Neural activity as samples: evidence from visual and auditory cortex

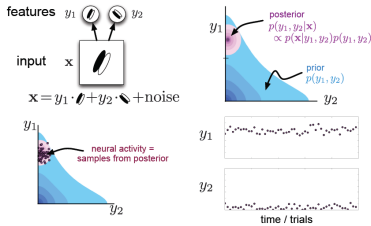
Pietro Berkes[1], **Stephen V. David**[2], **Jonathan Fritz**[2], **Máté Lengyel**[3], **Shihab A. Shamma**[2], **József Fiser**[1,4]

[1] Volen Center for Complex Systems, Brandeis University [2] Institute for Systems Research, University of Maryland [3] CBL, Dept Engineering, University of Cambridge [4] Dept of Psychology and Neuroscience Program, Brandeis University

Introduction

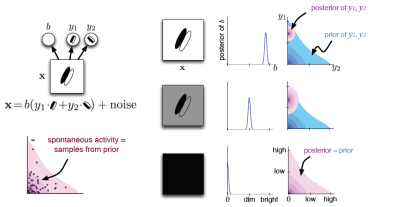
The central nervous system is believed to maintain internal models of its environment for perception, motor control, and decision making. For such internal models to be useful, they need to be adapted to the statistical properties of the environment. While the statistical optimality of internal models has been demonstrated in several behavioral studies, direct neural evidence for it has been lacking. We recently introduced a novel approach to quantify how much the responses of multi-neuron populations are adapted statistically to an ensemble of stimuli by comparing the statistical structure of spontaneous and stimulus-evoked activity (SA and EA) (Fiser *et al.*, TICS 2010). Using this approach, we have shown that the population activity of primary visual cortical (V1) cells of awake, freely-viewing ferrets becomes gradually adapted to the statistics of natural-scene film images from the time of eye-opening to maturity. Here we report novel data from the primary auditory cortex of awake ferrets showing a similar adaptation for natural sounds, suggesting the match between SA and EA may be a universal hallmark of representation and computation in sensory cortex.

Neural activity as samples



This accounts for several experimental predictions: high trial-by trial variability, noise correlations, neural responses to bistable percepts, and visual illusory contours.

Spontaneous activity as samples from the prior



- A number of natural images models have the property that the posterior distribution for zero contrast or zero luminance stimuli reduces to the prior:
  - models with contrast or luminance variables, e.g. Gaussian scale mixture models (Schwartz & Simoncelli, Nature Neurosci, 2001)
  - models with object identity variables, e.g. Berkes *et al.* (PLoS Comp Bio, 2009)
  - models with occlusion (Luecke et al., NIPS 2010)
- Consistent with experimental observations of luminance invariance in evoked activity (Rossi, Science 1996) and human psychophysics (Adelson, Science 1993).

Predictions

$$\mathrm{P}_\theta(\mathbf{y}) \xrightarrow{\text{learning from } \mathrm{P}_{\text{data}}(\mathbf{x})} \int \mathrm{P}_\theta(\mathbf{y}|\mathbf{x})\,\mathrm{P}_{\text{data}}(\mathbf{x})\,d\mathbf{x}$$

$$\mathrm{P}_{\text{SA}}(\mathbf{y}) \longrightarrow \langle \mathrm{P}_{\text{EA}}(\mathbf{y}|\mathbf{x}) \rangle_{\mathrm{P}_{\text{data}}(\mathbf{x})}$$

spontaneous activity — evoked activity — natural scenes

The distribution of spontaneous activity and that of evoked activity, averaged over natural stimuli, will become increasingly similar with accumulating visual experience

1. **Probability of visiting a given neural activity pattern should be identical**
2. **Probability of transitioning between patterns should also match**
3. **Similarity should be specific to natural scene ensembles, not to other stimulus ensembles**

Data analysis

Visual data

awake ferrets
multi-unit recordings from layers 2-3 in V1
aged P29 (eye opening) – P151 (mature visual system)
16 implanted electrodes, with 200 µm spacing
analysis performed on 16 channels

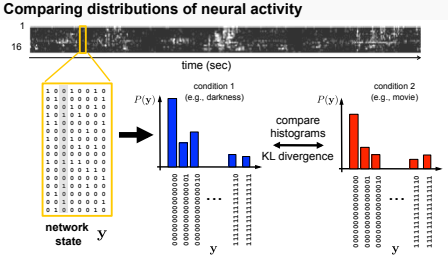
spontaneous activity in darkness — drifting gratings
movie evoked activity — dynamic block noise

Auditory data

awake ferrets
single-unit recordings from A1
aged 1-3 years
1-4 electrodes, recording 4-7 single units
analysis performed on all combinations of 4 units

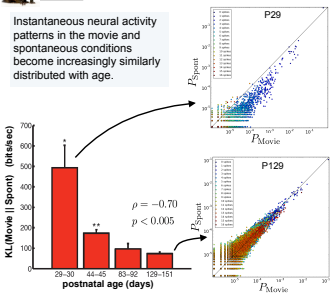
spontaneous activity in silence — white noise (0-20 kHz)
stream of continuous speech

Comparing distributions of neural activity

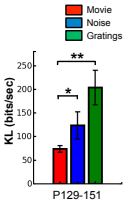


Results from visual cortex (V1)

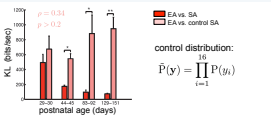
Instantaneous neural activity patterns in the movie and spontaneous conditions become increasingly similarly distributed with age.



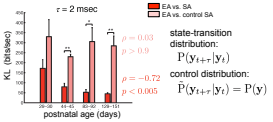
By adulthood, spontaneous activity is significantly more similar to movie-evoked activity than to noise- or gratings-evoked activity.



The match between EA and SA is due to a match of their correlational structure.

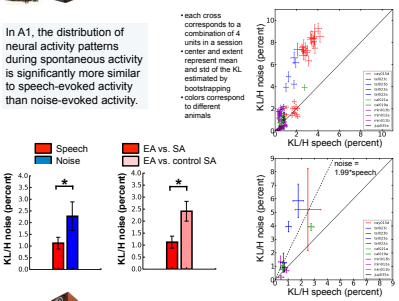


Temporal correlations are also increasingly matched between subsequent neural activity patterns.

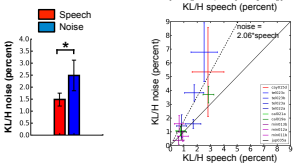


Results from auditory cortex (A1)

In A1, the distribution of neural activity patterns during spontaneous activity is significantly more similar to speech-evoked activity than noise-evoked activity.

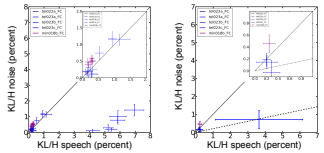


The distribution of transitions between neural states in spontaneous activity is also closer to speech evoked activity than noise evoked activity.



Results from prefrontal cortex (PFC)

Preliminary results show that SA and EA do not match in PFC. however, it is unclear at present whether this is due to a different coding strategy in PFC, or to undersampling of the representation in PFC, and thus to a poor estimation of the integral over the posterior. The data here serves as a control.



Conclusions

- The distribution of instantaneous neural activity patterns, and the distributions of pattern transitions collected during spontaneous activity closely match those collected during activity evoked by stimuli with natural statistics.
- This match is significantly better for natural than for artificial stimuli, suggesting that the sensory cortex is optimally adapted to process natural input.
- The similarity between the two distributions can be found in both the visual and the auditory cortex, suggesting that it might be a hallmark of a universal computational strategy in sensory cortex.
- The results support the hypothesis that the sensory cortex represents the incoming stimuli and their uncertainty using a probabilistic, sampling-based representation.

Supported by the Swartz foundation.