**INTRODUCTION:** Why use a metric space method to estimate information?

For neural systems, the "transmitted information" (Shannon) is the extent to which observation of a neural response removes the uncertainty about the stimulus. Straightforward estimation of transmitted information requires experimental estimation of the probabilities of all joint stimulus-response events. The difficulty with this approach is that, in principle, each different spike train configuration constitutes a different "response." Thus, the number of possible responses can dominate the estimates of information. When the set of possible responses is severely undersampled, biases in the "responses" may be astronomically large, especially for multineuronal activity.

**METRIC SPACE METHOD FOR SINGLE-NEURON RESPONSES**

A single parameter, $q$, expresses the sensitivity of the distance to the timing of individual spikes. The distance $D(A,B)$ between two spike trains $A$ and $B$ is the total cost of any sequence of allowed transformations from $A$ to $B$. The allowed transformations consist of:

1. **Delete a spike:** cost=$1$
2. **Shift a spike in time:** cost=$T$

With this notion of distance, spike trains are similar only if spikes occur at similar times (i.e., within $1/T$ sec). A spike count code corresponds to $q=0$ (i.e., timing is irrelevant).

Efficient calculation of distances can be achieved using the following steps:

1. **The METRIC SPACE ALGORITHM: AN OVERVIEW**
   - For each metric (notion of distance between spike trains):
     - Calculate pairwise distances between all responses to all stimuli.
     - Construct a response space from the pairwise distances.
     - Quantify degree of clustering via the "confusion matrix.
   - Repeat the above for each metric.

2. **Step 1**
   - **Delete** a spike from $A$: $D(A,B) = D(A',B) + 1$, where $A'$ is the response after deletion.
   - **Shift** a spike in time: $D(A,B) = D(A,t,B) + T$, where $A(t)$ is the response with the $t$th spike shifted.
   - **Insert** a spike: cost=1

3. **Step 2**
   - **Shift** a spike in time: $D(A,B) = D(A(t'),B) + T$, where $A(t')$ is the response with the $t$th spike shifted.

4. **Step 3**
   - Weak clustering
   - Strong clustering

**A 2-PARAMETER FAMILY OF CODES AND METRICS**

Information ($I$) = row entropy + column entropy - table entropy

**METRIC SPACE METHOD FOR MULTI-NEURON RESPONSES**

Several neurons' joint response is considered to be a single sequence of labeled events, with labeling neuron of origin (shown below as color). The distance between two multineuronal responses, $A$ and $B$, is defined similarly to the single-neuron case but a second parameter, $k$, is added that expresses the sensitivity of the distance $D_k(A,B)$ to the neuron of origin of spikes. The new transformation is:

- **Change spike label (neuron of origin):** cost=$k$

At the two extremes:

- $k=0$, neuron of origin is ignored ("summed population code").
- $k=2$, neuron of origin is fully considered ("labeled line code").

**ANALYSIS OF SPATIAL PHASE RESPONSES IN MACAQUE VISUAL CORTEX**

Responses of three neurons (A, B, and C) to a random set of spatial frequencies are shown in the first row of the table. Each neuron's response is represented by a line with a different color. The last row shows the labeled line code, which is calculated by adding the individual responses of each neuron.

**REFERENCES**


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