Malleability of gamma rhythms enhances population-level correlations

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Joint work with Lai-Sang Young

Outline

1. A local population of neurons
   - Modeling one neuron
   - Properties of a population
2. Numerical study of correlations between neuronal populations
3. Comparison with rigid oscillations
4. Mechanistic explanations for observed phenomena

Membrane potential of a neuron

Leaky integrate-and-fire equations:

normalized membrane potential V of a neuron n is governed by

$$\dot{V} = -\frac{1}{\tau_{leak}}V - (V - V_E)g_E - (V - V_I)g_I$$

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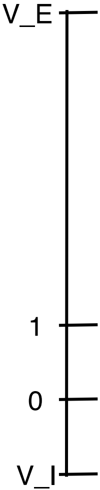

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Evolution of g_E and g_I:

- neuron n is of type $Q \in \{E, I\}$
- $M_E(n)$ and $M_I(n)$ are sets of presynaptic E and I neurons

Exc. conductance

$$\tau_E \dot{g}_E = -g_E + S^{QE} \sum_{m \in M_E(n)} \sum_{i=1}^{\infty} \delta(t - t_i^m) + S^{QE} \sum_{i=1}^{\infty} \delta(t - t_i^{ext}) + S^{amb} \sum_{i=1}^{\infty} \delta(t - t_i)$$

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$$\tau_I \dot{g}_I = -g_I + S^{QI} \sum_{m \in M_I(n)} \sum_{i=1}^{\infty} \delta(t - t_i^m)$$

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$$\tau_I \dot{g_I} = -g_I + S^{QI} \sum_{m \in M_I(n)} \sum_{i=1}^{\infty} \delta(t - t_i^m)$$

- τ_Q is a biophysical constant for conductance leakage
- Main parameters, $S^{EE}, S^{EI}, S^{IE}, S^{II}$ and external drive rate, based on experimental data

Membrane potential over time

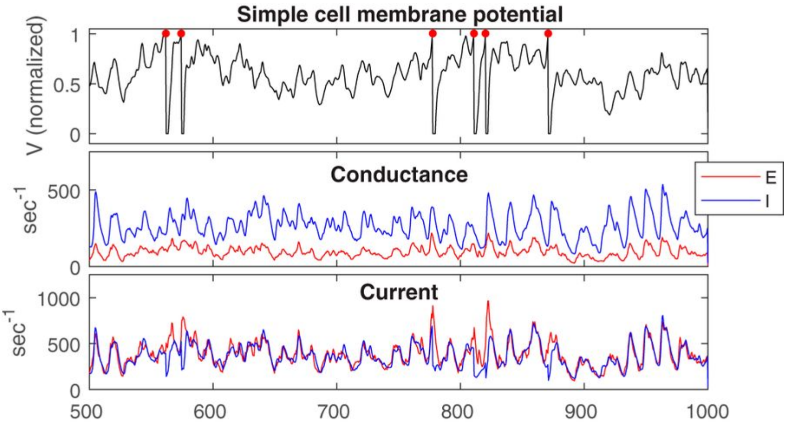


Figure 2 A-C; Chariker, Shapley, and Young 2018

Assembling a local population

- $N_E = 300$, $N_I = 100$
- E neurons postsynaptic to $\approx$ 80 E neurons and $\approx$ 50 I neurons
- I neurons postsynaptic to $\approx$ 240 E neurons and $\approx$ 50 I neurons

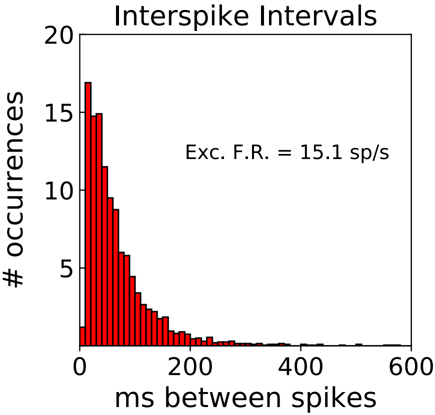
To Note:

- The size of local populations in hundreds to thousands of neurons

- As in the brain, not all-to-all nor sparse coupling

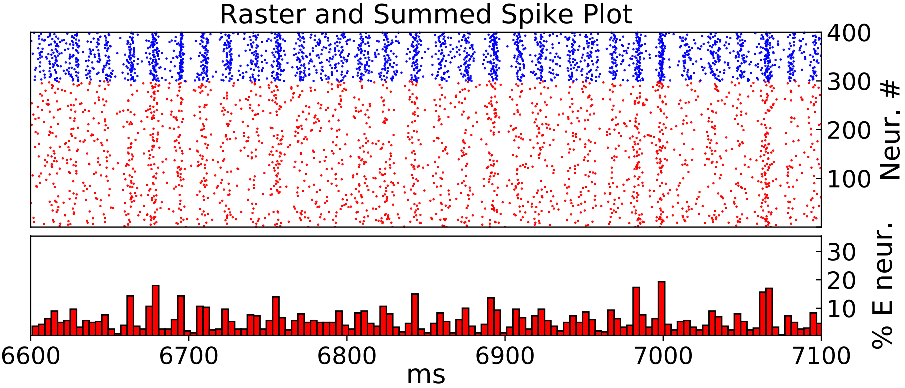
- The E $\rightarrow$ E connections are less dense, due to anatomical data

Simulation statistics



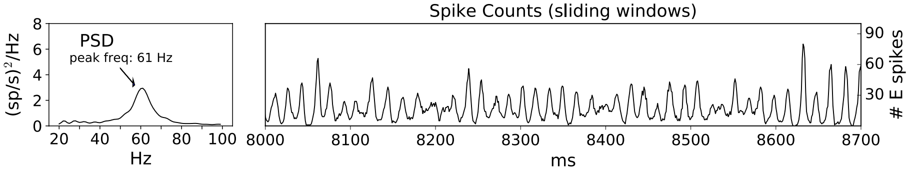
Individual neurons behave almost randomly

Simulation statistics



Collective response is more rhythmic

Simulation statistics



- Population rhythm has a peak frequency in the gamma-band

- Rhythm is broad-band, and not periodic. It has oscillatory and irregular components, and also degrades sometimes

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- irregular, episodic, broadband, and degrades sometimes while still having an oscillatory component

Outline

Our motivation

Fries, 2005; 2015 *communication through coherence* (CTC) hypothesis:

• Effective communication is subserved by synchronization between pre- and post-synaptic populations

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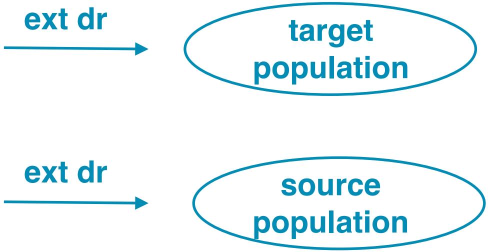
• ". . . communication is prevented by the absence of a **reliable phase relationship between the oscillations** in the the sending and the receiving group." Fries, 2005

• Can the gamma-rhythms of a receiving population be entrained by a sending population, even when displaying the **irregular, broad-band rhythms typical of sensory cortices**?

Connecting two populations



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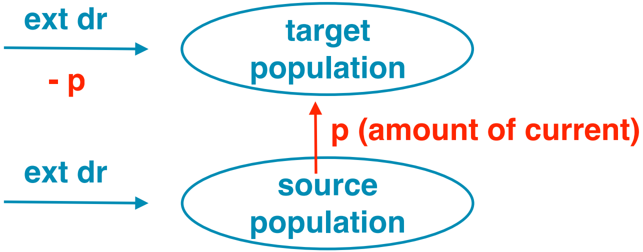


Typically p ~ 7-10% total E-current

Definition of correlation metric

One way to measure the coherence between the spiking activity of two neuronal populations:

- Fix a large time interval $[0, T]$

- X and Y are random variables defined on the probability space $\Omega = \{0, 1, ..., T-4\}$, and equal probability is assigned to each sample point

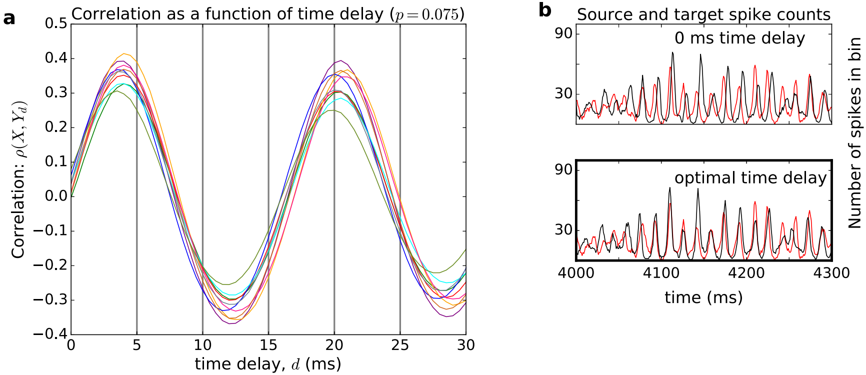
- $X(t) =$ "instantaneous" population firing rate (total number of spikes) of source on 4 ms: $[t, t+4)$

- $Y(t)$ defined similarly for the target

$$\rho(X, Y) = \frac{COV(X, Y)}{\sqrt{Var(X)Var(Y)}}$$

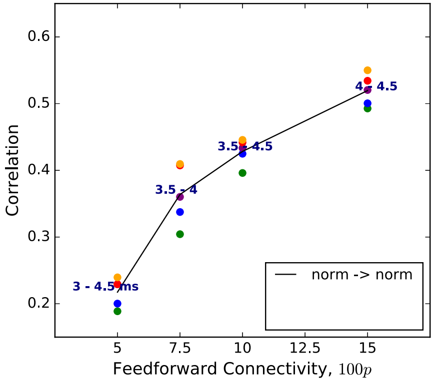
Existence of the optimal time delay

Consider now the correlation between $X(t)$ and $Y(t+d)$, where d is some number of ms



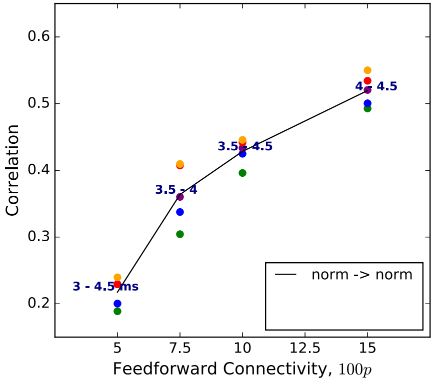
The optimal delay is **independent of initial condition** and network realization

Results



0.6
0.5
0.4
0.3
0.2
Correlation
5
7.5
10
12.5
15
Feedforward Connectivity, $100p$
3 - 4.5 ms
3.5 - 4
3.5 - 4.5
4 - 4.5
norm -> norm

Results



- Correlations are quite high (.2 - .6) considering the source only applied a small percentage of current to the target

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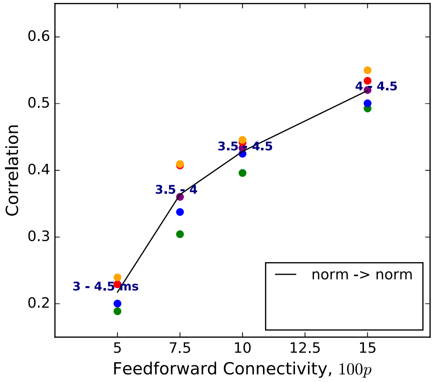

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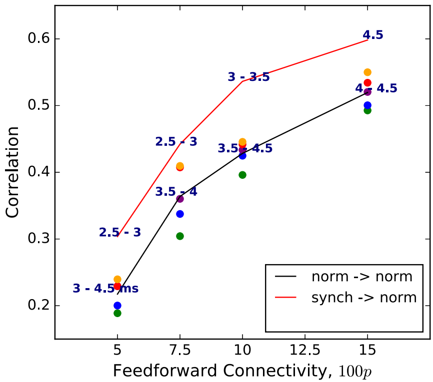

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3.5 - 4
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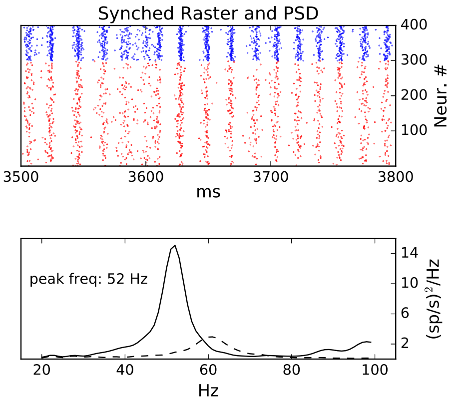
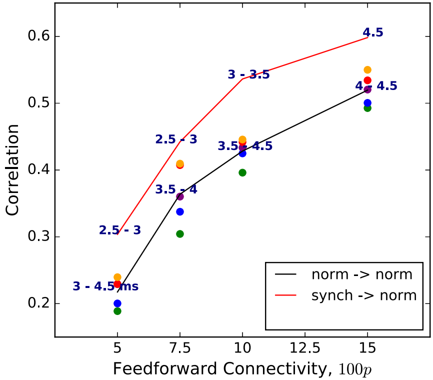
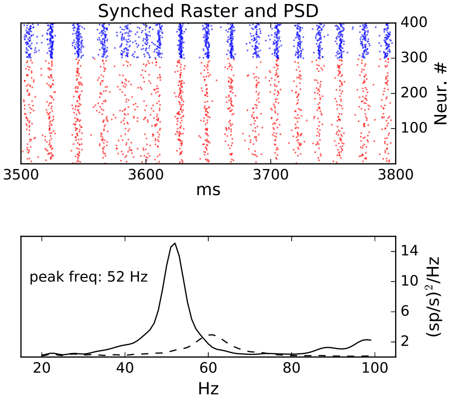
3 - 4.5 ms
norm -> norm
synch -> norm



Synched Raster and PSD
400
300
200
100
Neur. #
3500
3600
3700
3800
ms
peak freq: 52 Hz
14
10
6
2
$(sp/s)^2$/Hz
20
40
60
80
100
Hz

Results





- Correlations are higher when the source is more synchronized, regardless of differing peak frequencies

Our Goals

To recap

• CTC hypothesis: reliable phase relationships are needed for effective communication between neuronal groups; higher synchrony leads to better communication (Fries, 2005; 2015)

• Many gamma-rhythms in the brain are actually broad-band and irregular, making a reliable phase relationship between two of these rhythms near impossible - yet correlations are high

• **Question:** How might communication be possible when irregular rhythms are involved?

Outline

Rigid oscillations setup

Setup:

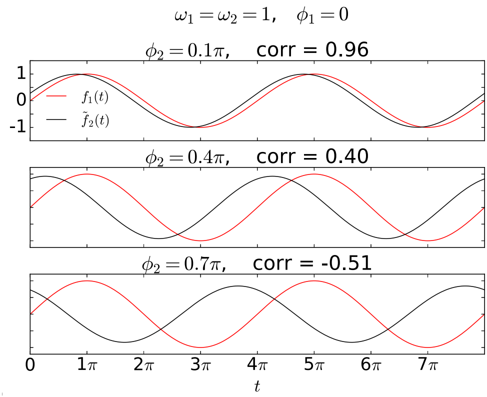
- The two systems: $f_i(t) = \sin(\omega_i t + \phi_i)$, $i = 1, 2$

- If p again represents the percentage of feedforward connectivity, the target's new system is written as $\tilde{f}_2(t) = pf_1(t) + (1-p)f_2(t)$

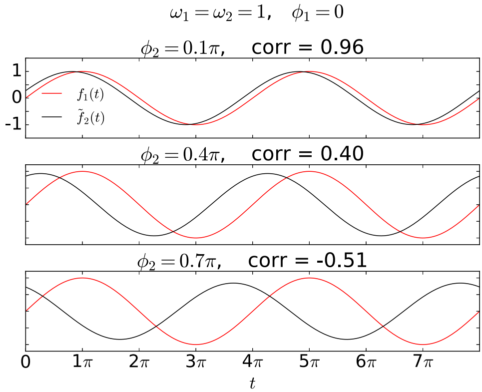
- Correlations between $f_1(t)$ and $\tilde{f}_2(t)$ are computed as before

- In the following, $p = 0.1$

Results

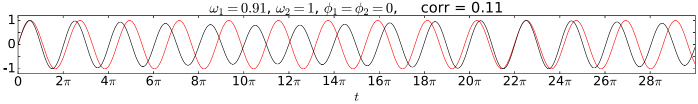

$\omega_1 = \omega_2 = 1, \quad \phi_1 = 0$
$\phi_2 = 0.1\pi$, corr = 0.96
1
0
-1
$f_1(t)$
$\tilde{f}_2(t)$
$\phi_2 = 0.4\pi$, corr = 0.40
$\phi_2 = 0.7\pi$, corr = -0.51
0
1π
2π
3π
4π
5π
6π
7π
t

Results

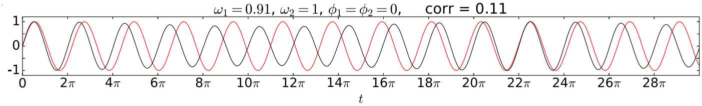


If frequencies match, correlations are quite high *when the initial phases match*; i.e., optimal delay depends on initial phase

Results


$\omega_1 = 0.91$, $\omega_2 = 1$, $\phi_1 = \phi_2 = 0$, corr = 0.11
1
0
-1
0
2π
4π
6π
8π
10π
12π
14π
16π
18π
20π
22π
24π
26π
28π
t

Results



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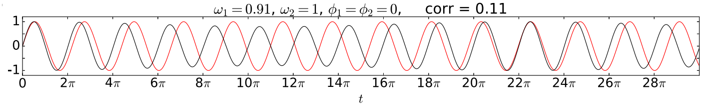


- In shorter time samples, correlations depend on initial phase

- If frequencies don't match, large time-correlations don't exceed ≈ 0.1 (time $\rightarrow \infty$ case)

Questions to discuss

Q1 How can a mere 7.5 percent connectivity cause the source and target to show such nontrivial alignment?

Q2 Why should there be a notion of intrinsic optimal delay that is independent of initial condition?

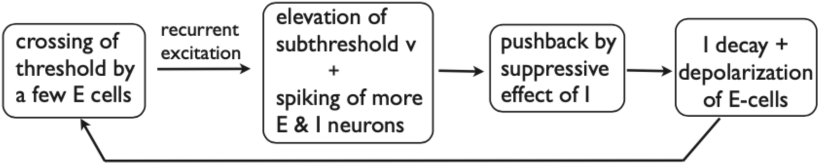
Q3 Why do more synchronized sources produce higher correlations, even though frequencies are incommensurate?

Outline

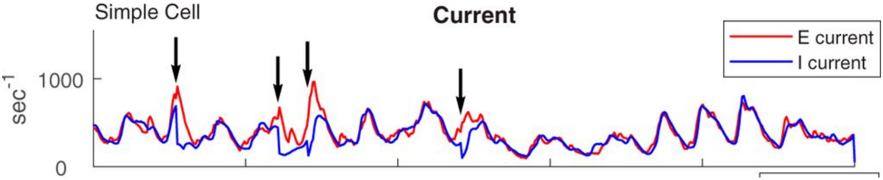
Gamma rhythms in single populations:

• Multiple firing events (MFEs) are instrumental in creating gamma-band rhythms (Rangan and Young 2013a,b)

• Recurrent-excitation-inhibition (REI) describes how MFEs and the gamma-band rhythm comes about (Chariker, Shapley, Young 2018):



Malleability of the gamma rhythm



Chariker, Shapley, and Young 2018

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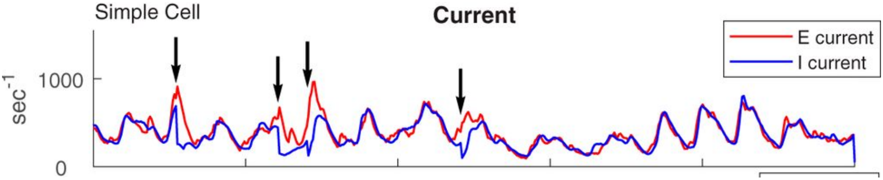

Chariker, Shapley, and Young 2018

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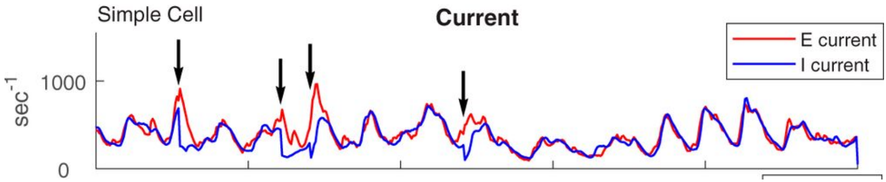

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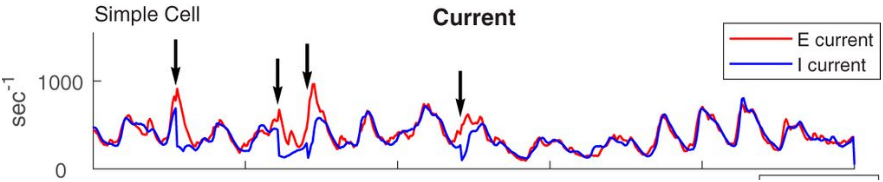
- Small amounts of excess E current are able to cause spikes (indicated by arrow)

Malleability of the gamma rhythm



Chariker, Shapley, and Young 2018

- E and I currents into a cell are tightly coupled, moment-by-moment
- Small amounts of excess E current are able to cause spikes (indicated by arrow)
- Gamma-rhythms are **malleable** to increased external input - concentrated input from the source population provides exactly this

Question 1:

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- The susceptibility to external input allows the target to align itself to the source's MFEs

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• The irregularity and degradation of gamma rhythms allow the target to realign itself with the source by allowing the system to lose memory of earlier phases

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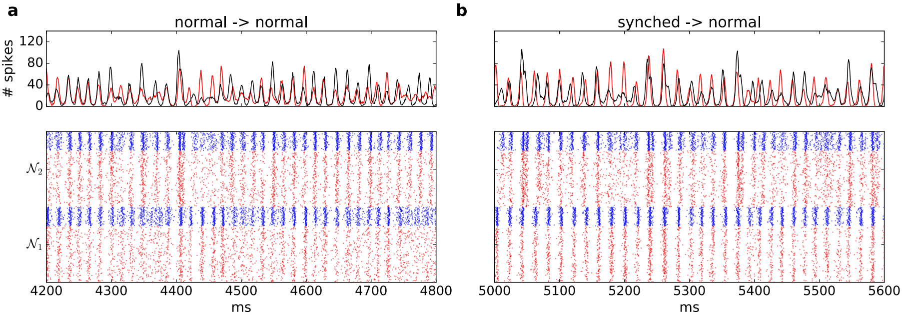
- The frequencies being different is an opposing force, that likely lowers correlations

Illustration



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• This is “a new paradigm in dynamical systems,” Lai-Sang Young. It is important to study behavior in between the extremes of chaotic and periodic, as are rhythms produced naturally by the brain