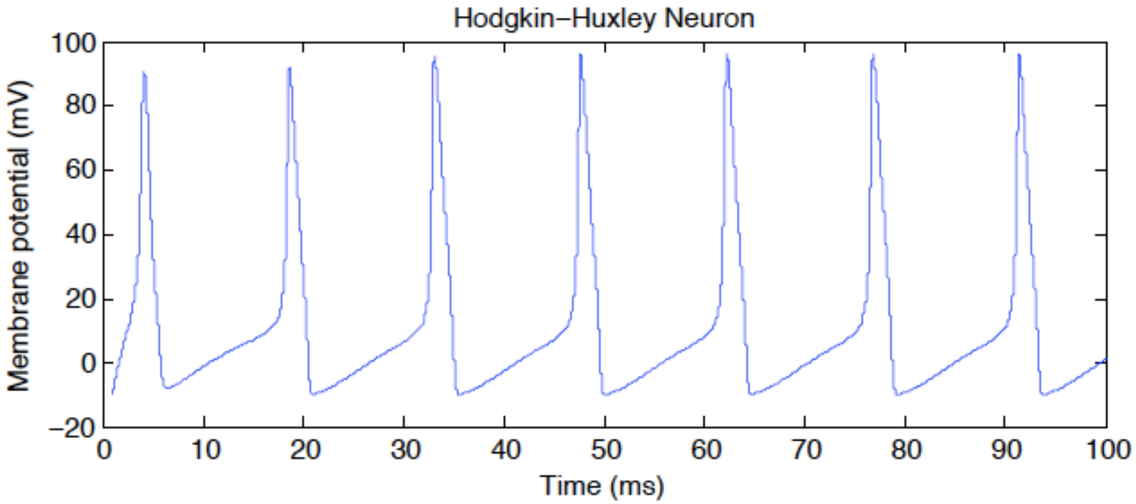
Synchronised Coalitions

- This mechanism potentially allows coalitions of processes to form, to the exclusion of rival coalitions



Neurons Oscillate

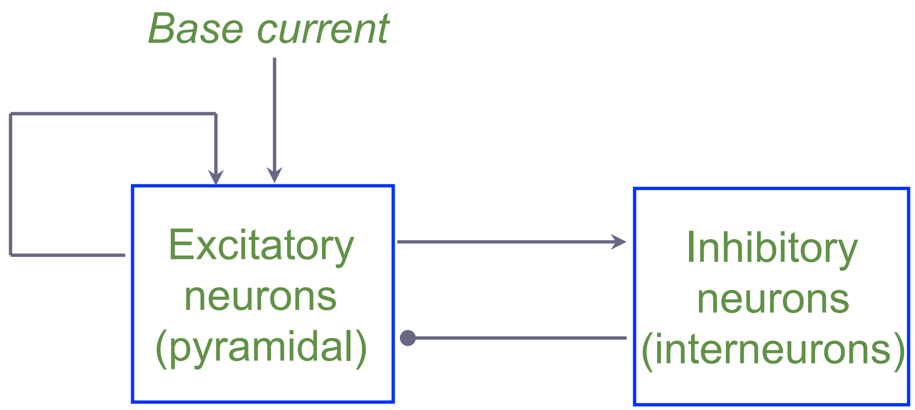
- Neurons are natural oscillators. Subject to a constant dendritic current, they will fire rhythmically. We already saw this when we looked at models of single neurons
- But the most interesting questions arise in the context of neuronal populations



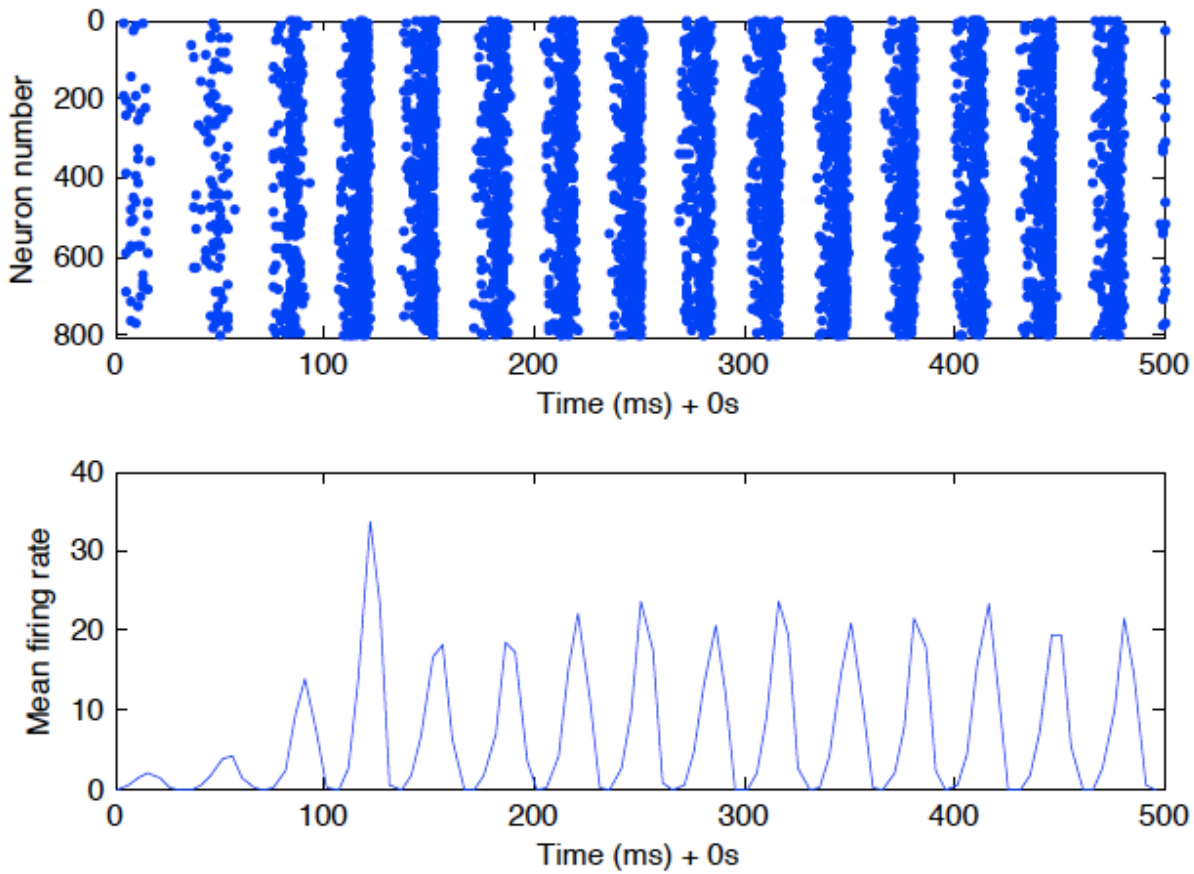
- How does a whole collection of neurons exhibit rhythmic activity?

PING 1

- One way in which synchronous gamma-band oscillations can arise is through reciprocally connected populations of excitatory and inhibitory neurons
- This is known as PING (Pyrammidal InterNeuron Gamma)
- We see the effect even in the absence of recurrent inhibitory connections



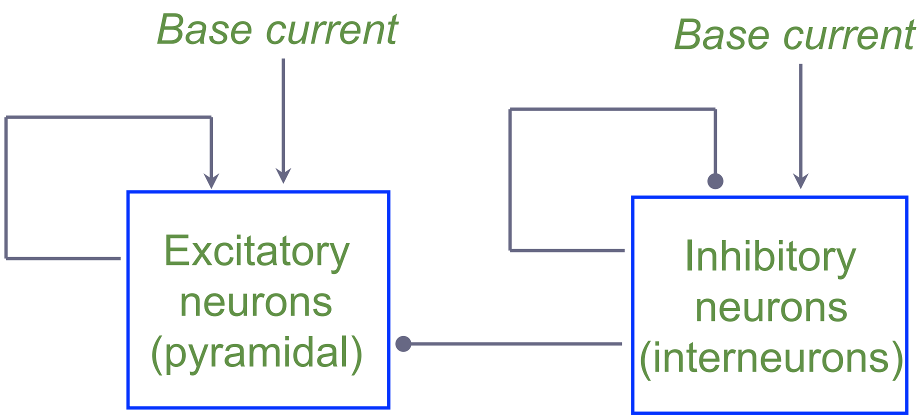
PING 2



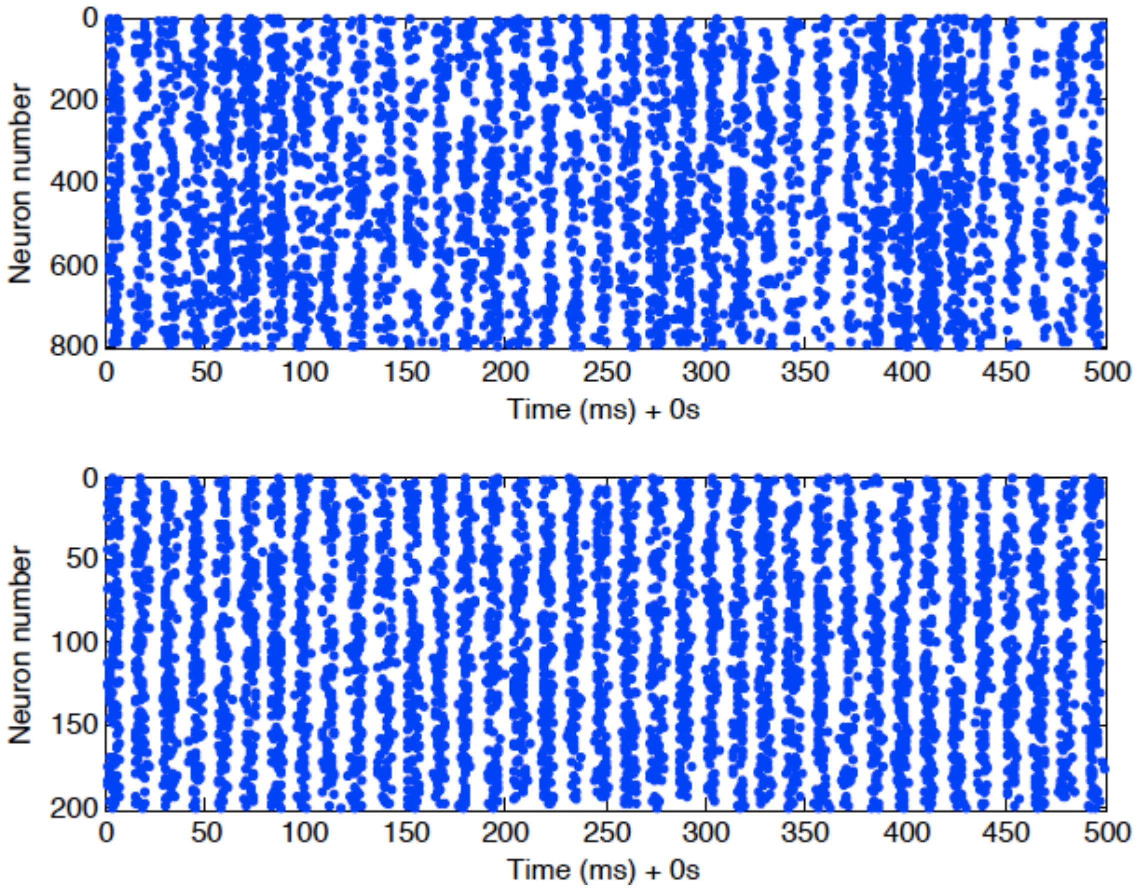
- Here is a raster plot for this arrangement
- Only the excitatory population is shown, oscillating at about 35Hz
- Below is the mean firing rate of the excitatory population, averaged over a moving 10ms window

ING 1

- Recurrent connections within an inhibitory population are also sufficient to generate gamma-band oscillations, if that population is sufficiently excited to be active without the input of the excitatory population it is modulating
- This is known as ING (InterNeuronal Gamma)

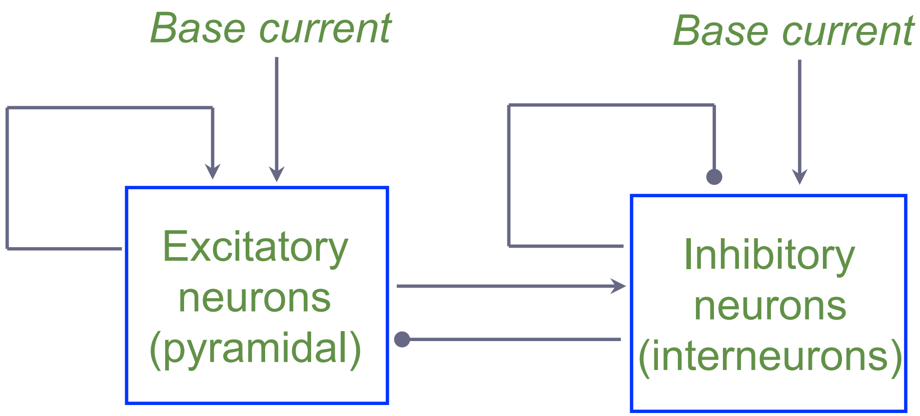


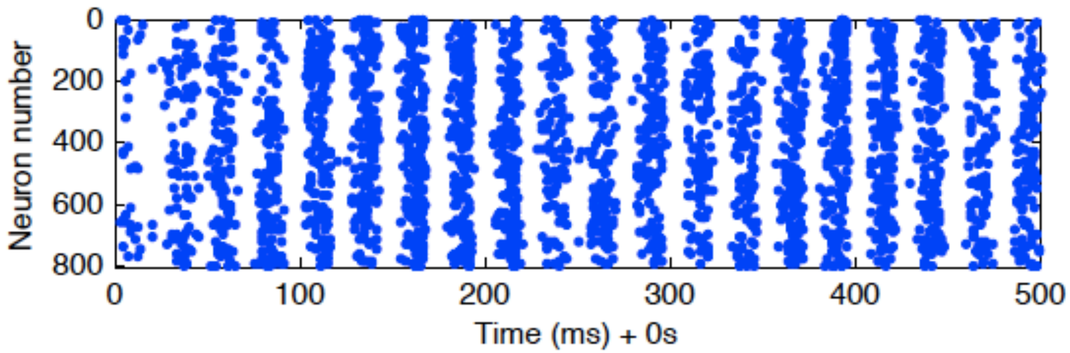
ING 2



- Here is a raster plot of ING at work
- The lower plot is the inhibitory population
- It will oscillate (in this case at a high gamma rate of about 70Hz) regardless of what the excitatory population is doing

Gamma Oscillation 1

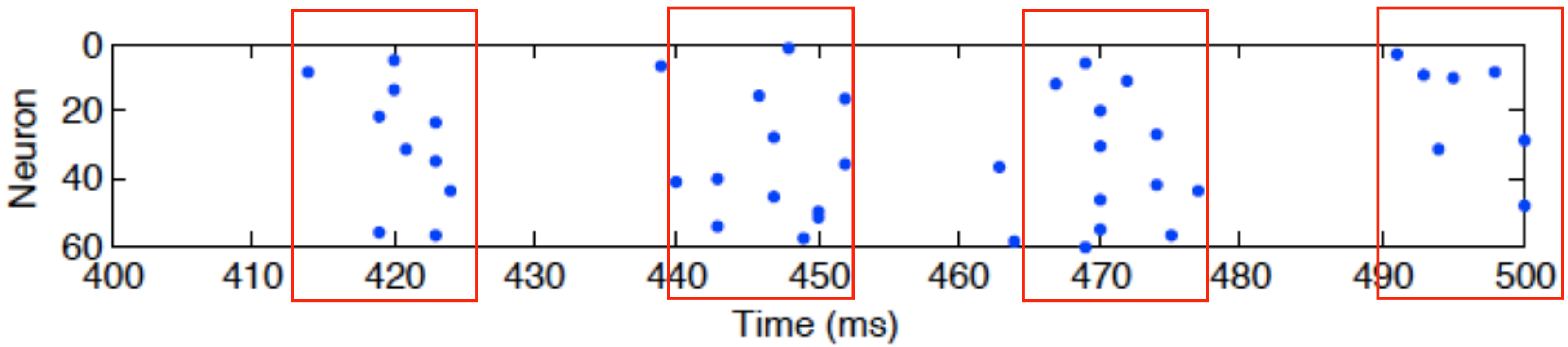




- The full PING setup combines both mechanisms, which reflects the connectivity of cortex
- With this arrangement we can obtain clear 40Hz oscillation. (Only the excitatory population is shown)

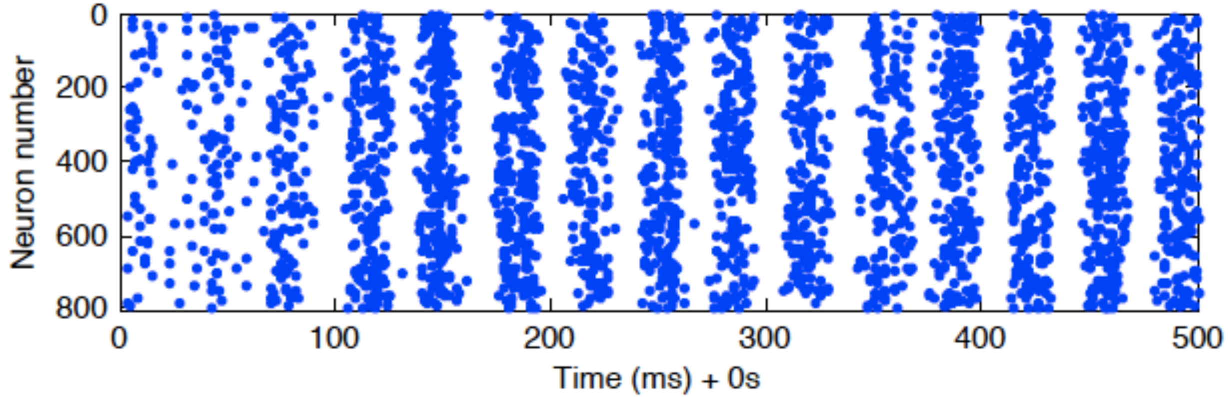
Gamma Oscillation 2

- For a population of neurons to exhibit synchronous gamma-band oscillation (40Hz), it is *not* necessary for individual neurons to fire regularly at 40Hz (a spike, or a burst, every 25ms)
- Rather, it needs to be the case that
  - there is plenty of firing in the population, and
  - neurons typically only fire in a 12.5ms window

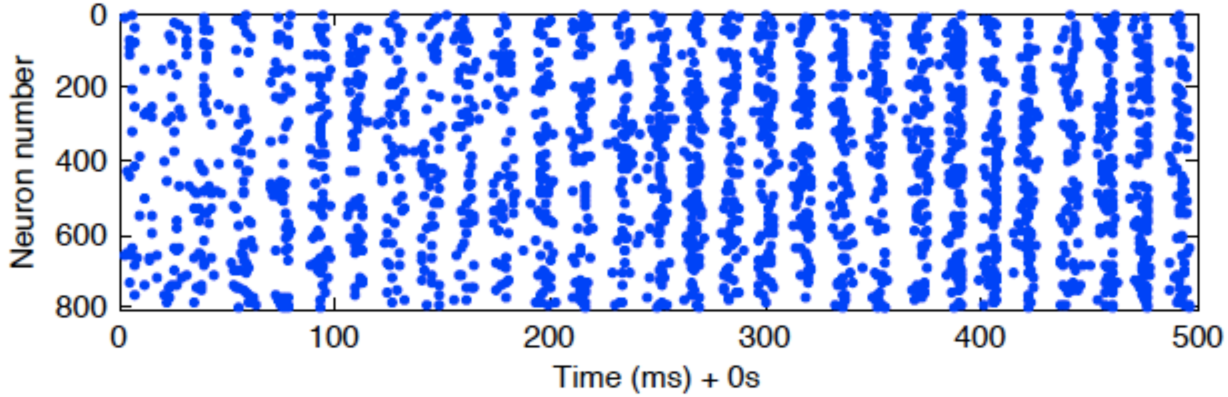


Varying Frequency

8ms delay, 32Hz oscillation

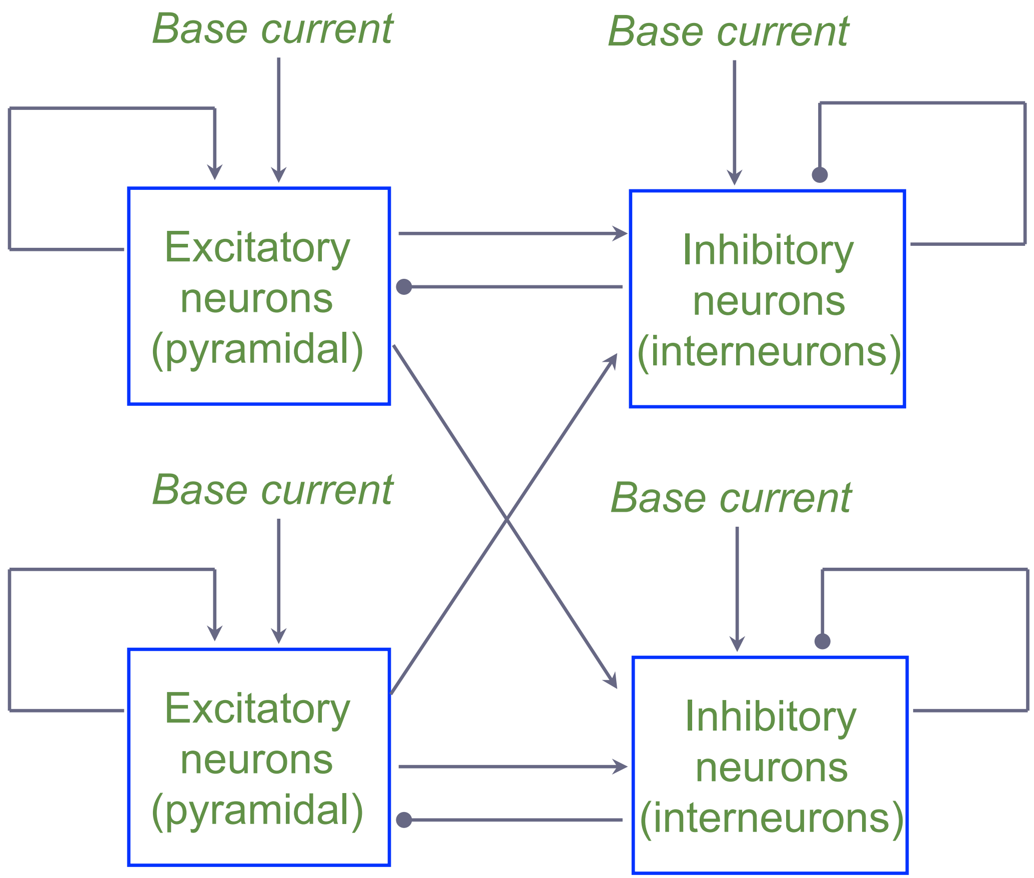


2ms delay, 56Hz oscillation



- In the preceding slides, all conduction delays were set to 5ms
- By varying the conduction delay, we can adjust the frequency of synchronous oscillation

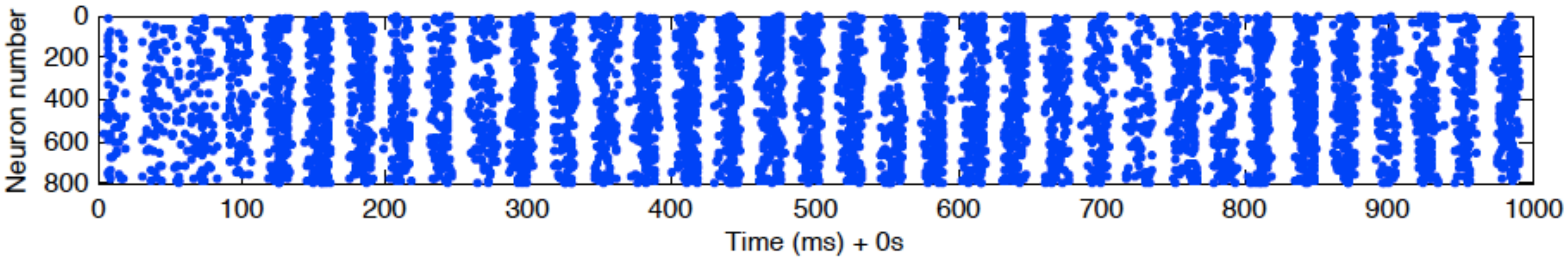
Coupled Populations

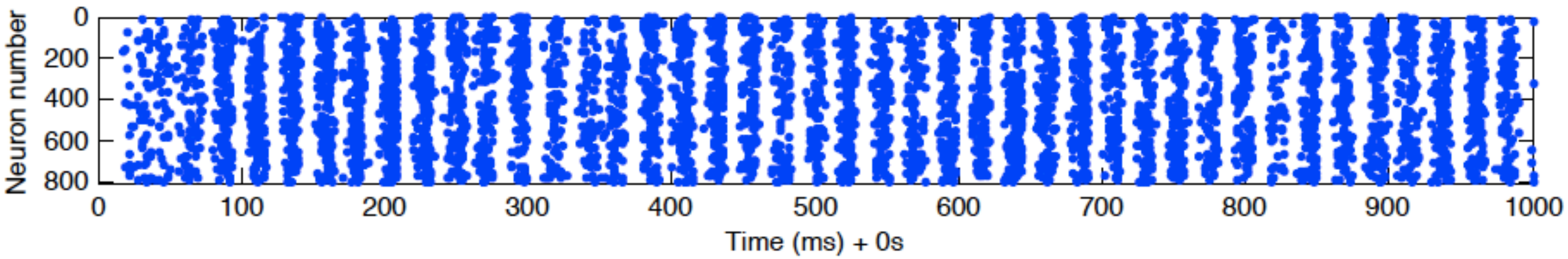


- Two independent oscillating populations can be coupled by exciting each other’s inhibitory neurons
- With sufficient coupling strength, this can cause the populations to synchronise

Synchronised Populations 1

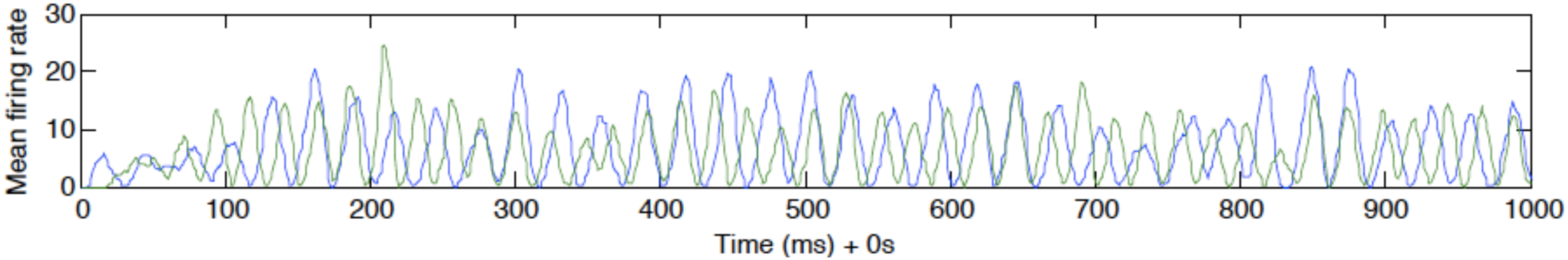
- First we'll consider the *decoupled* case, for two populations with *different* natural frequencies
- Here are the raster plots (excitatory neurons only). The two populations are oscillating freely at different frequences

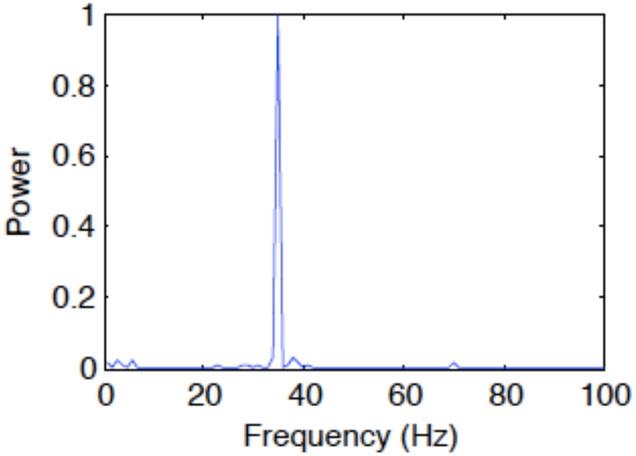


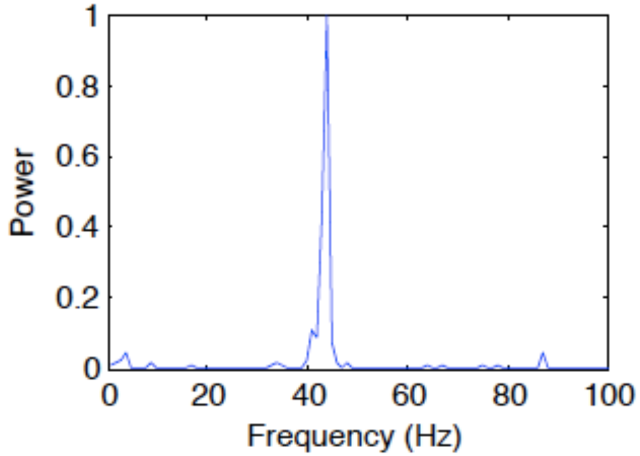


Synchronised Populations 1

- If we plot the mean firing rates, and the power spectrums of the resulting two time series we can see this more clearly



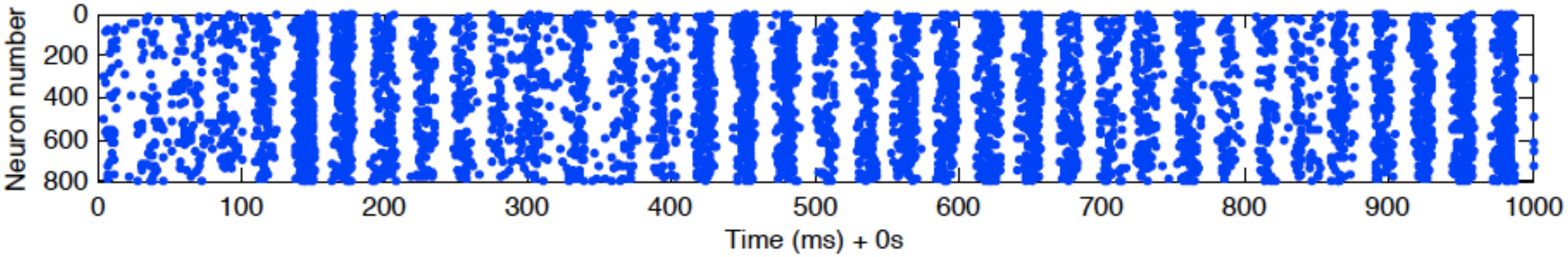


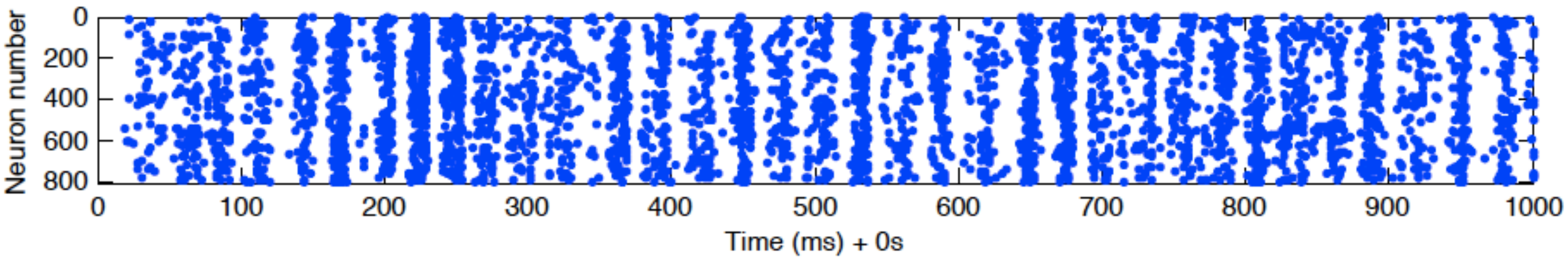


- The two populations are exhibitting high gamma power, but at different frequencies

Synchronised Populations 3

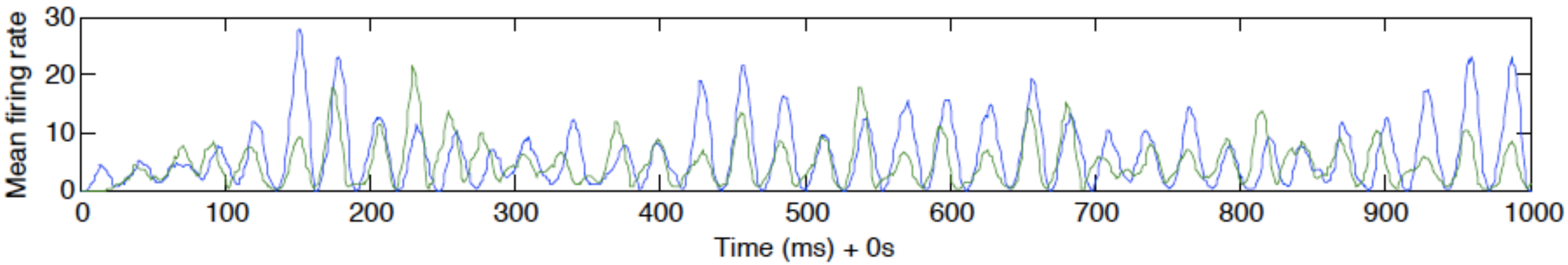
- Now we'll consider the coupled case, where one population's excitatory neurons are connected to the other population's inhibitory neurons
- Now we get synchronisation, despite the fact that the two populations have a different natural frequency

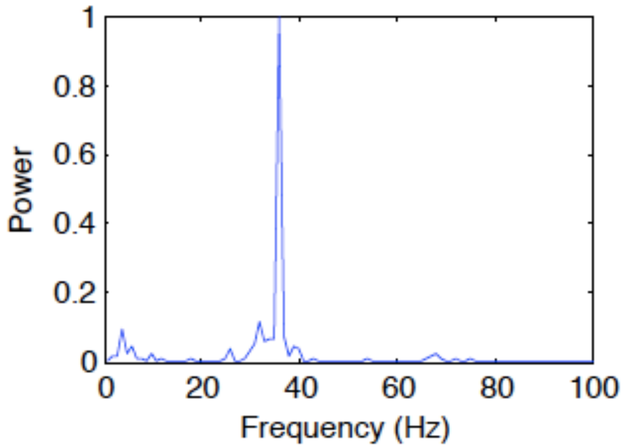


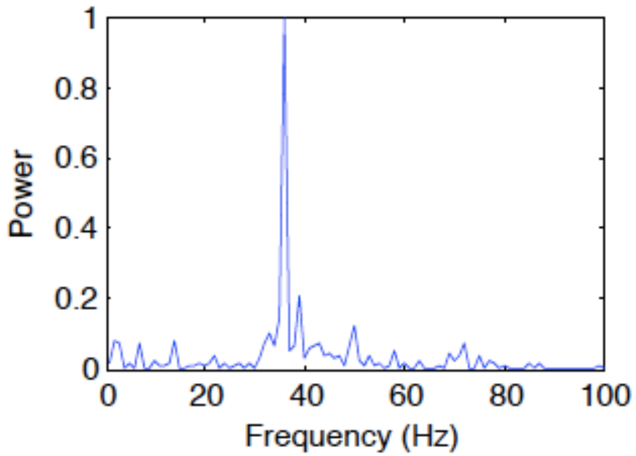


Synchronised Populations 4

- Again, we can see this more clearly by plotting the mean firing rates, and the power spectrums of the resulting two time series



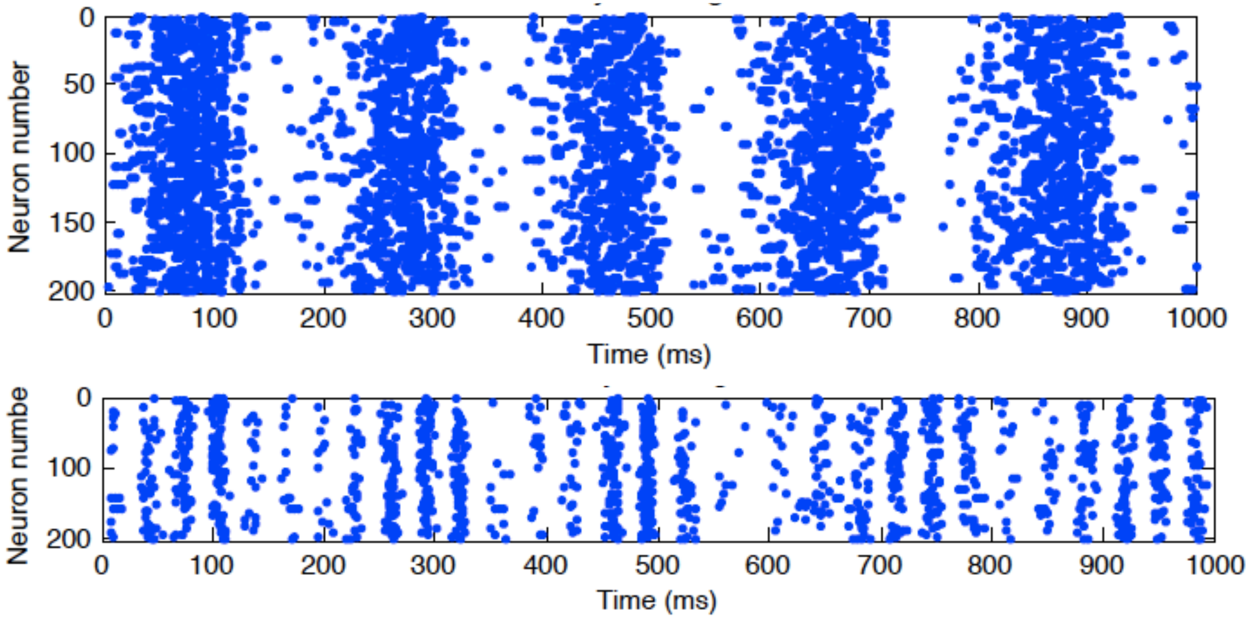




- The two populations still have high gamma power, but now at the same frequency

Theta Oscillation

- We have so far focused on gamma rhythms (30Hz-80Hz. Another prevalent rhythm is theta (4-8Hz)
- Theta rhythms can be present on their own
- But we also find theta-modulated gamma



Related Reading

Buzsáki, G. (2006). *Rhythms of the Brain*. Oxford University Press.

Fries, P. (2009). Neuronal Gamma-Band Synchronization as a Fundamental Process in Cortical Communication. *Annual Review of Neuroscience* 32, 209–224.

Wang, X.-J. (2010). Neurophysiological and Computational Principles of Cortical Rhythms in Cognition. *Physiological Reviews* 90, 1195–1268.