From neurons to circuits: linear estimation of local field potentials

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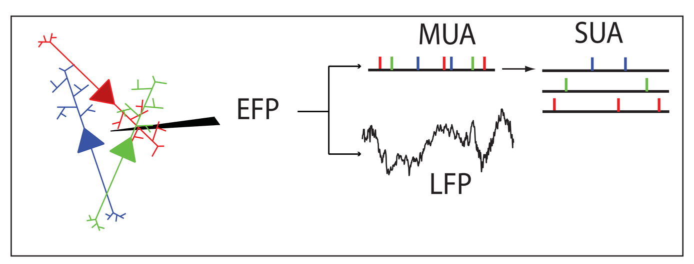
1. Motivation

Local field potentials (LFPs) represent the low frequency component (<100 Hz) of extracellular recordings. The LFPs are thought to reflect the activity of large numbers of neurons in a sphere of one to several millimeters around the recording electrode (Mitzdorf 1985). Current-source density analyses and simultaneous recordings of spikes and LFPs have suggested that LFPs are more strongly correlated with EPSPs, afterpotentials and dendritic spikes than with the output action potentials of the surrounding neurons (Haberly and Shepherd, 1973; Mitzdorf, 1985; Logothetis, 2002). This has led to the notion that LFPs better represent the input to and local processing within a given brain area as opposed to the output represented by action potentials. To further understand the relationship between LFPs and spikes, we asked whether it is possible to estimate the detailed timecourse of the LFPs based solely on the local spiking activity.

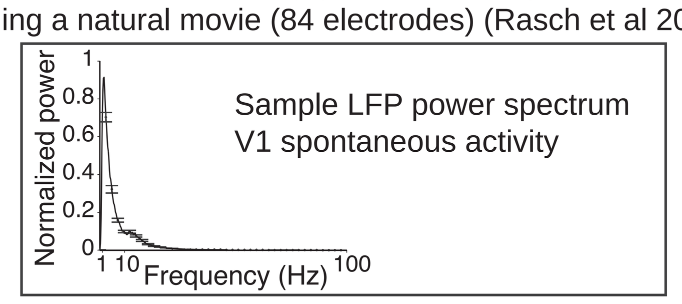


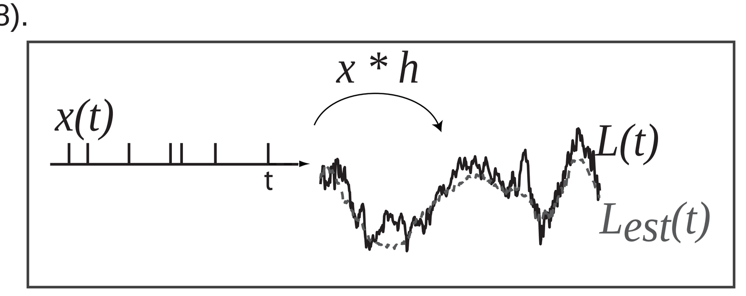
What can a single neuron say about the local circuit properties?

2. Methods

2.1 Experimental Data

1. Spontaneous activity (MUA and LFPs) recorded from LGN and V1 of 7 anesthesized monkeys (109 electrodes) (Rasch et al 2008).
2. "Stimulation" activity (MUA and LFPs) recorded from LGN and V1 of 6 anesthesized monkeys while showing a natural movie (84 electrodes) (Rasch et al 2008).





2.2 Linear estimation of time varying-signals from neuronal spike trains

$$x(t) = \sum_i \delta(t - t_i) - x_0$$

spike train, with the mean firing rate (x_0) subtracted.

$$L_{est}(t) = \int_0^T d\tau\, h(t-\tau)x(\tau).$$

A linear estimate of the LFP given the spike train can be obtained by convolving $x(t)$ with a filter $h(t)$

$$\varepsilon^2 = \frac{1}{T}\int_0^T dt[L(t) - L_{est}(t)]^2$$

where the filter is chosen to minimize the mean squared error between the LFP and its estimate [WK-filter, Wiener-Kolmogorov] (Bialek et al 1991, Kreiman et al 2000)

$$h(t) = \int_{-f_c}^{f_c} \frac{P_{Lx}(-f)}{P_{xx}(f)} e^{i2\pi ft} df$$

$P_{Lx}(f)$ is the cross-power spectrum
$P_{xx}(f)$ is the spike train power spectrum

$$\varepsilon^2 = 2(1-r)$$

$<L(t)=0>$ and $\sigma(L(t))=1$
r = correlation coefficient between $L(t)$ and $L_{est}(t)$
r = "Estimation accuracy"

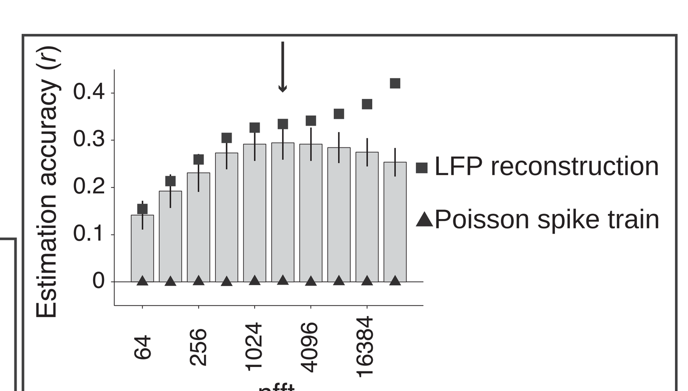
2.3 Different ways of computing *h* and *r*

1. "LFP reconstruction". The same data are used to compute *h* and *r*. ■
2. "Trial-specific" filters. Half of each "trial" is used to compute *h* and the other half to compute *r*.
3. "Electrode-specific" filters. Half of the trials are used to compute *h* and the other half to compute *r*. ← default
4. "Area-specific" filters. Half of the electrodes are used to compute *h* and the other half to compute *r*.

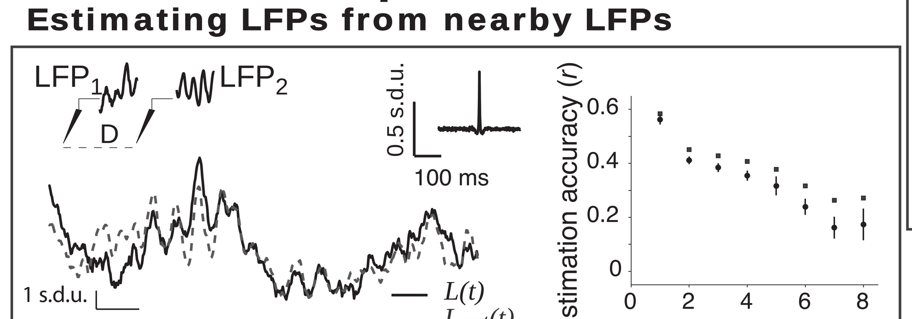
2.4 Null hypothesis for *r* ▲

Poisson spike trains with the same mean firing rate.
Recompute *h* and *r* for the Poisson spike trains.
Estimate distribution of *r* under the null hypothesis.

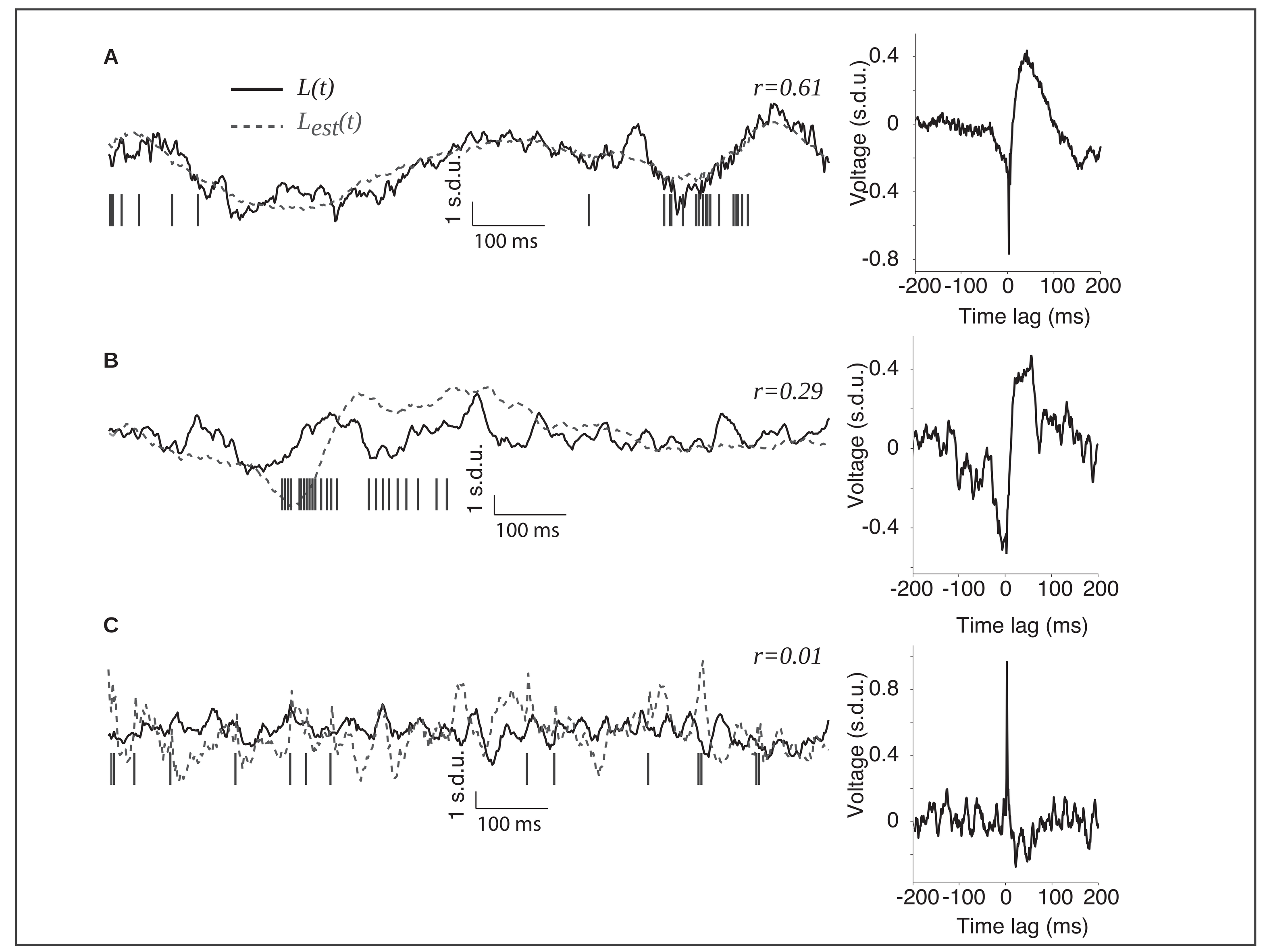
2.5 Technical point 1: nfft



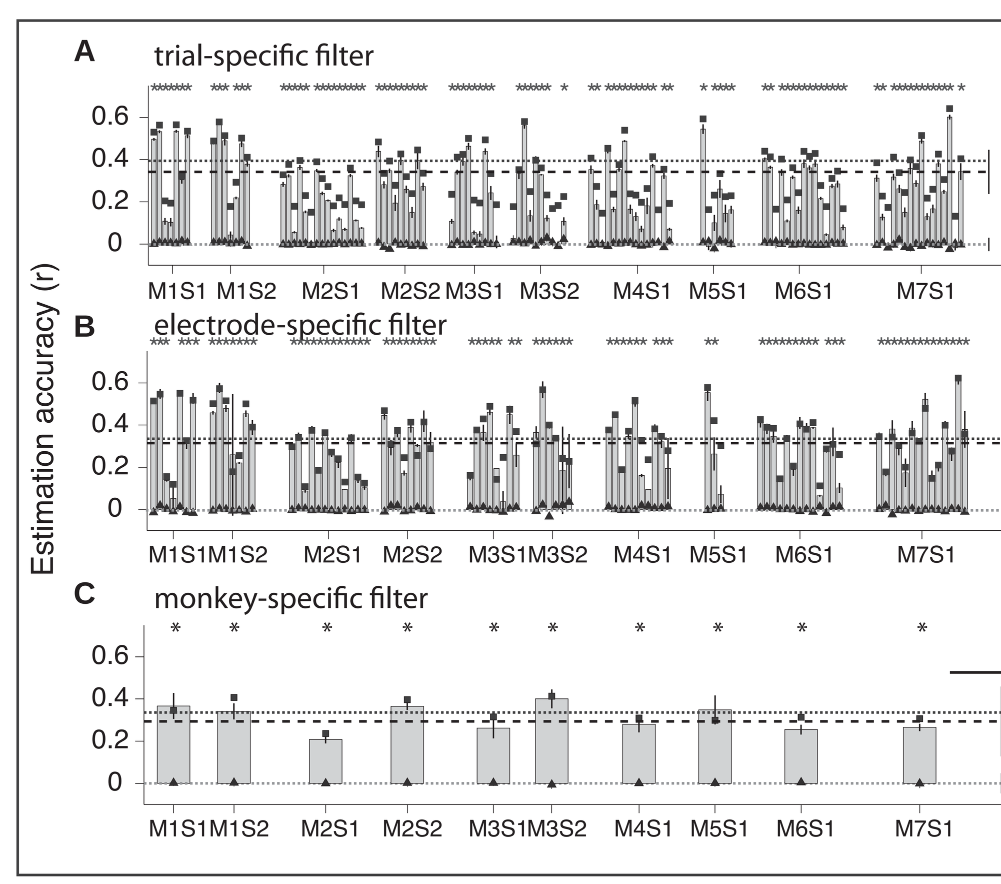
2.6 Technical point 2: Estimating LFPs from nearby LFPs



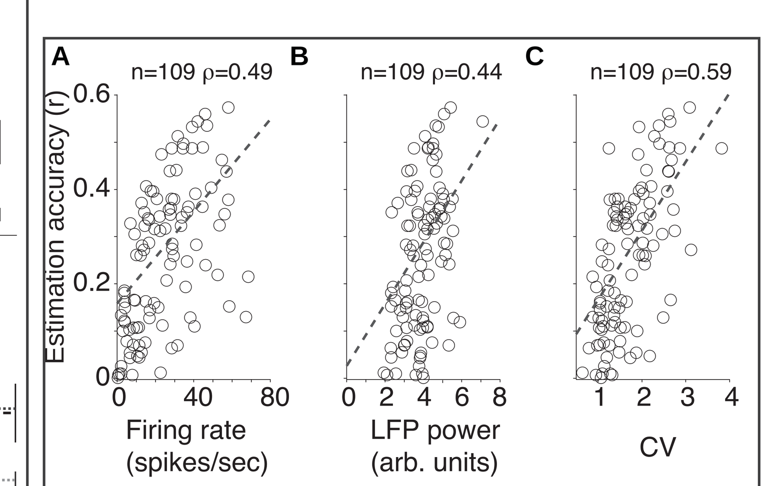
3. Linear estimation of LFPs from spike trains



4. LFP estimation across electrodes



5. Dependance on firing rate and power



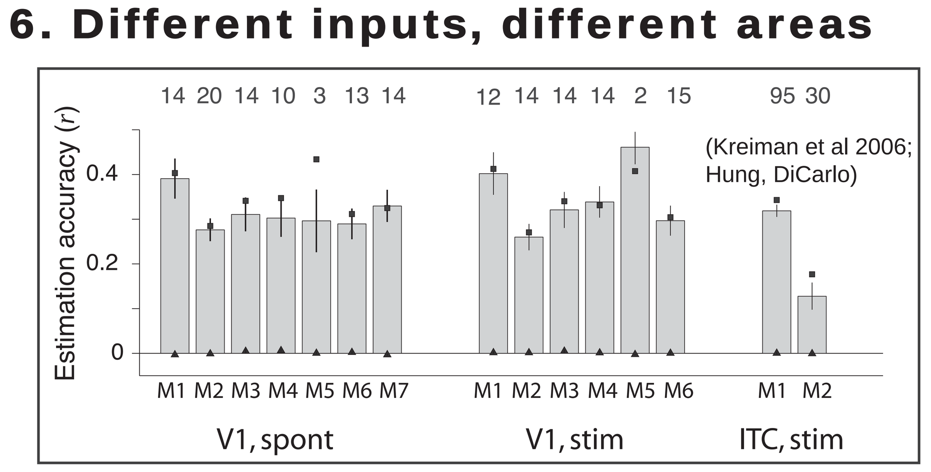
LFP estimation using multiple spike trains

$$\varepsilon^2 = \frac{1}{N}\sum_j^N \int_0^T dt \left[L_j(t) - \int_0^T h_{mean}(t-\tau)x_j(\tau)d\tau \right]^2$$

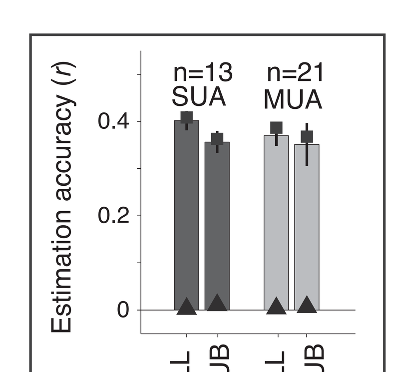
$$\hat{h}_{mean}(f) = \frac{\sum_j P_{Lx}(f)}{\sum_j P_{xx}(f)}$$

Given *N* spike trains, *h* minimizes the sum of the estimation errors.

6. Different inputs, different areas

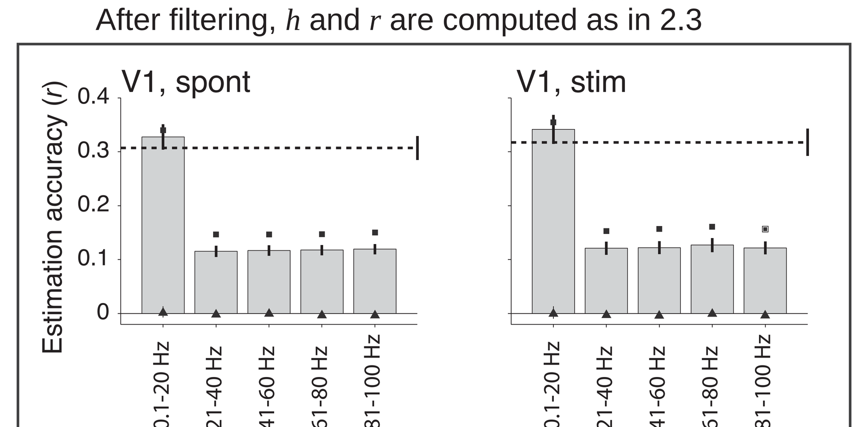


7. Technical point 3: SUA vs MUA

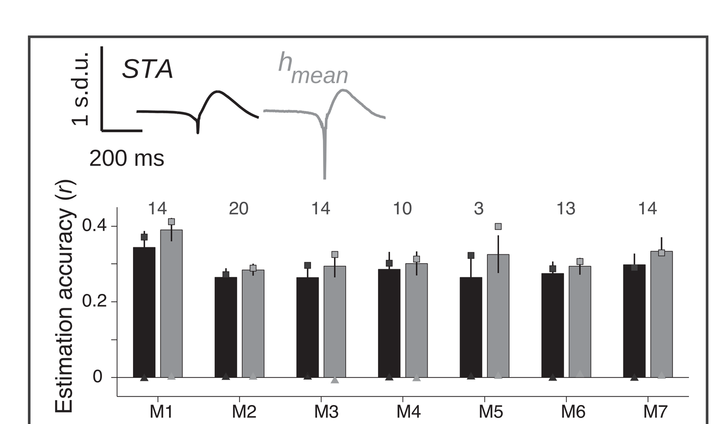


8. Frequency analysis

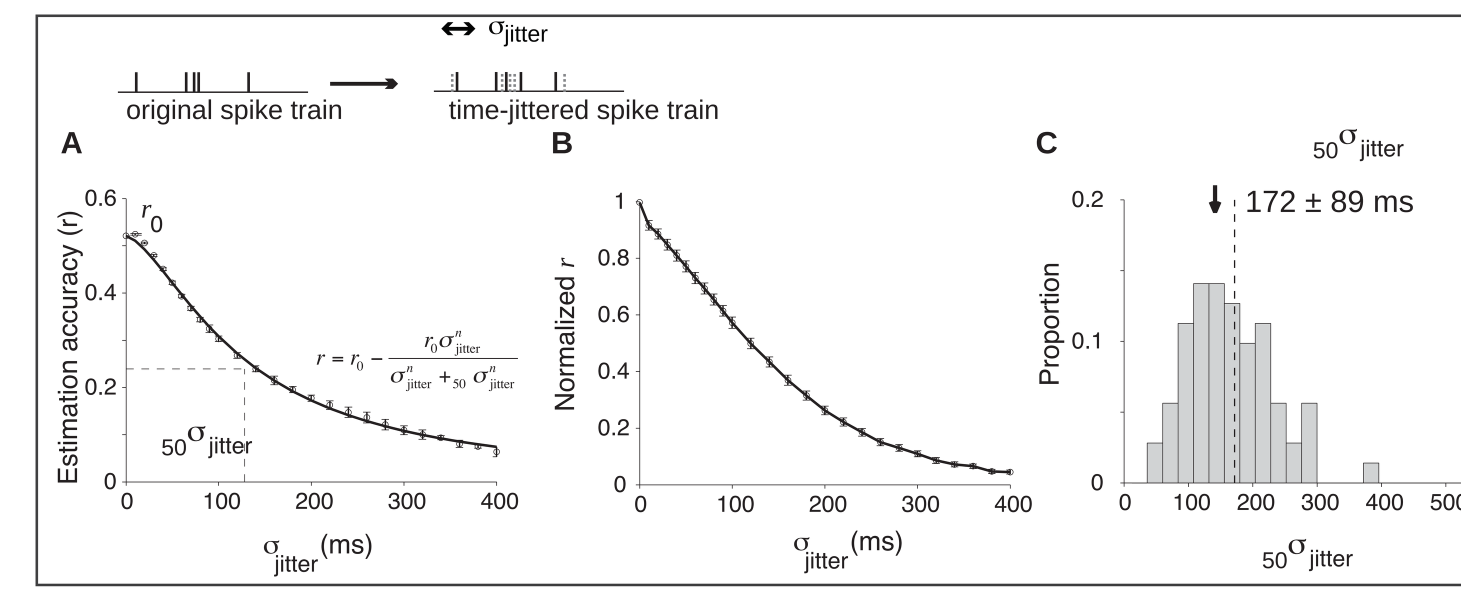
LFP filtered in five different frequency bands
After filtering, *h* and *r* are computed as in 2.3



9. Spike-triggered average

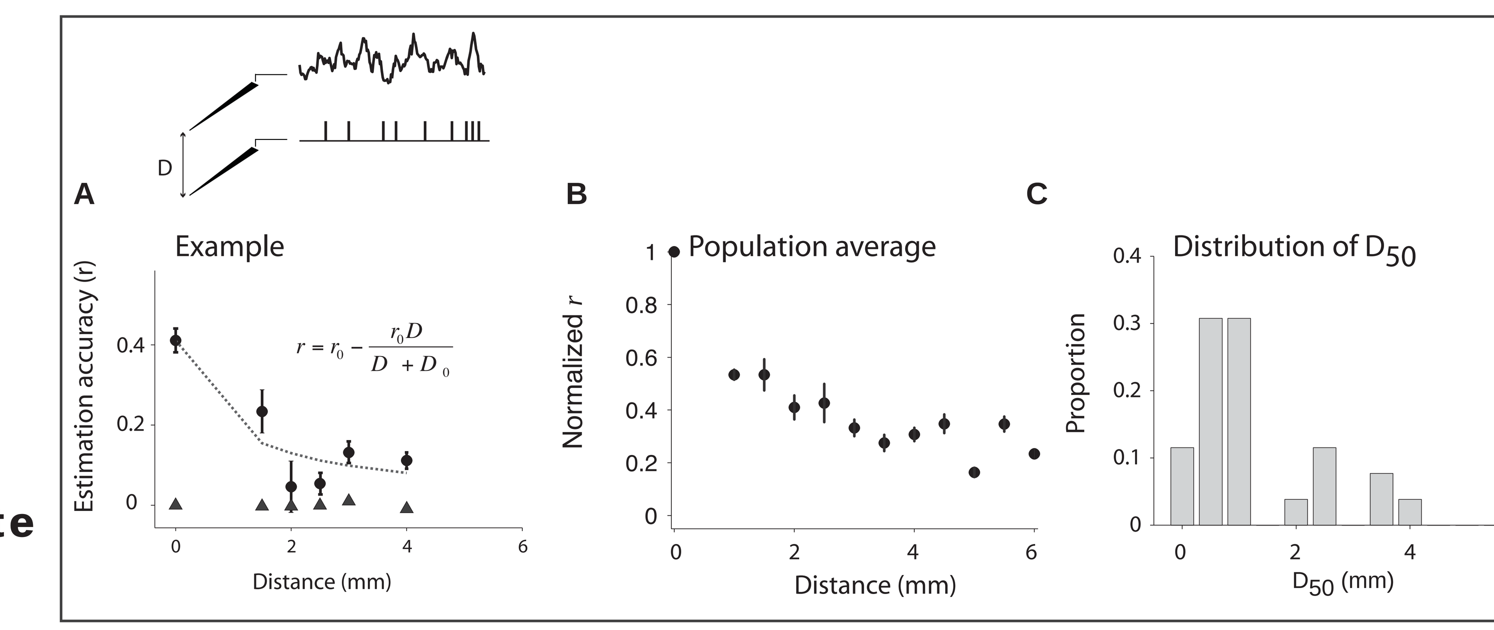


10. Robustness to spike time jitter



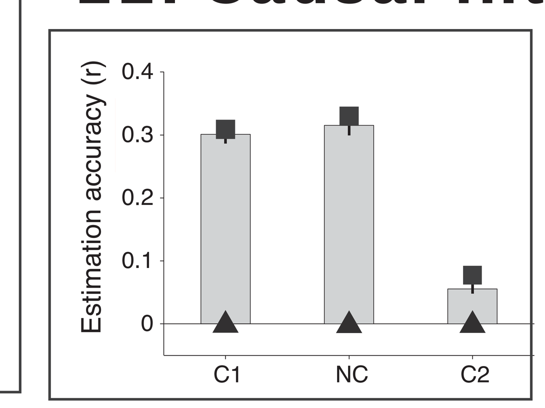
1. Created synthetic spike trains by randomly jittering spike times in the experimental spike trains
2. LFP estimated from synthetic spike trains as in 2.3

11. How local is local?



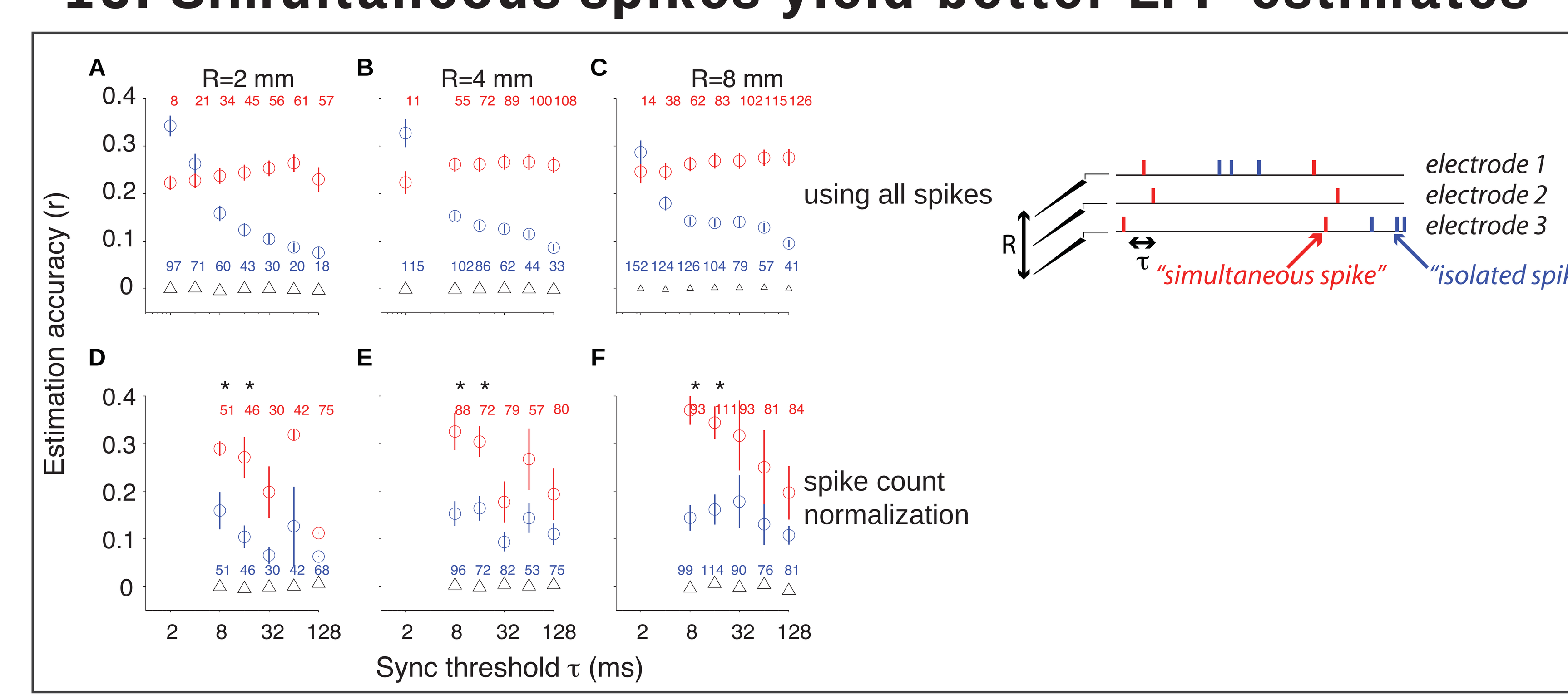
1. Here we use the spike train at one location to estimate the LFP recorded from a separate electrode located at a distance D from the spike train.
2. At D = 1 mm, the estimation accuracy drops about 50%.

12. Causal filters



NC = noncausal filter
C1 = filter that uses only the spikes after the LFP time $h_{C1}(\alpha)=0$ for $\alpha>0$
C2 = filter that uses only the spikes before the LFP time $h_{C2}(\alpha)=0$ for $\alpha<0$

13. Simultaneous spikes yield better LFP estimates



14. Summary

1. A linear filter operation on the activity of one or a few neurons can explain a significant fraction of the LFP time course.
2. The linear filter was similar across different neocortical regions and behavioral conditions.
3. The linear estimations had a spatial resolution of ~1 mm and a temporal resolution of ~150 ms.
4. A causal filter revealed an asymmetry between spikes preceding the LFP and spikes occuring after the LFP. The latter conveyed more information about the LFP time course.
5. Spikes occurring within ~10 ms of spikes from nearby neurons yielded better estimation accuracies than isolated spikes.