Behaviorally Relevant Spatio-Temporal Spike Patterns in Parallel Spike Trains

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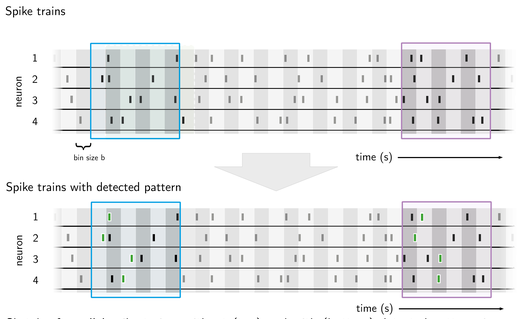
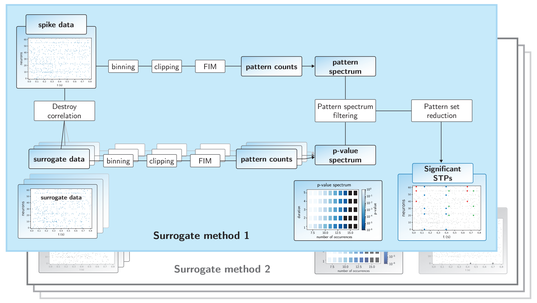
Context

The Hebbian hypothesis [1, 2, 3] states that assemblies of co-active neurons act as information processing units. We hypothesize that assembly activity is expressed by the occurrence of precise spatio-temporal patterns (STPs) of spikes - with precise (5ms) temporal delays between the spikes - emitted by neurons that presumably are members of an assembly.



Sketch of parallel spike trains, without (top) and with (bottom) detected pattern, in green. Figure adapted from [10].

Methods



Workflow of the SPADE analysis. The workflow of SPADE shows the sequence of analysis steps of the original data until the STPs are returned.

We developed a method, called SPADE (Spatio-temporal PAttern Detection and Evaluation) [4, 6, 10], that detects significant STPs in massively parallel spike trains.
SPADE involves three steps:

1. it identifies repeating STPs using Frequent Itemset Mining [11];
2. it evaluates the detected patterns for significance through surrogates (trial-shifting);
3. it removes the false positive patterns that are a by-product of true patterns and the background activity.

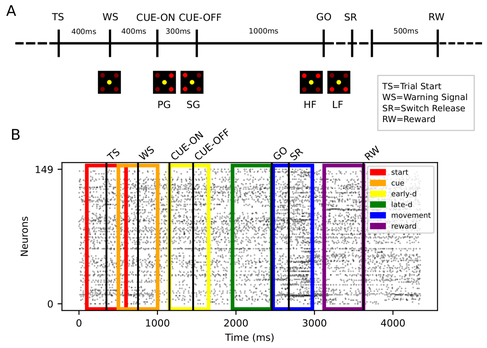
Experiment

Characteristics of the data set [7, 9] analyzed by the method:

- **pre-/motor cortex** of two **macaque monkeys**
- activity recorded by a **10x10 Utah multielectrode array**
- monkeys are performing a **reach-to-grasp task**
- from **56 to 167** neurons recorded in parallel

Task:

- Reach an object and grasp it with side grip (SG) or precision grip (PG)
- Pull the object using high force (HF) or low force (LF) and hold it in a fixed position for 500ms
- Visual cues inform the animal about the grip and force



Scheme of the experimental paradigm.

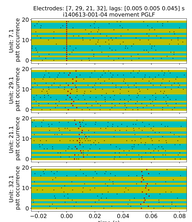
Results: Spatio-Temporal Patterns in experimental data

Spatio-temporal pattern analysis:

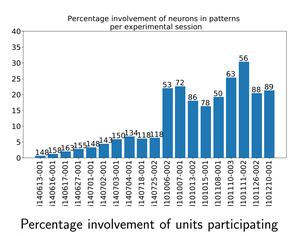
- 20 analyzed sessions (10 per monkey)
- 4 trial types (SGHF, SGLF, PGHF, PGLF)
- $\sim$ 30 trials per trial type per session
- We detect significant STPs for the 24 combinations of 6 epochs and 4 trial types (as previously done for synchronous patterns in [8])
- SPADE parameters:
  - binsize $= 5$ms
  - maximal pattern duration $= 60ms$
  - $\alpha = 0.05$

Data preprocessing:

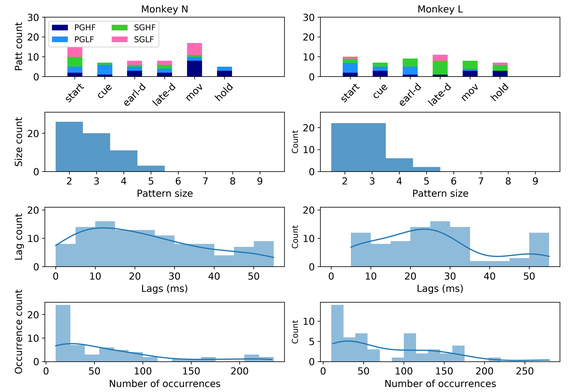
- hypersynchronous artefacts are removed
- Each trial segmented into 6 task-related epochs (500ms long) concatenated for each trial type and epoch



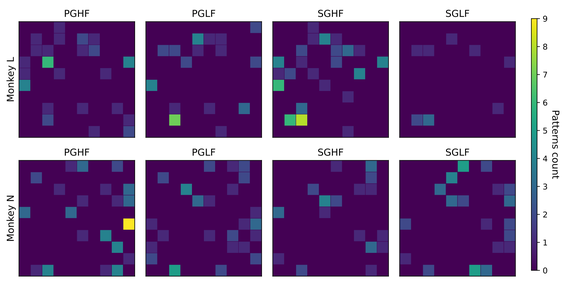
Raster plot of one specific pattern of size 4 detected during trial type PGLF and movement epoch for monkey N. Pattern occurrences are aligned to the first spike of the pattern. Spikes belonging to the pattern are marked in red. Different colored bands represent the pattern occurrence within one trial. Trials are ordered along the y-axis.



Percentage involvement of units participating in patterns over the total number of units analyzed per session. Bar height represents the percentage, number on top of bar represents the total number of units per session, after spike sorting, data cleaning and preprocessing. Sessions named with code i14[...] and l10[...] indicate monkeys N and L, respectively.



Pattern statistics for both monkeys (columns). Panel A. Histogram of pattern count in all behavioral epochs. Panel B, C Distribution of pattern size and pattern lags during the movement epoch.



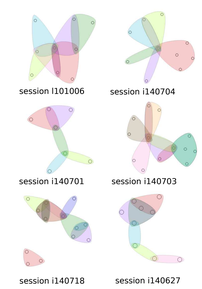
Count of number of patterns for each electrode in the Utah Array, for each monkey (rows) and trial type (columns).

Conclusions

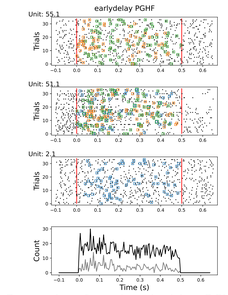
We analyzed 20 sessions of experimental data from macaque pre-/motor cortex with SPADE and detected numerous significant STPs occurring in relation to behavior. We find that STPs occur in all phases of the behavior, and, within a single session, are specific to a behavioral condition, suggesting that different assemblies are activated for each specific behavioral context. Also, we show that a few individual neurons appear as hubs, as they are involved in several patterns. We also find that pattern neurons are not located within a small region, but distributed across the entire cortical surface covered by the Utah array.

Results of the analysis:

- Pattern statistics across session:
  - Significant patterns are detected across all phases of the behavior (trial types and trial epochs)
  - Significant patterns are of different sizes (2-6), exhibit a variety of lags and number of occurrences (10 to 280)
- Pattern characteristics within sessions:
  - within a given session, some neurons can participate to multiple patterns (hubs)
  - patterns are distributed across the whole electrode array for both monkeys, differently distributed for the two grip types (PG/SG)
  - percentage involvement of neurons depends on the monkey, and can go up to 30%
  - patterns are different in composition depending on the behavioral context



Hypergraph representation of neurons involved in patterns within one experimental session. Each dot represents a unit. Each color groups together units involved in a single STP.



Raster plot of epoch early delay, PGHF, monkey N, for three units where STPs are detected. Three STPs are detected across trials (spikes colored in green, orange, blue). Bottom panel, in black and grey, respectively, PSTHs of all spikes and pattern spikes of the three units.

References

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