

Embedding Analysis of Neuron Responses under Various Stimuli in Vision Systems

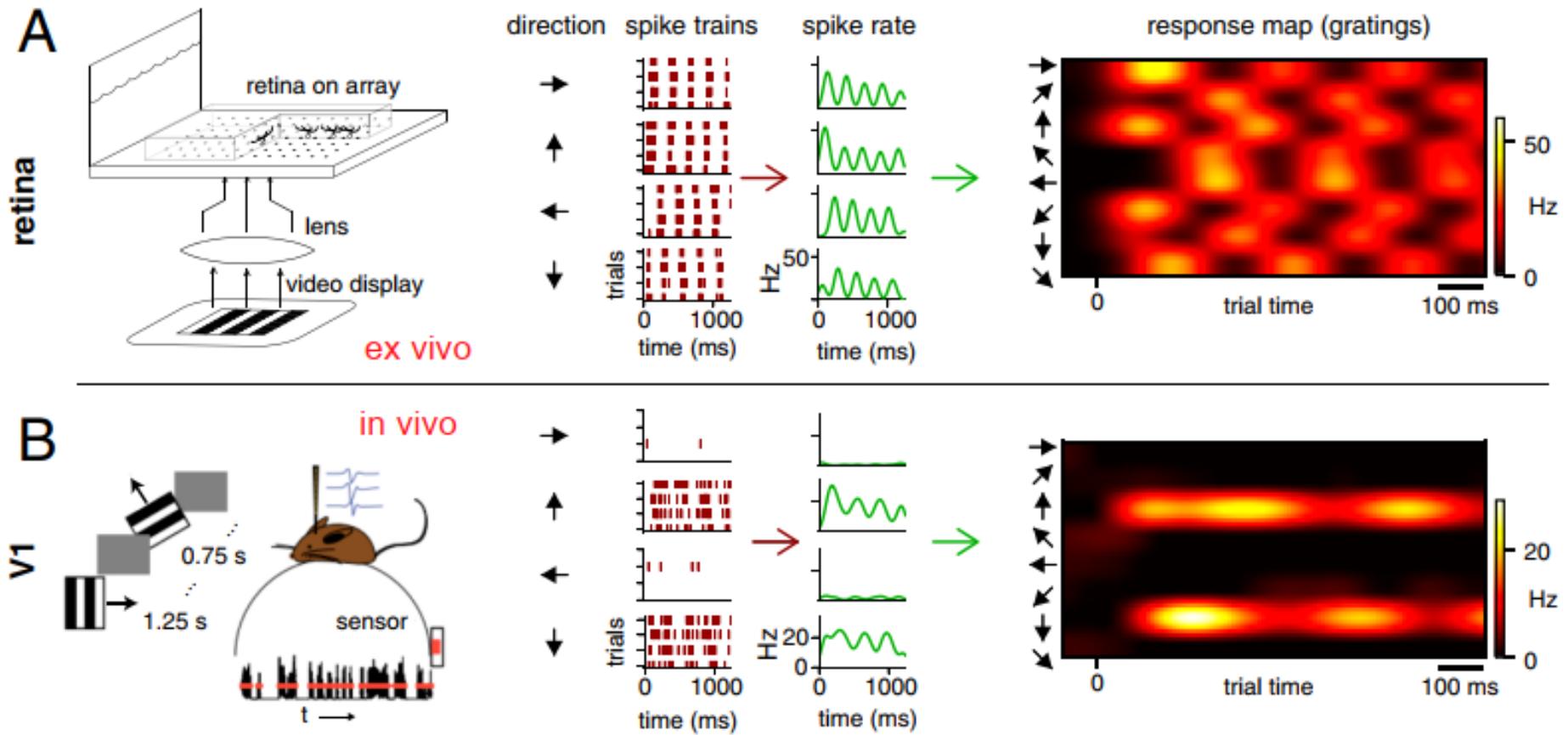
Huimiao Chen
June 20, 2025

Background

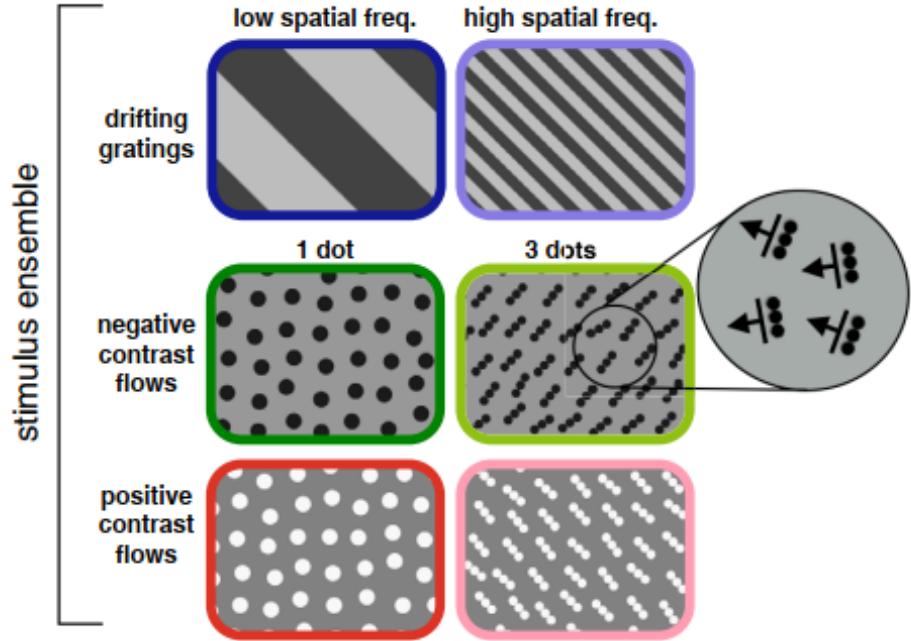
Retinal and cortical population encodings differ

Use multi-electrode array (MEA) recordings.

Data: Spike trains.



Retinal and cortical population encodings differ

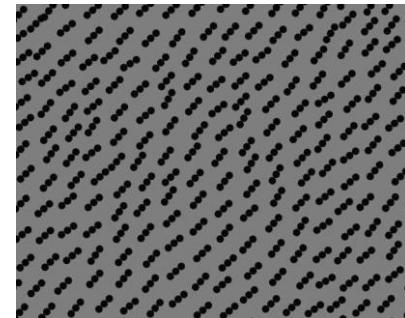


Stimuli and Data

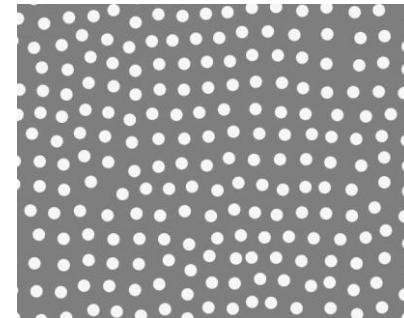
dir: 0, 45, 90, 135, 180, 225, 270

Low Freq Gratings
High Freq Gratings
Neg 1-dot Flows
Neg 3-dot Flows
Pos 1-dot Flows
Pos 3-dot Flows

In total, $6 * 8 = 48$ stimuli



neg_3flows_315

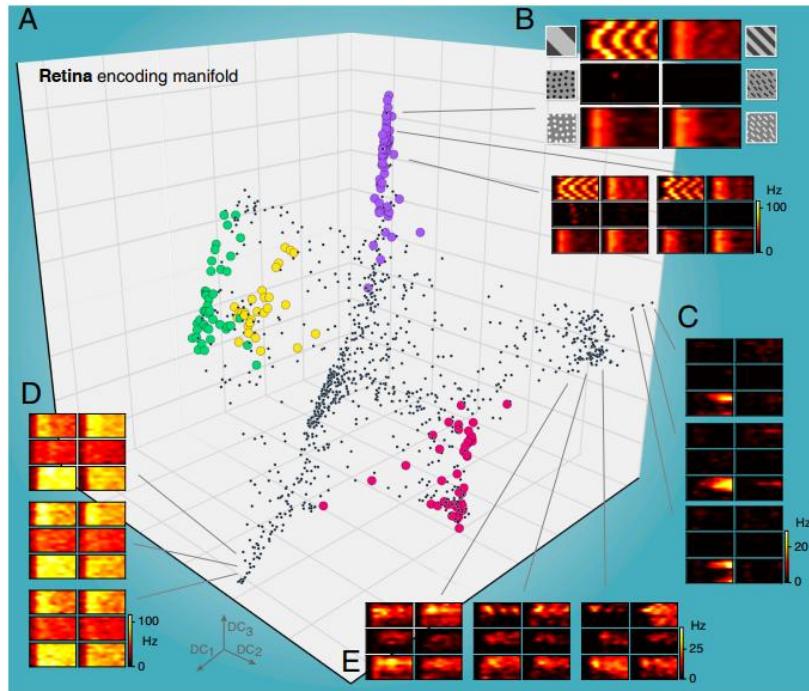


pos_1flows_225



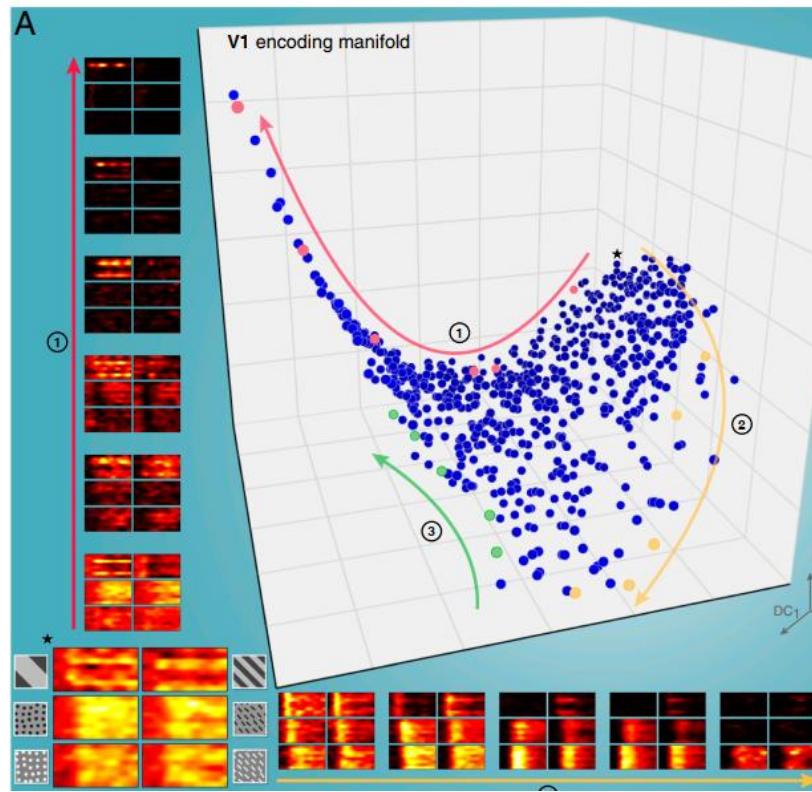
gratings_lf_45

Retina: Discrete clusters; V1: Continuous encoding

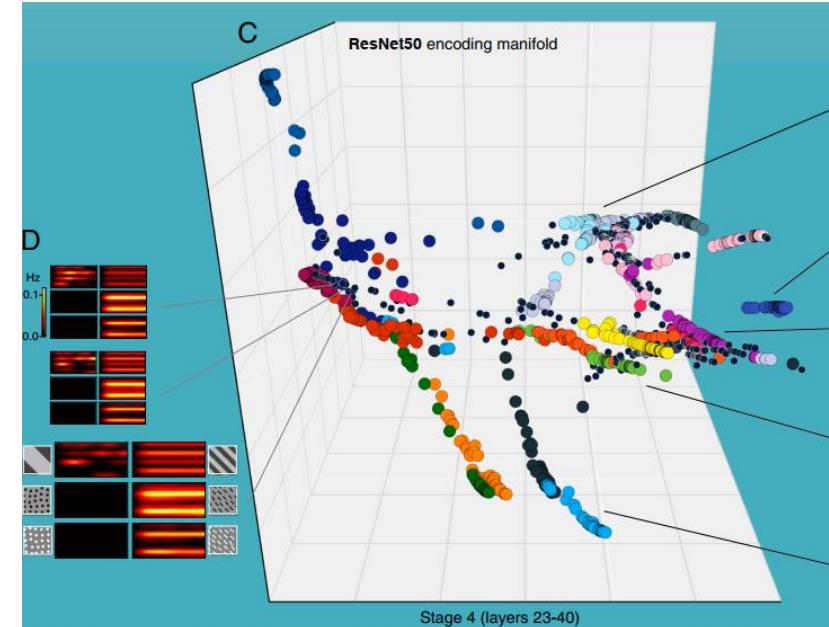


Retinal neurons' encoding manifold showing **discrete clusters**: each cluster corresponding to a specific functional type.

V1 neurons' encoding manifold showing a **continuous distribution**: feature selectivity and response dynamics varying smoothly across the manifold.

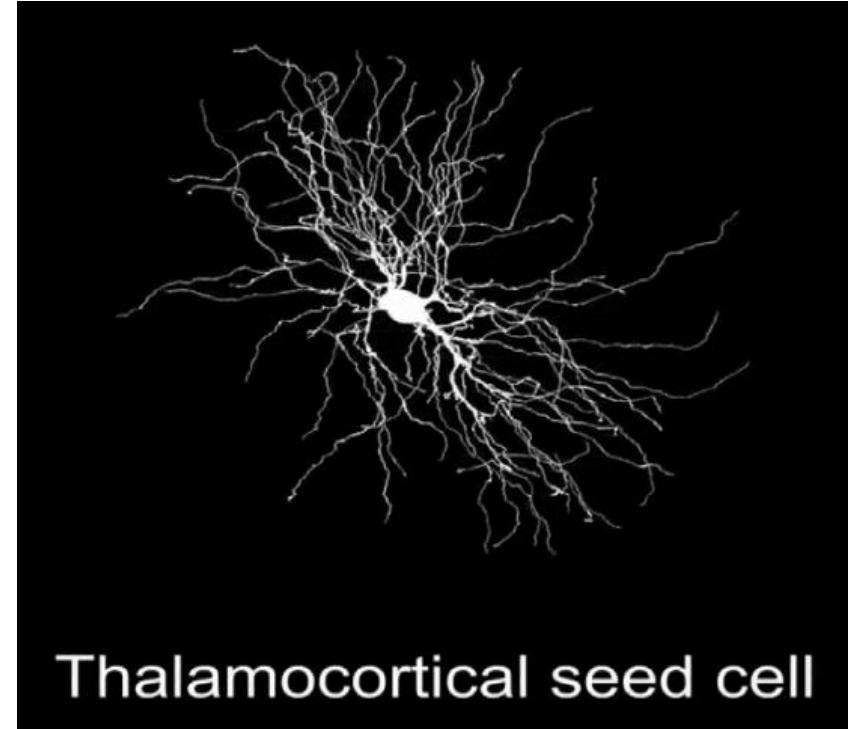
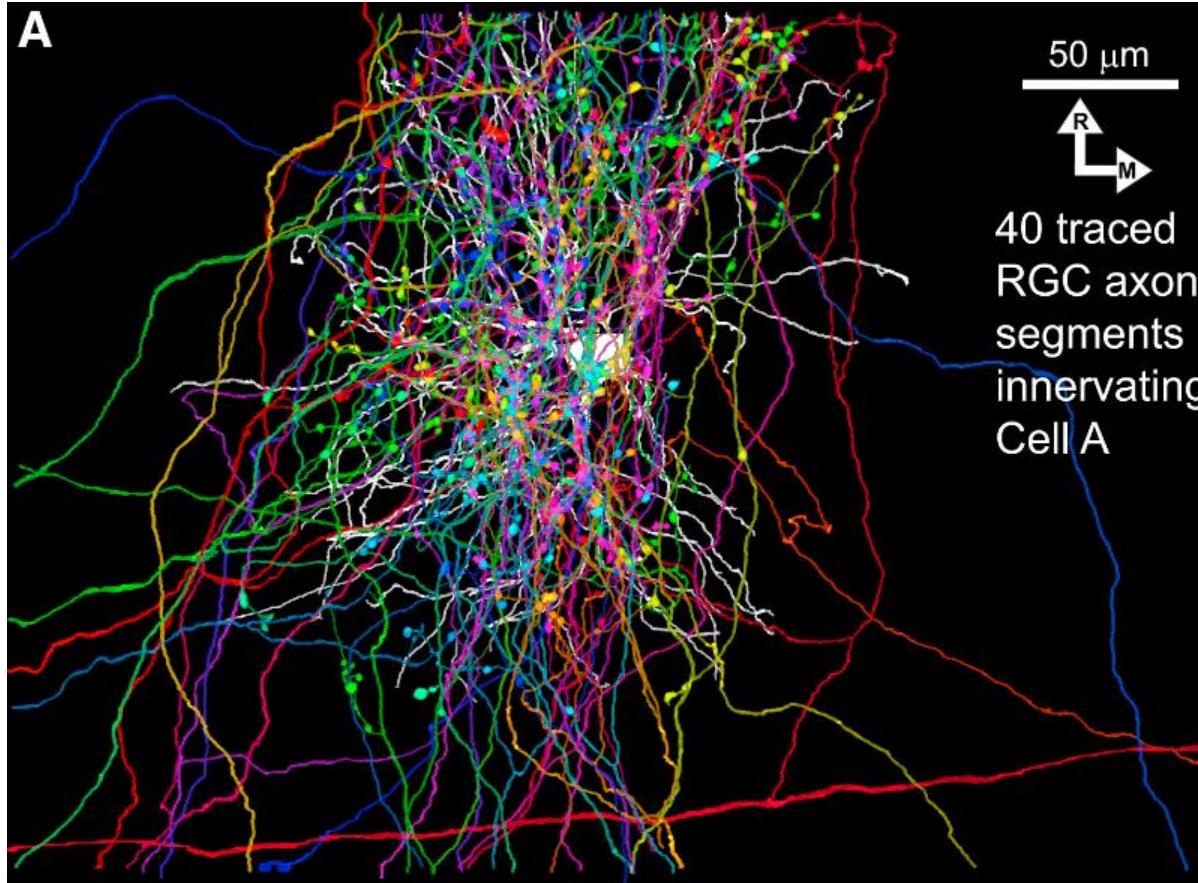


The encoding manifold was constructed using non-negative tensor factorization (NMF) and diffusion maps, showing how neurons are organized in stimulus–response space.



ResNet50 (CNN) network's encoding manifold showing **strong clustering**: more discrete than the retina, and unlike V1.

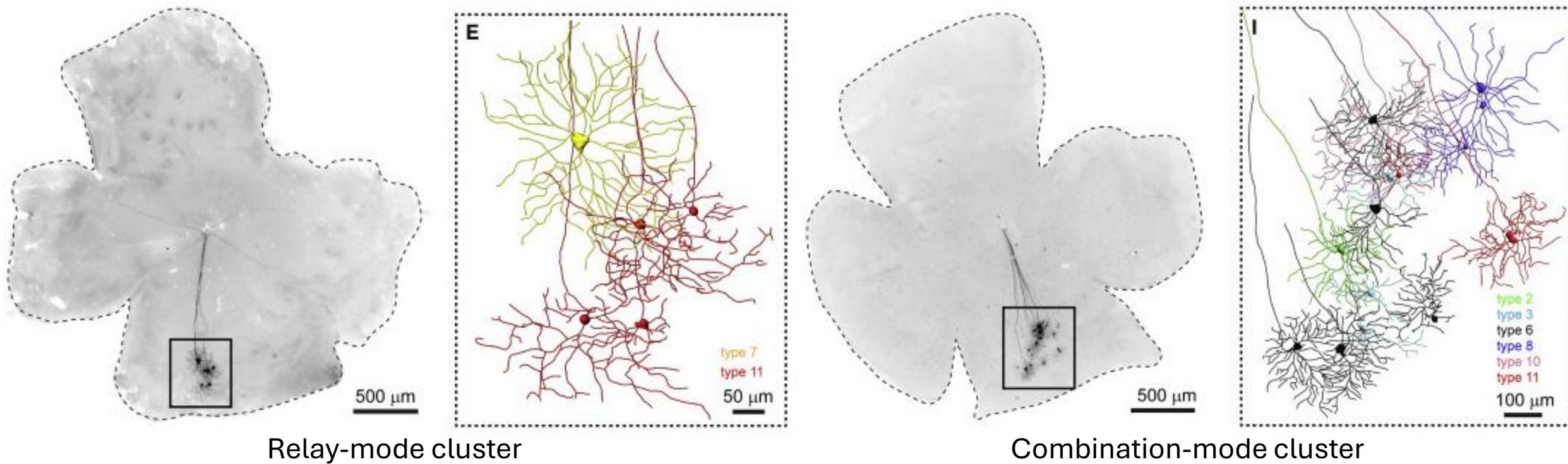
Tens of RGCs can converge to a single dLGN neuron



A single dLGN neuron (white) receives input from ~40 RGC axon segments (different colors).

Retrograde tracing shows inputs from multiple morphologically distinct RGC types.

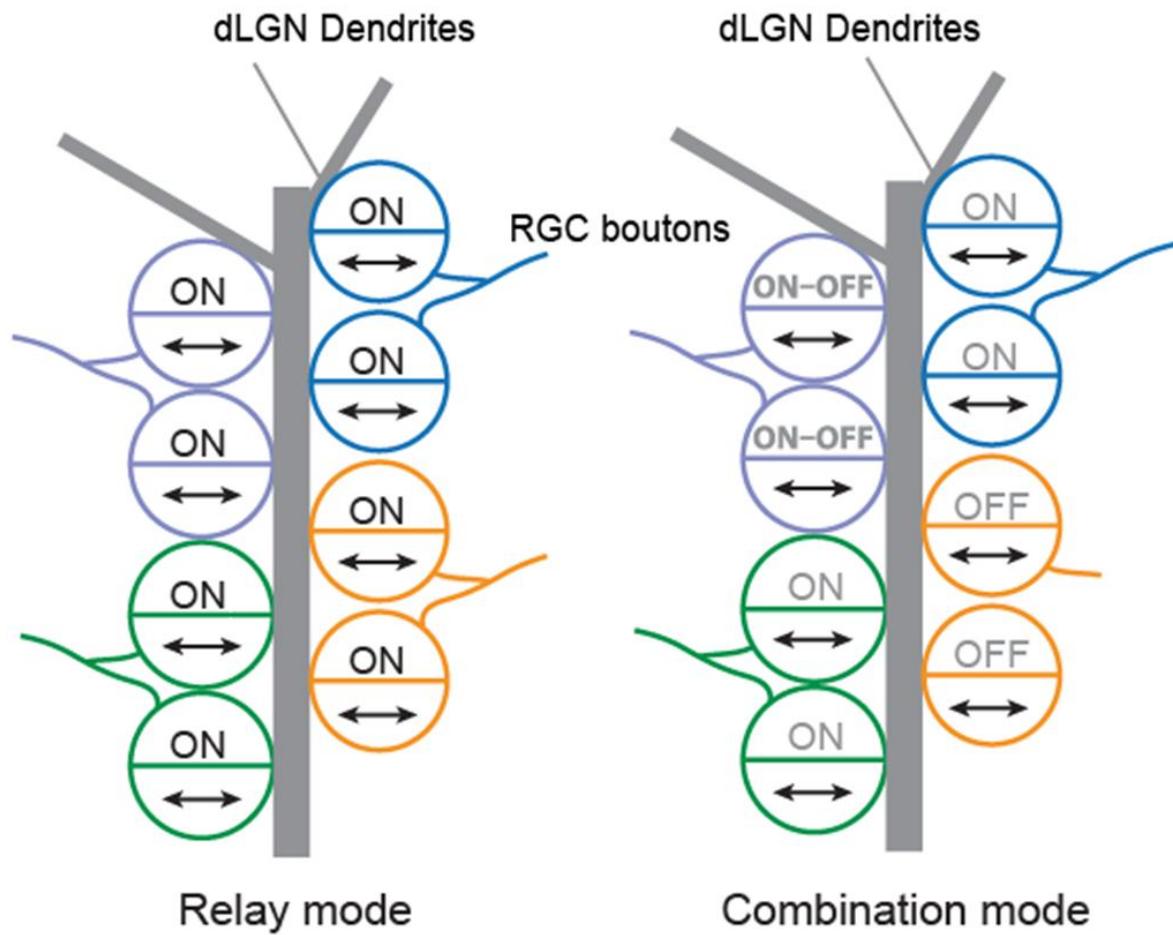
dLGN cells integrate retinal inputs in relay and combination mode



In addition to labeled-line connections (single RGC type), combination-mode connections (multiple RGC types) were observed.

More monocular LGN cells (8/15) received inputs from 2–6 different RGC types.

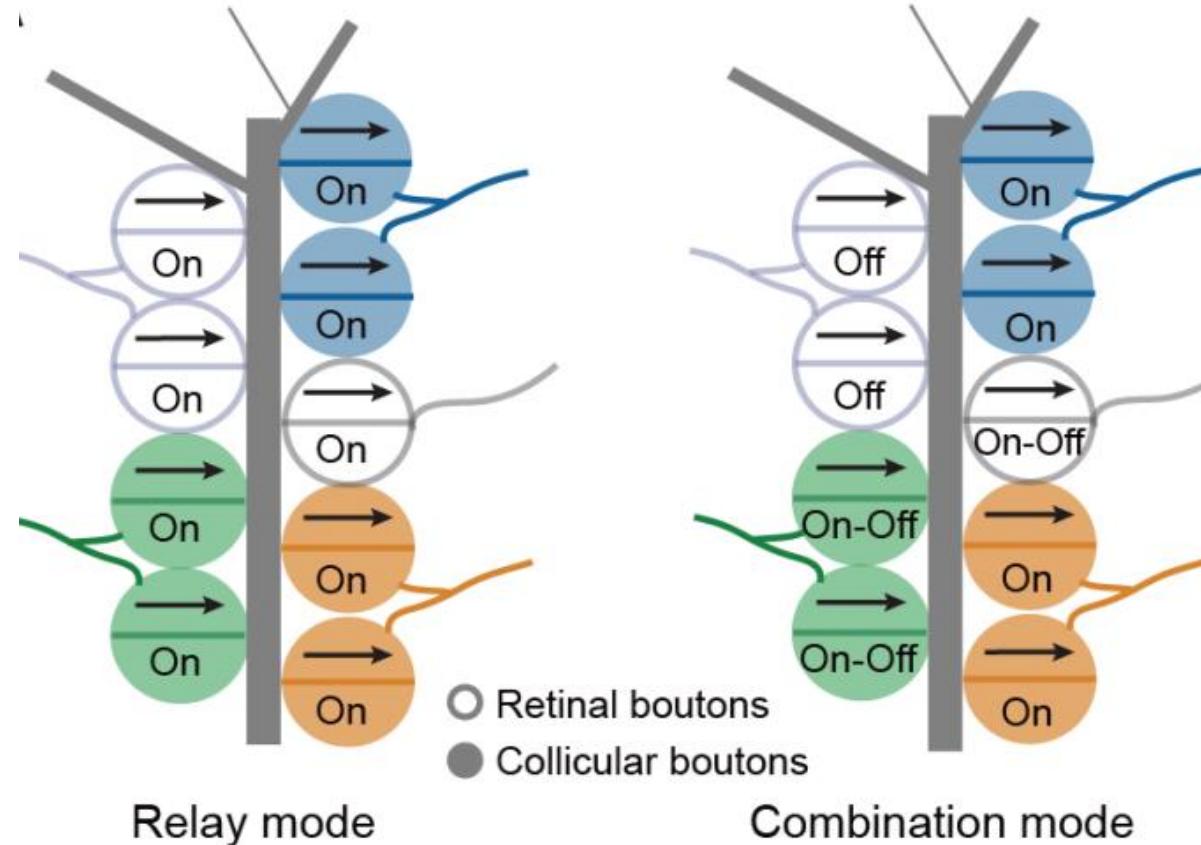
Nearby RGC boutons share one or several similar visual feature preference



Visual responses of RGC boutons in dLGN show local clustering by feature preference.

Nearby boutons tend to prefer similar visual features, beyond coarse retinotopy.

Relay- and Combination-mode Convergence of Nearby Retinal and Collicular Boutons

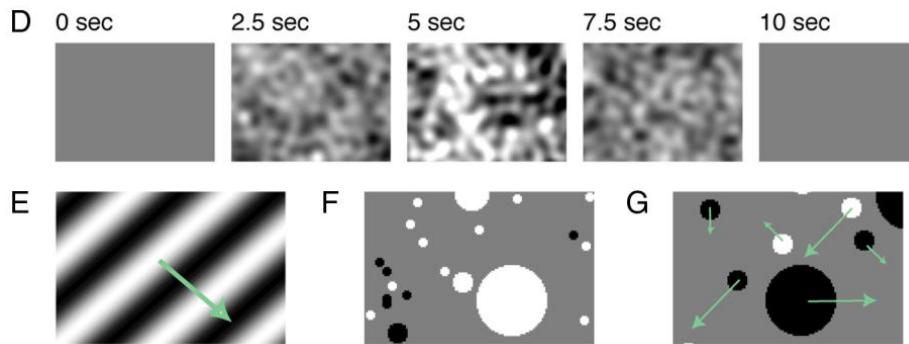


Relay mode: nearby boutons share preferences for a single feature

Combination mode: nearby boutons exhibit similar preferences for multiple features

between retinal and collicular boutons.

Functional Diversity of dLGN Neurons



Unsupervised clustering (k-means) based on responses to flashes, drifting gratings, and noise movies.

7 Discrete Cell Types Identified:

- **ON sustained:** Persistent response to bright stimuli
- **OFF sustained:** Persistent response to dark stimuli
- **ON transient:** Brief response to bright stimuli
- **OFF transient:** Brief response to dark stimuli
- **ON-OFF:** Responsive to both bright and dark stimuli
- **Suppressed-by-contrast:** Reduced activity during stimulus
- **Orientation/Direction selective (OS/DS):** Selective for stimulus orientation or direction

Four stimulus sets used.

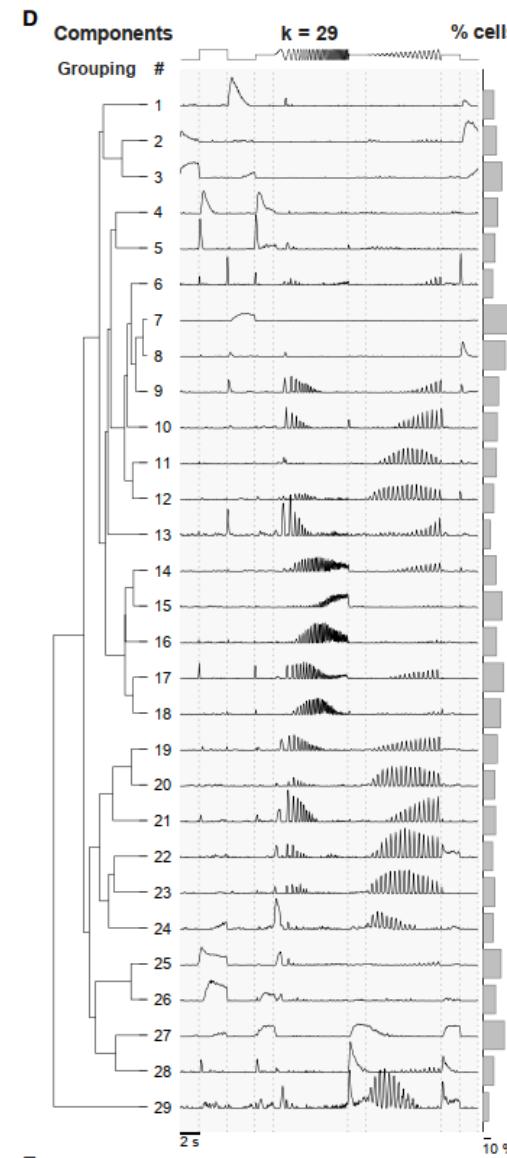
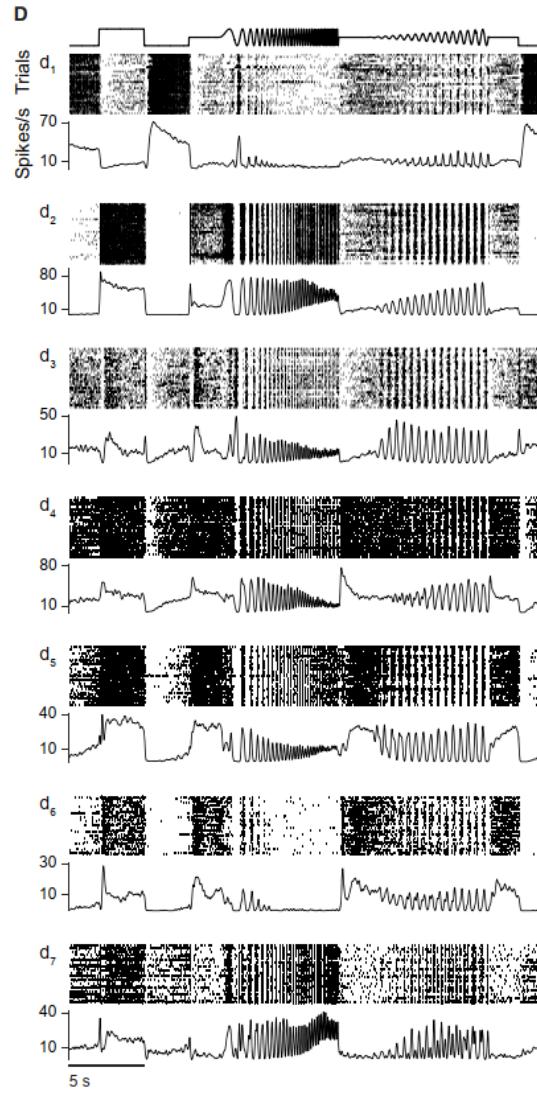
D, Contrast modulated band-limited noise.

E, Drifting sinusoidal gratings.

F, Flashing spots.

G, Moving spots.

Limited Convergence, Rich Responses in dLGN



Each dLGN neuron typically integrates signals **from about 5 types, with 2 having dominant influence.**

Despite this limited convergence, the dLGN shows rich response diversity, suggesting both feature-specific input selection and functional integration.

Non-negative matrix factorization (NMF) was used to reveal around 29 distinct response components .

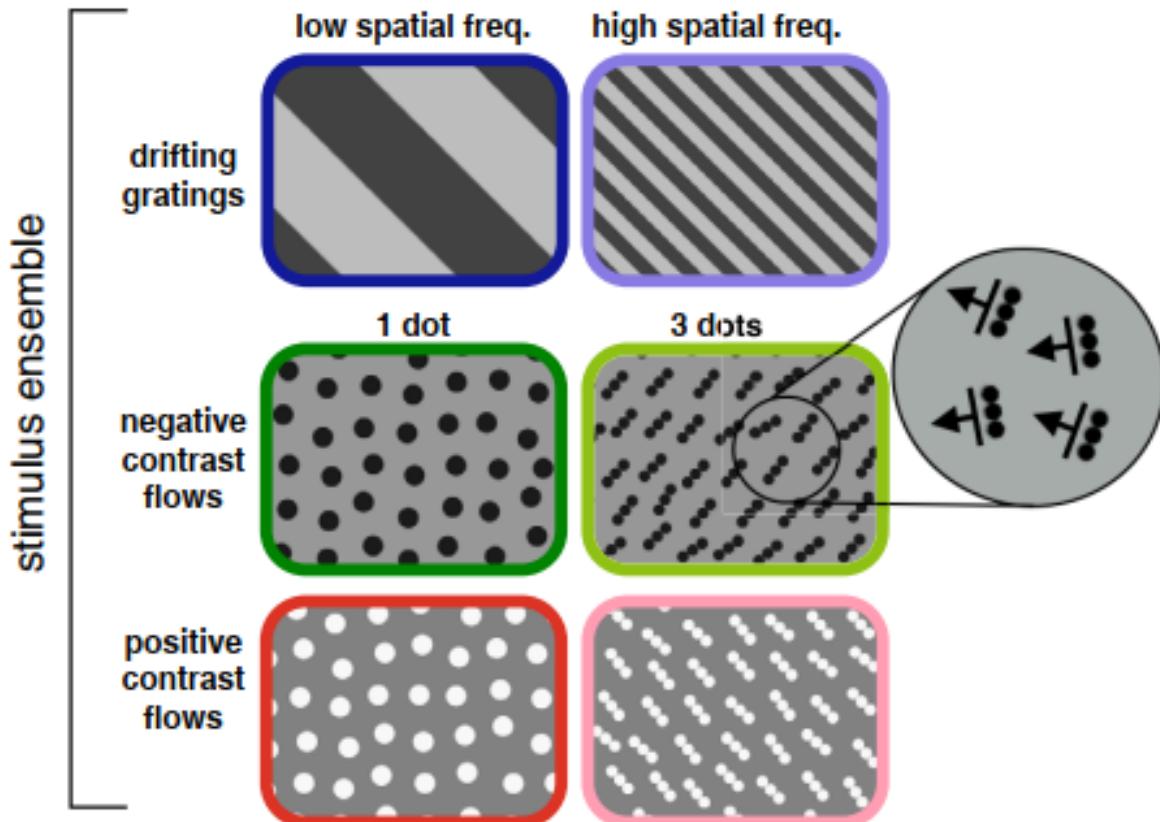
Hypothesis on dLGN Cell Type Organization

We hypothesize that dLGN neurons are not as discretely organized into cell types as RGCs.

Instead, dLGN may exhibit a more continuous distribution of response properties, resembling an intermediate stage between the discrete organization in the retina and the continuous representations in V1.

Data, Methods, Results

Same stimuli set used for RGC, SC, and dLGN.



Luciano et al., 2024

Stimuli and Data

dir: 0, 45, 90, 135, 180, 225, 270

Low Freq Gratings

High Freq Gratings

Neg 1-dot Flows

Neg 3-dot Flows

Pos 1-dot Flows

Pos 3-dot Flows

In total, $6 * 8 = 48$ stimuli

Flow stimuli were chosen because they mimic certain features of naturalistic stimuli, and previous work has shown that they engage nonlinearities in V1 that are not predicted based on the responses to gratings.

Luciano et al., 2018

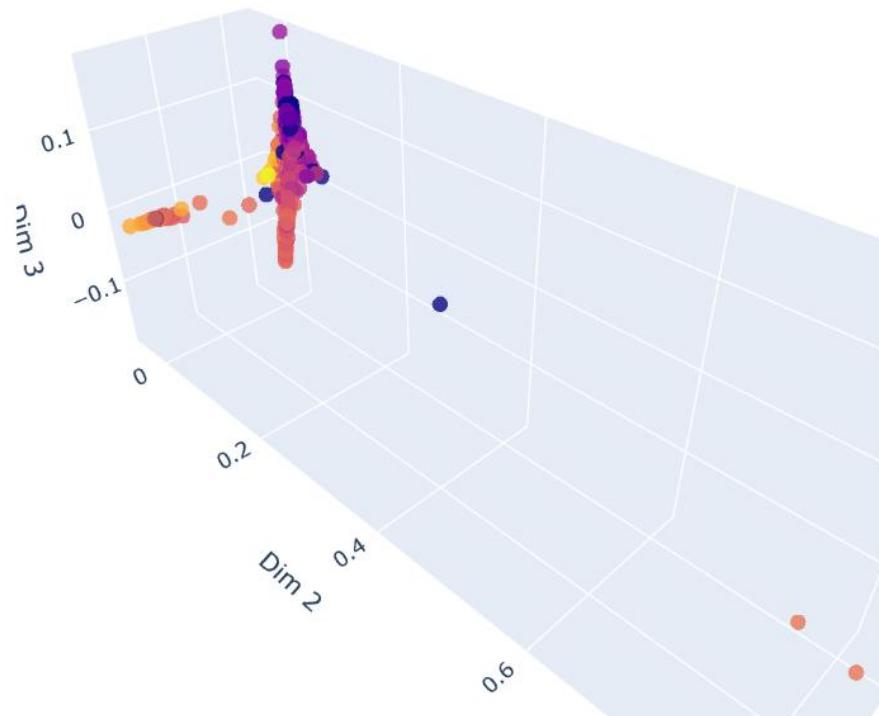
Data collected by Yue Fei

RGC
2145 significant boutons

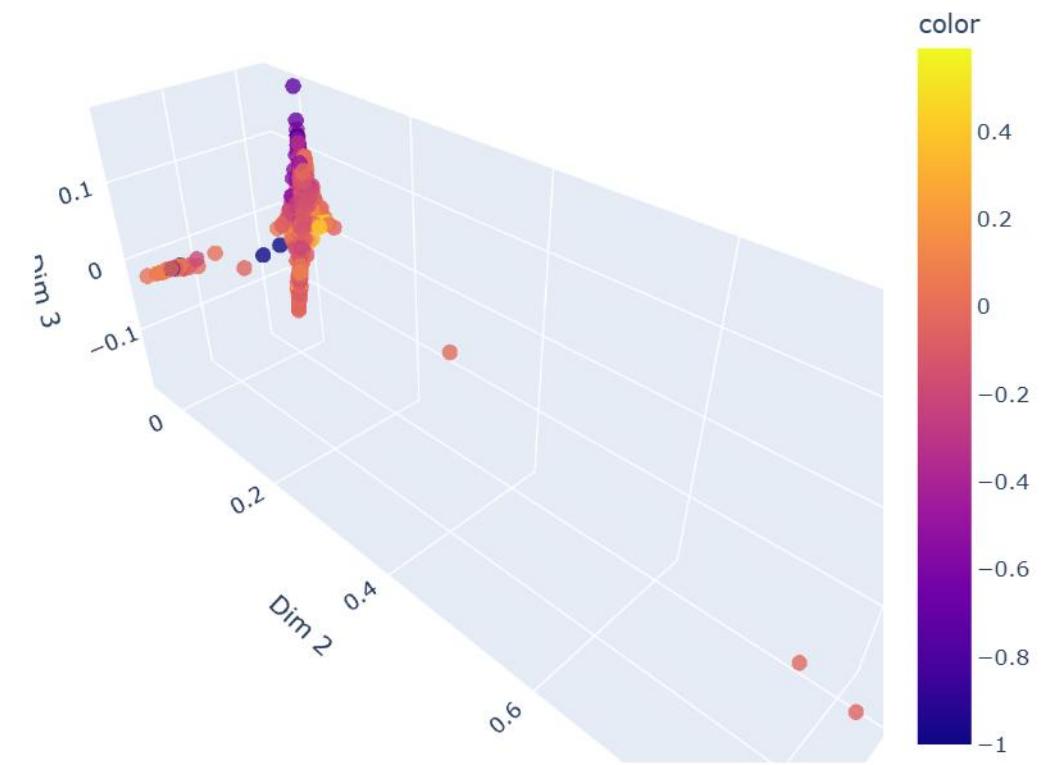
$$\text{Grating Selectivity Index} = \frac{\Delta R_g - \Delta R_f}{|\Delta R_g| + |\Delta R_f|}$$

$$\text{Flow Polarity Index} = \frac{\Delta R_{\text{pf}} - \Delta R_{\text{nf}}}{|\Delta R_{\text{pf}}| + |\Delta R_{\text{nf}}|}$$

Neuron Diffusion Map (Grating Selectivity Index)



Neuron Diffusion Map (Flow Polarity Index)



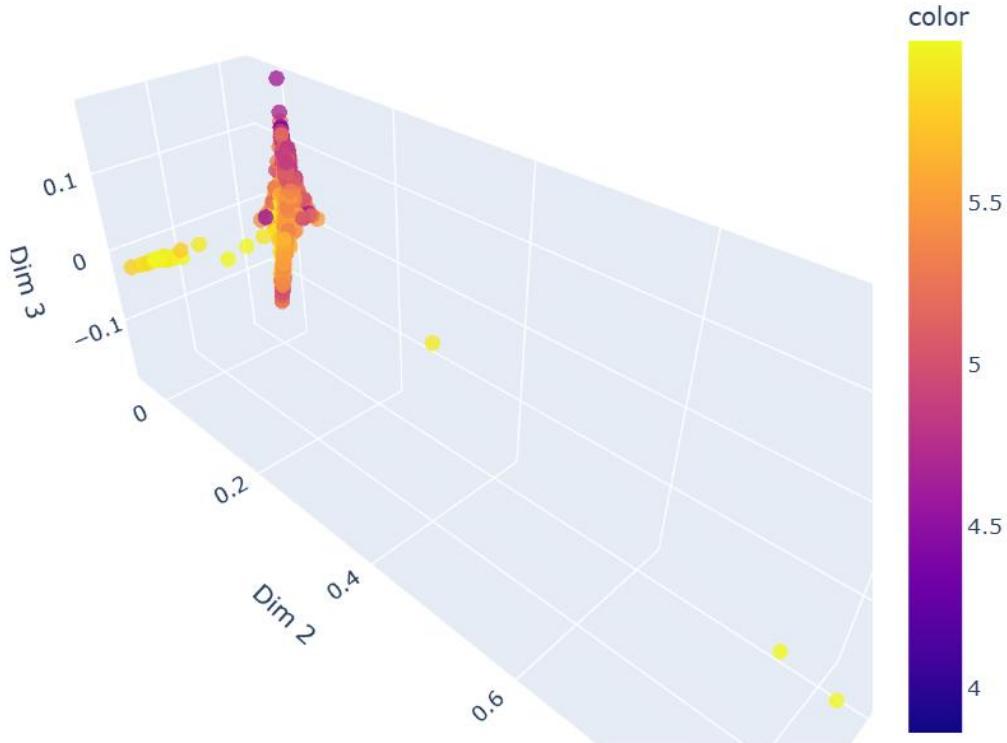
Higher stimulus specificity: An index close to 1 indicates strong selectivity — the neuron responds strongly to a specific stimulus and weakly (or not at all) to others.

Uniform responses: An index close to 6 indicates no selectivity — the neuron has similar amplitudes across all six stimuli.

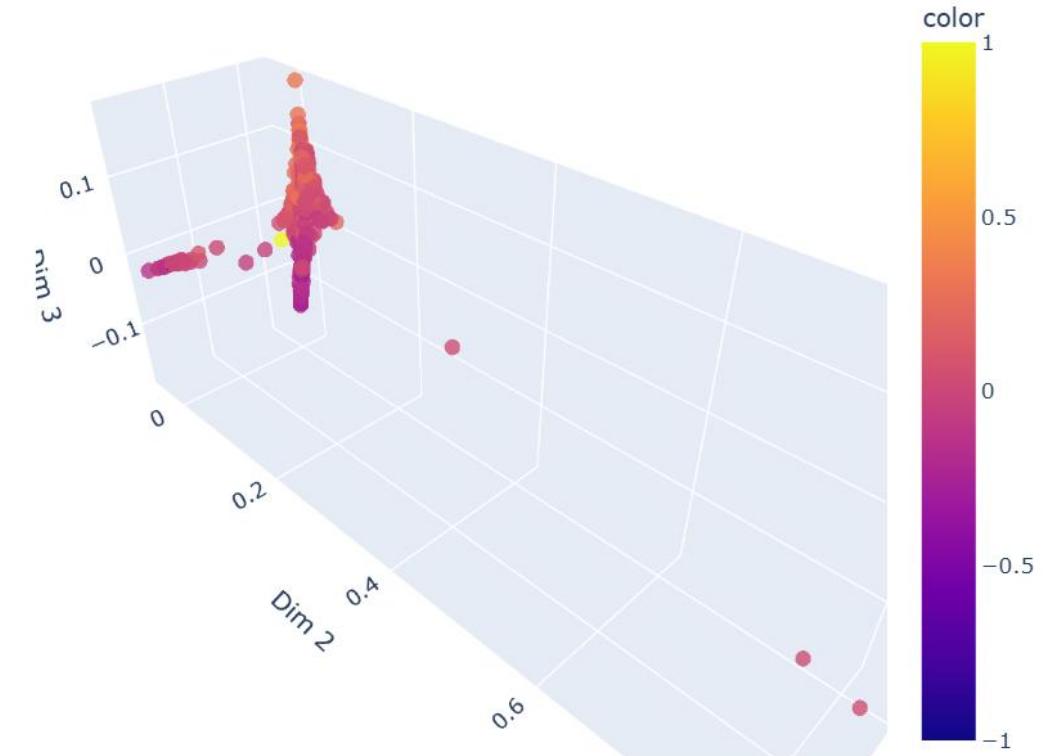
Note: the index only reflects the response magnitudes only. It does not distinguish the signs of responses.

$$\text{Dot Selectivity Index} = \frac{\Delta R_{1\text{dot}} - \Delta R_{3\text{dot}}}{|\Delta R_{1\text{dot}}| + |\Delta R_{3\text{dot}}|}$$

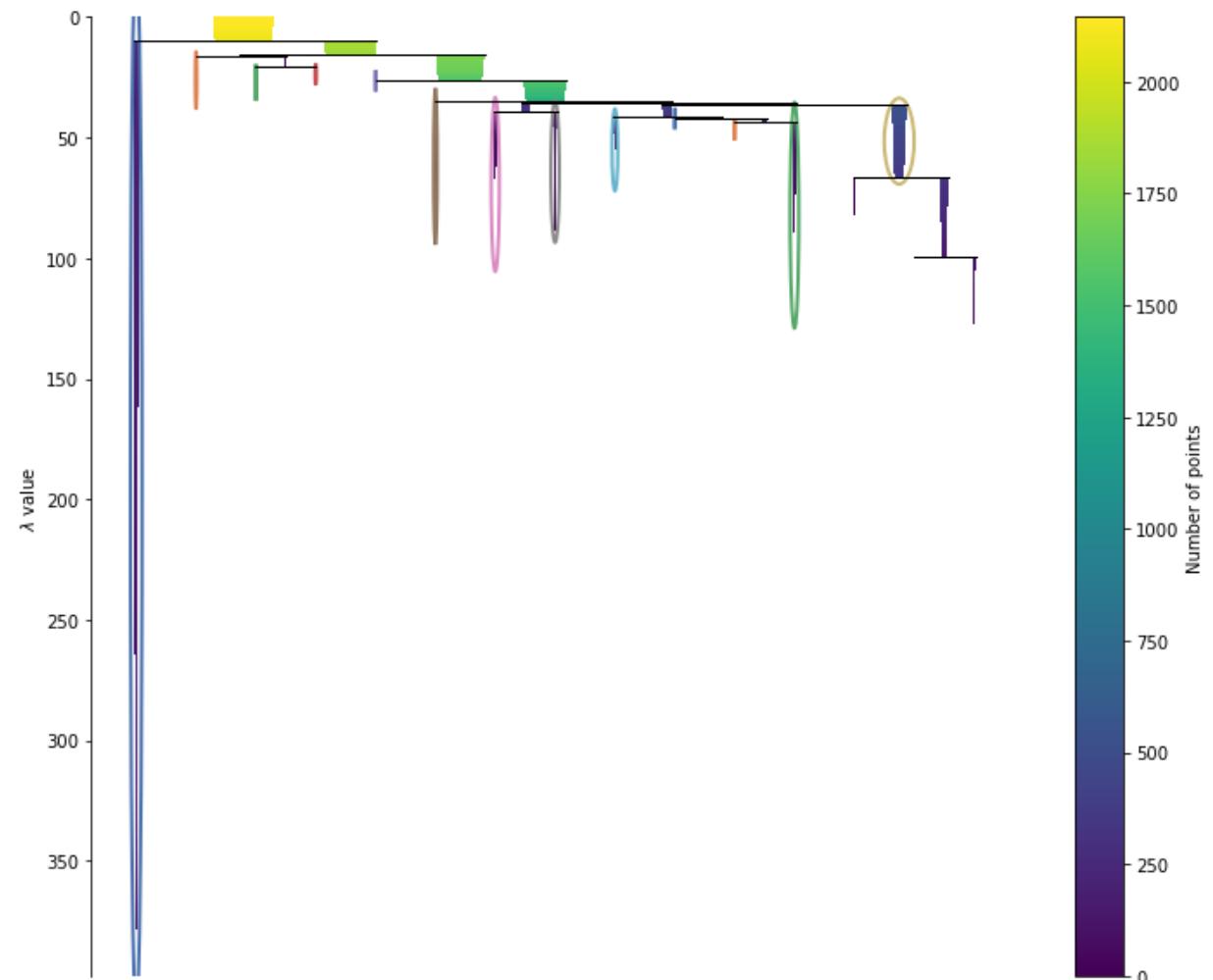
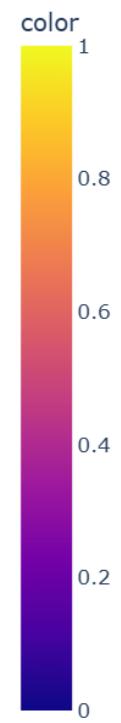
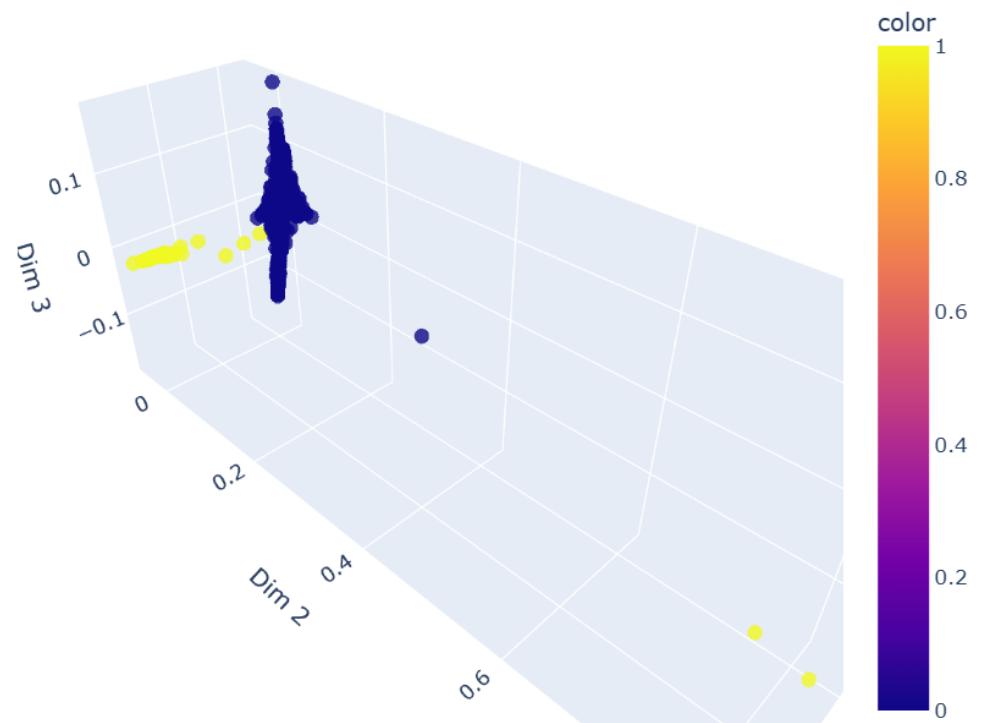
Neuron Diffusion Map (Stimulus Entropy Index)



Neuron Diffusion Map (Dot Selectivity Index)



Neuron Diffusion Map (Negative Response Index)

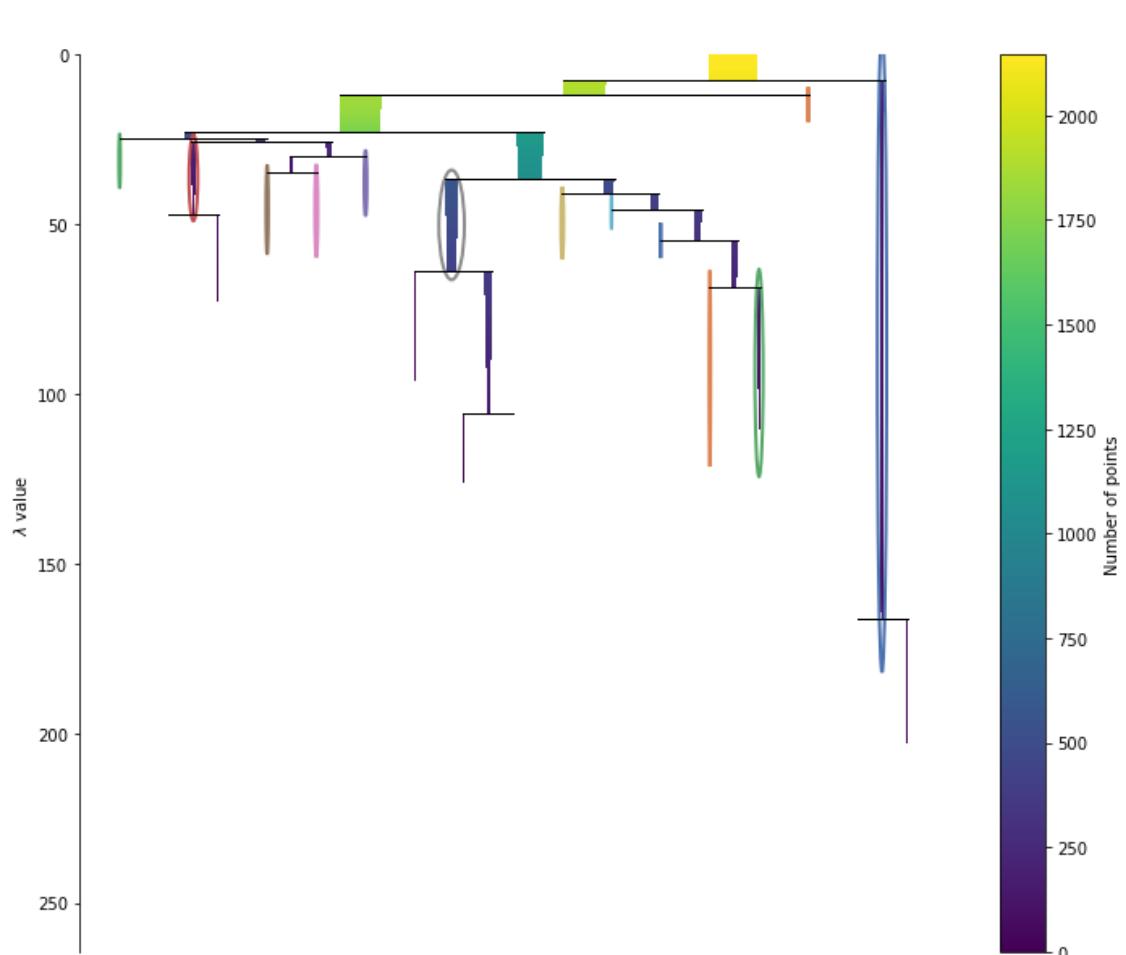


13 classes

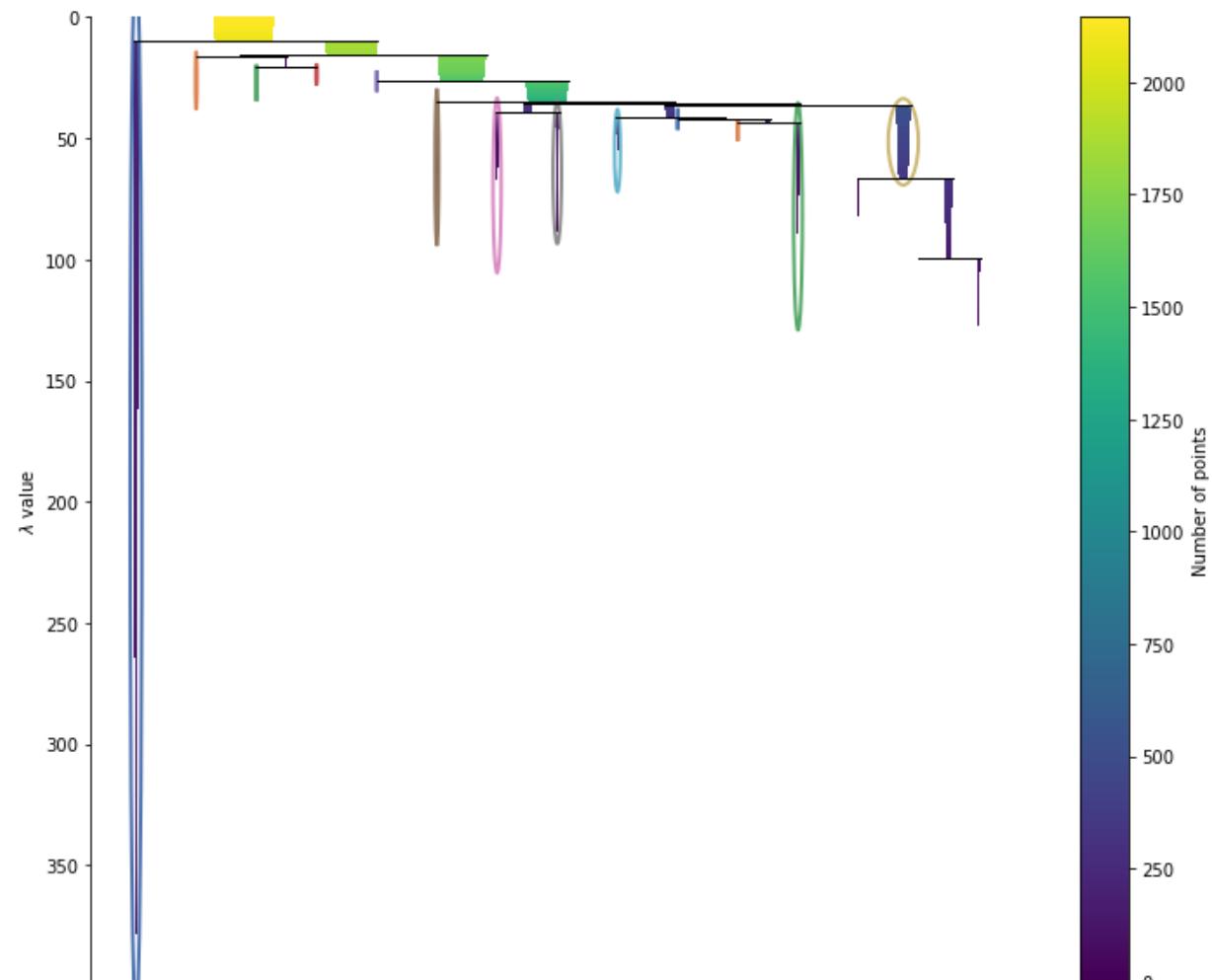
`min_cluster_size=15`

If `min_cluster_size=5`, 36 clusters.

Original cut: 0.5s pre+1.5s trial+1s post

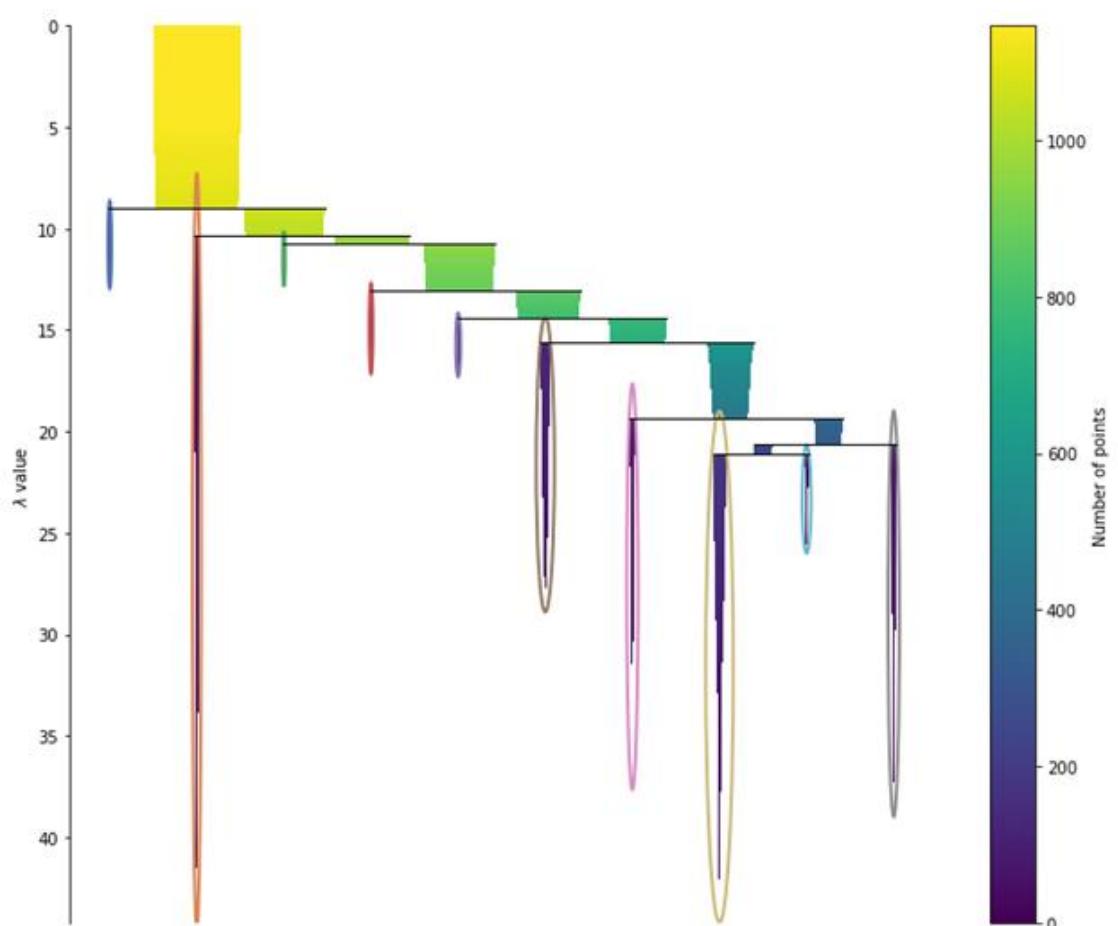


New cut: 0.5s pre+1.5s trial+2s post



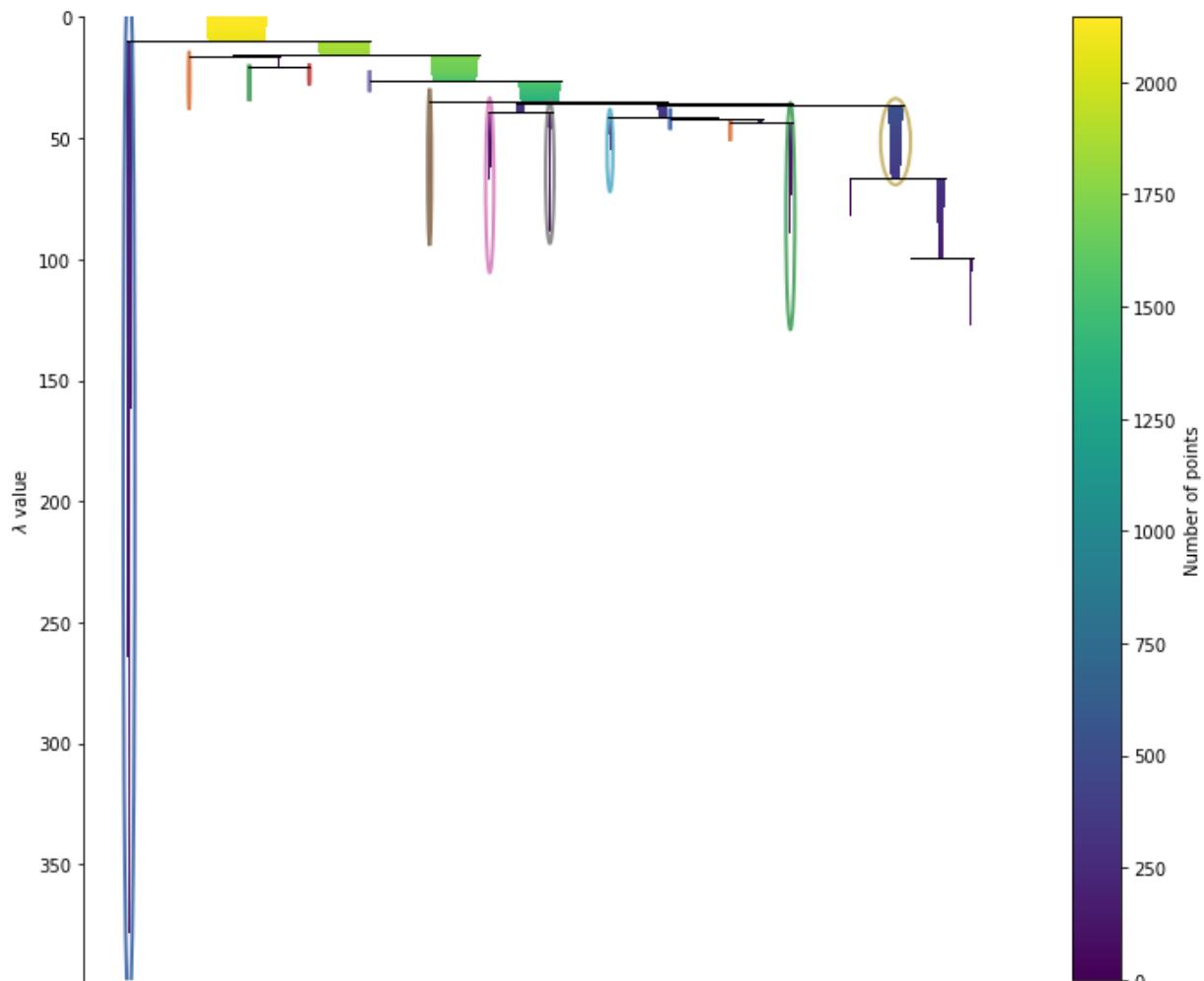
Both are 13 classes

Public retina data



10 classes

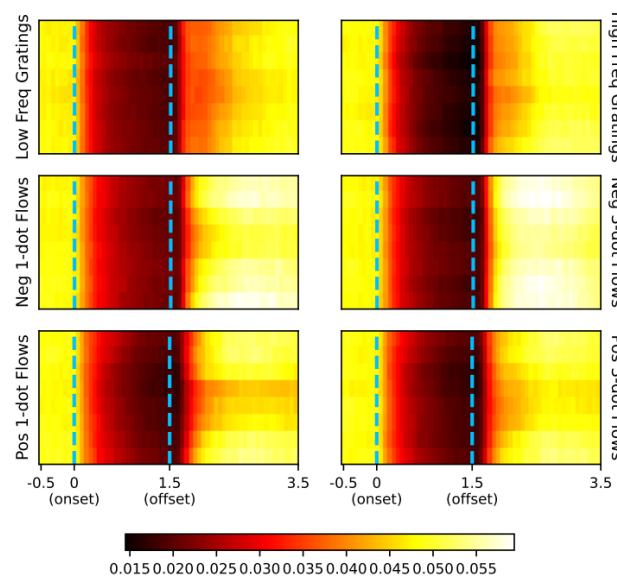
New cut: 0.5s pre+1.5s trial+2s post



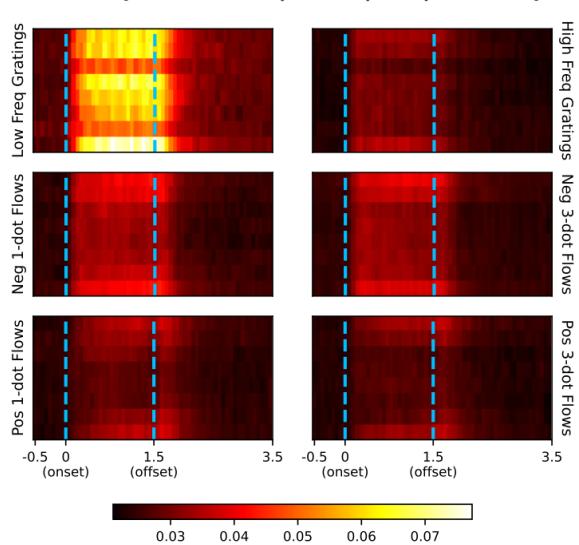
13 classes

Examples of Cluster Average response

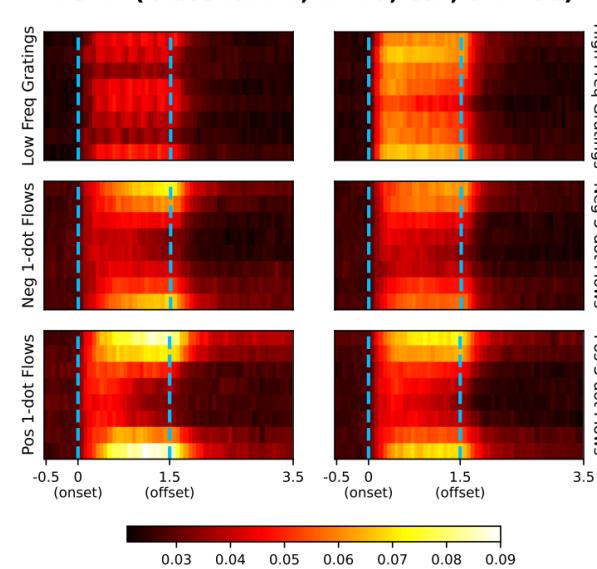
PSTH (Class idx: 0, n=209, cut, shifted)



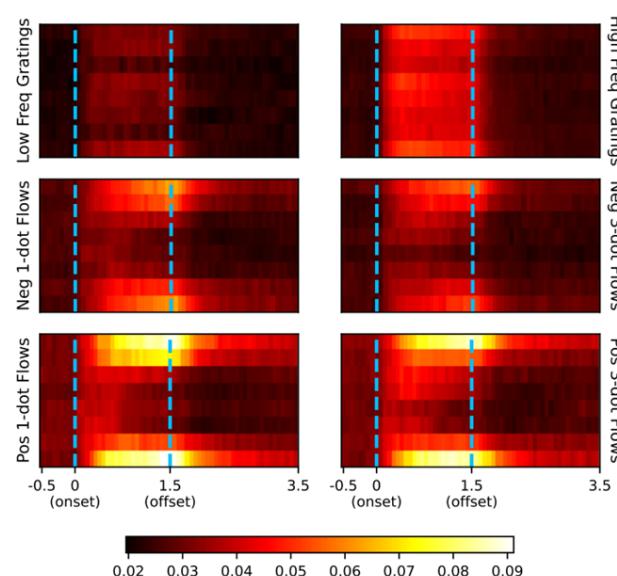
PSTH (Class idx: 1, n=29, cut, shifted)



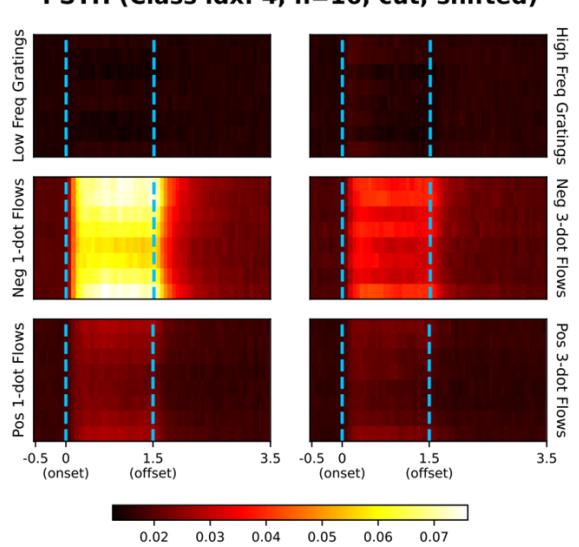
PSTH (Class idx: 2, n=20, cut, shifted)



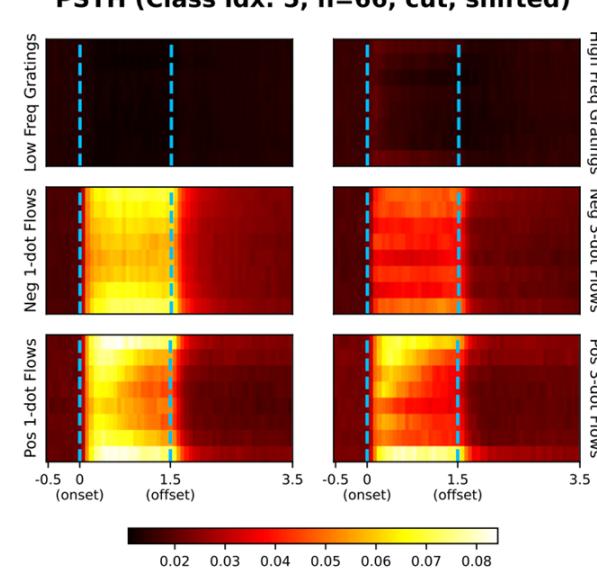
PSTH (Class idx: 3, n=23, cut, shifted)

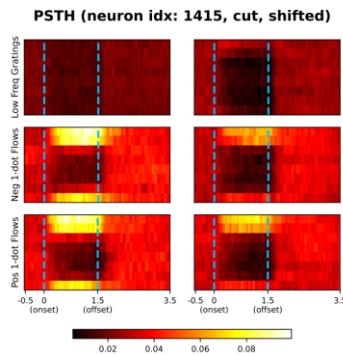


PSTH (Class idx: 4, n=16, cut, shifted)

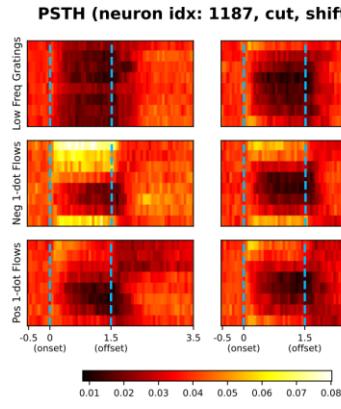


PSTH (Class idx: 5, n=66, cut, shifted)

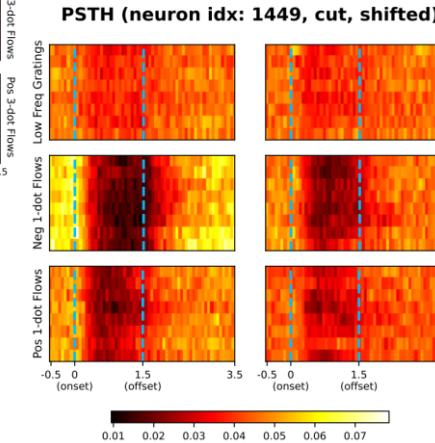




Class:-1

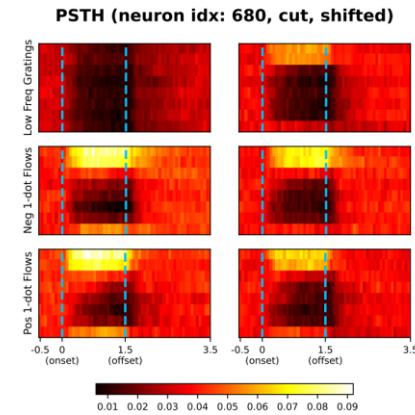
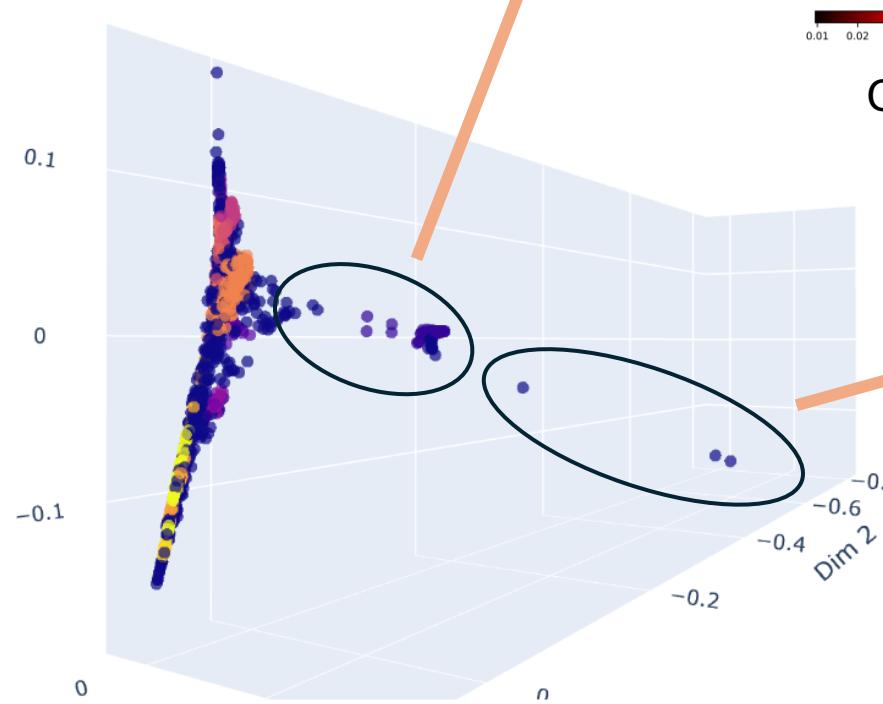


Class:0

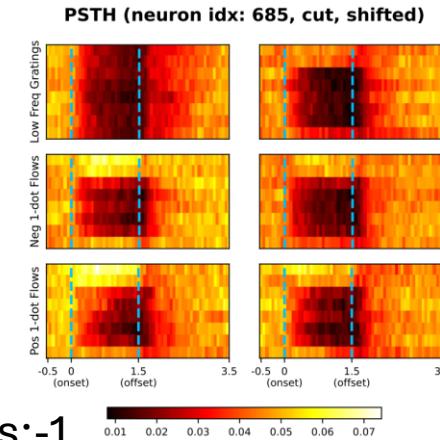


Class:-1

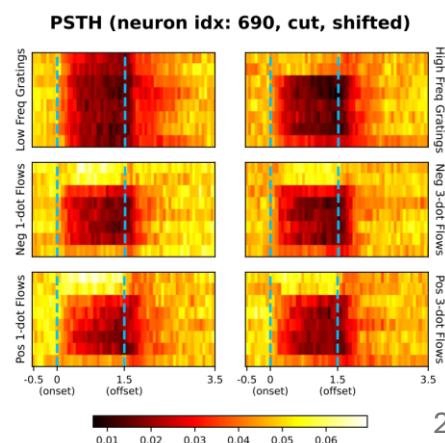
Dim 3



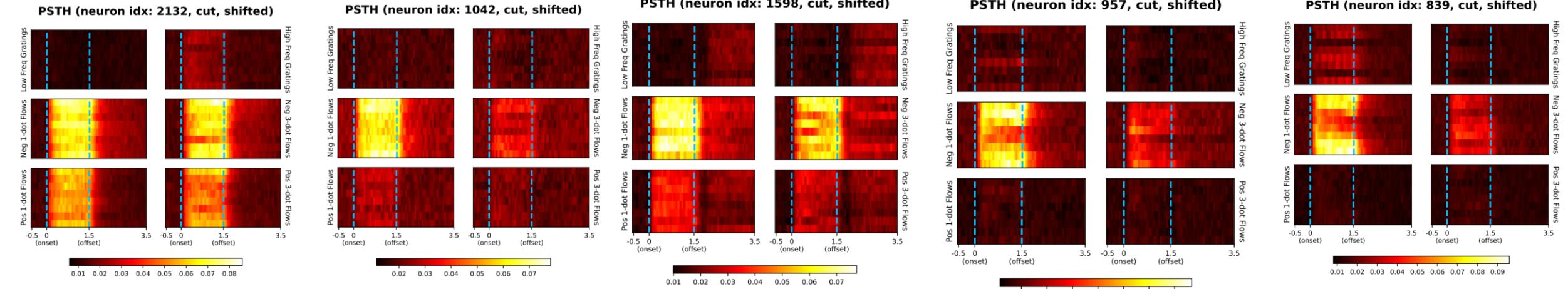
Class:-1



Class:-1



Class:-1



Class:7

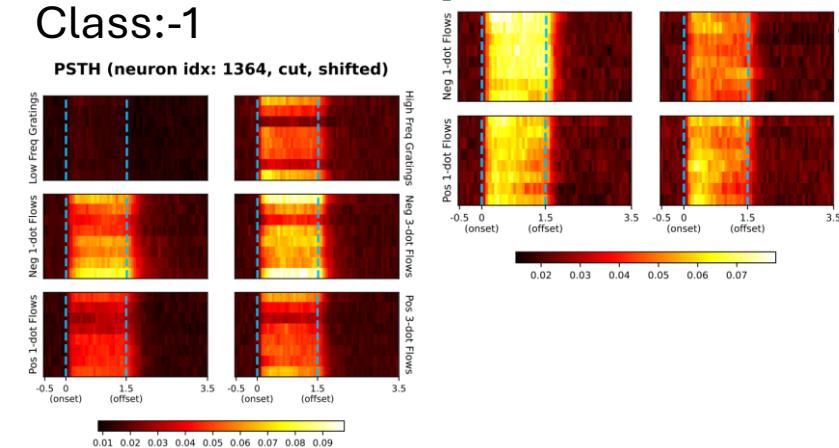
Class:-1

Class:-1

0.02

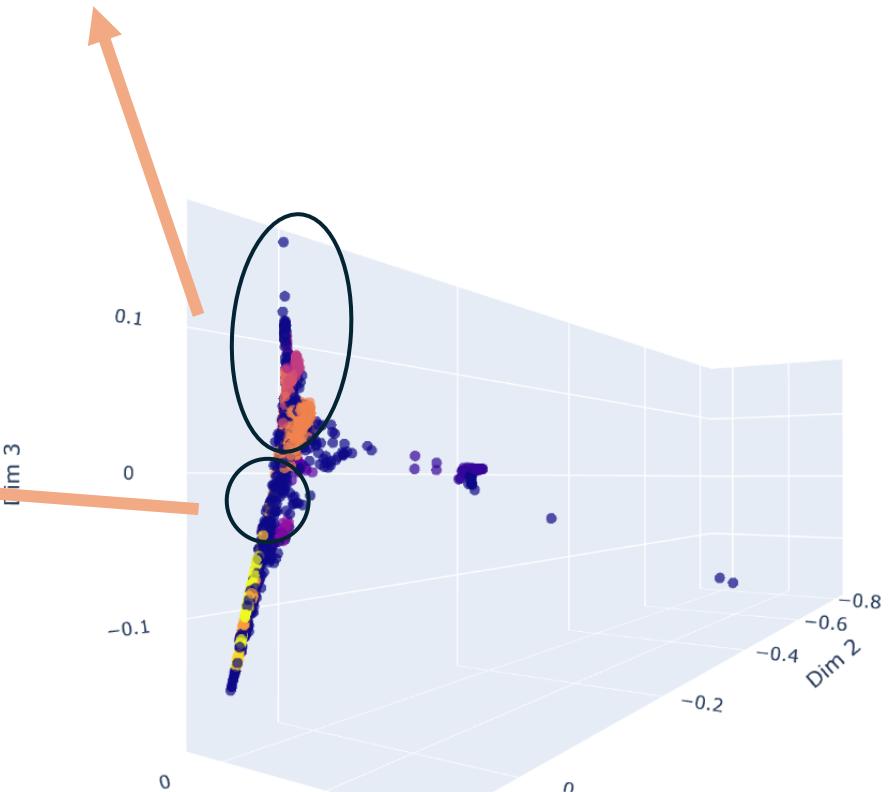
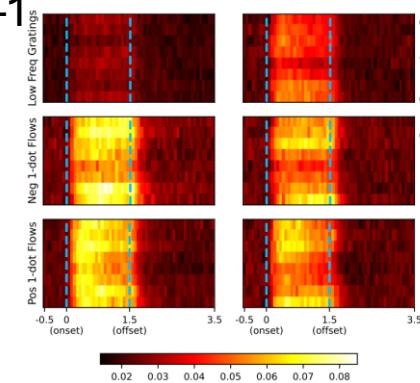
Class:-1

PSTH (neuron idx: 1549, cut, shifted)

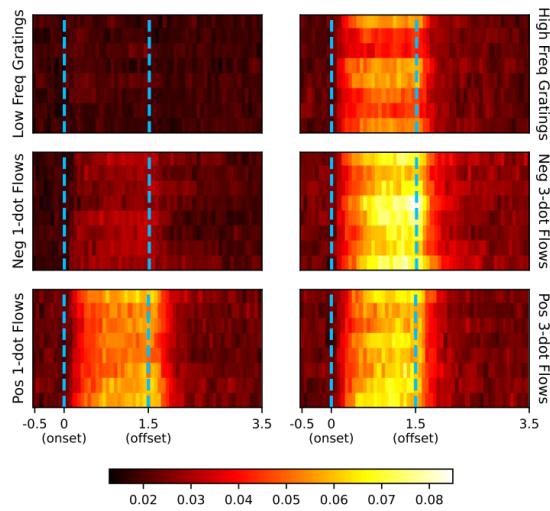


Class:-1

PSTH (neuron idx: 1789, cut, shifted)

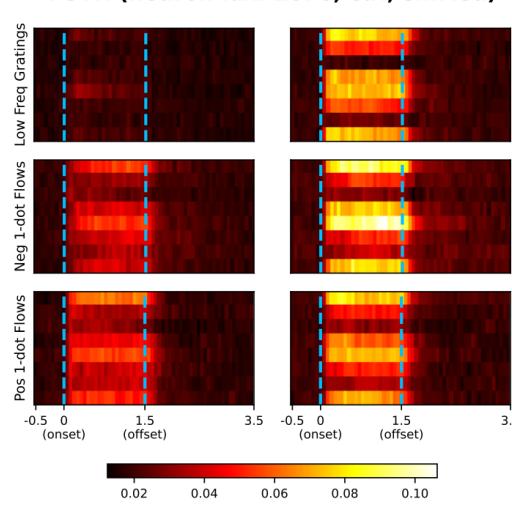


PSTH (neuron idx: 1441, cut, shifted)



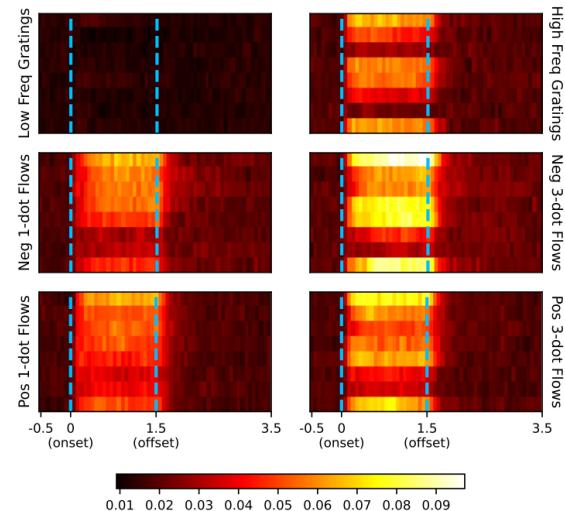
Class:12

PSTH (neuron idx: 2076, cut, shifted)



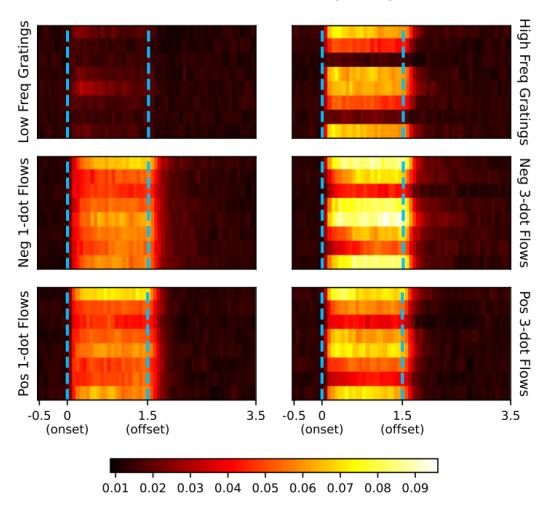
Class:12

PSTH (neuron idx: 1963, cut, shifted)



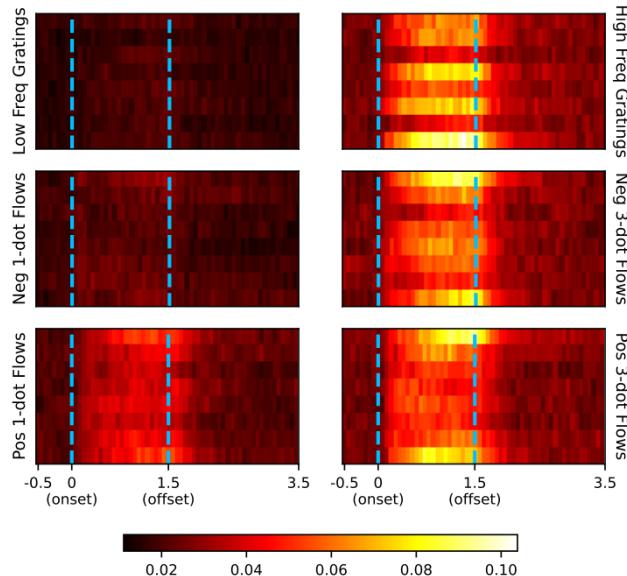
Class:12

PSTH (neuron idx: 2078, cut, shifted)

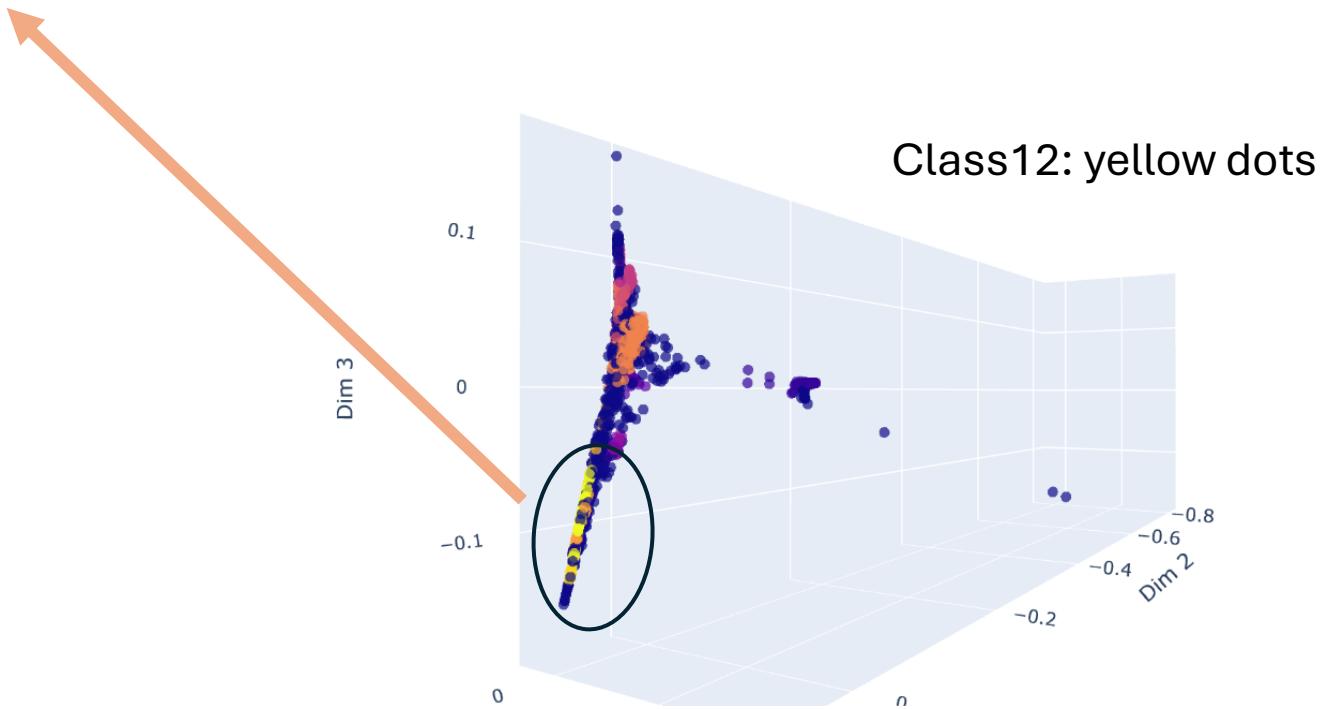


Class:12

PSTH (neuron idx: 816, cut, shifted)

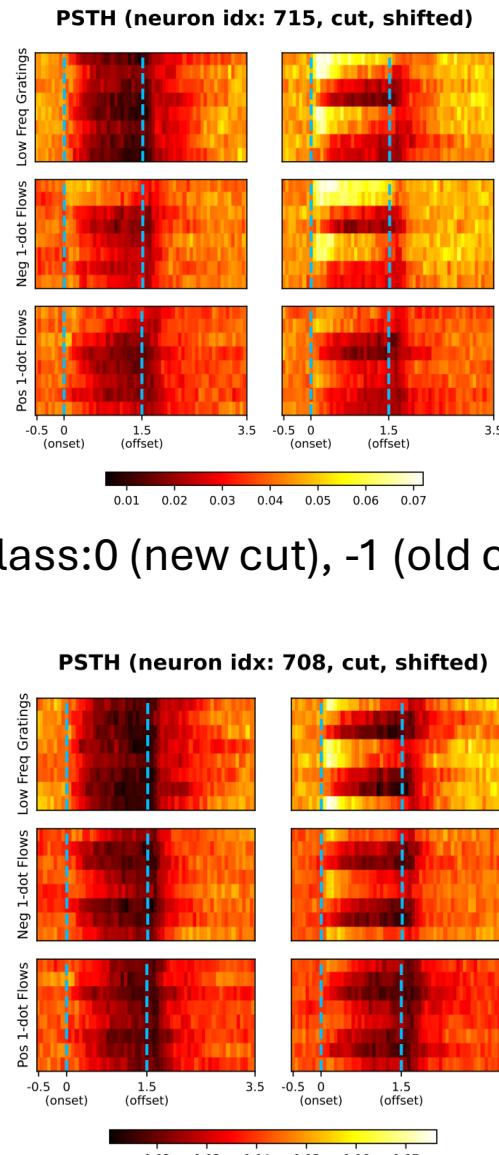
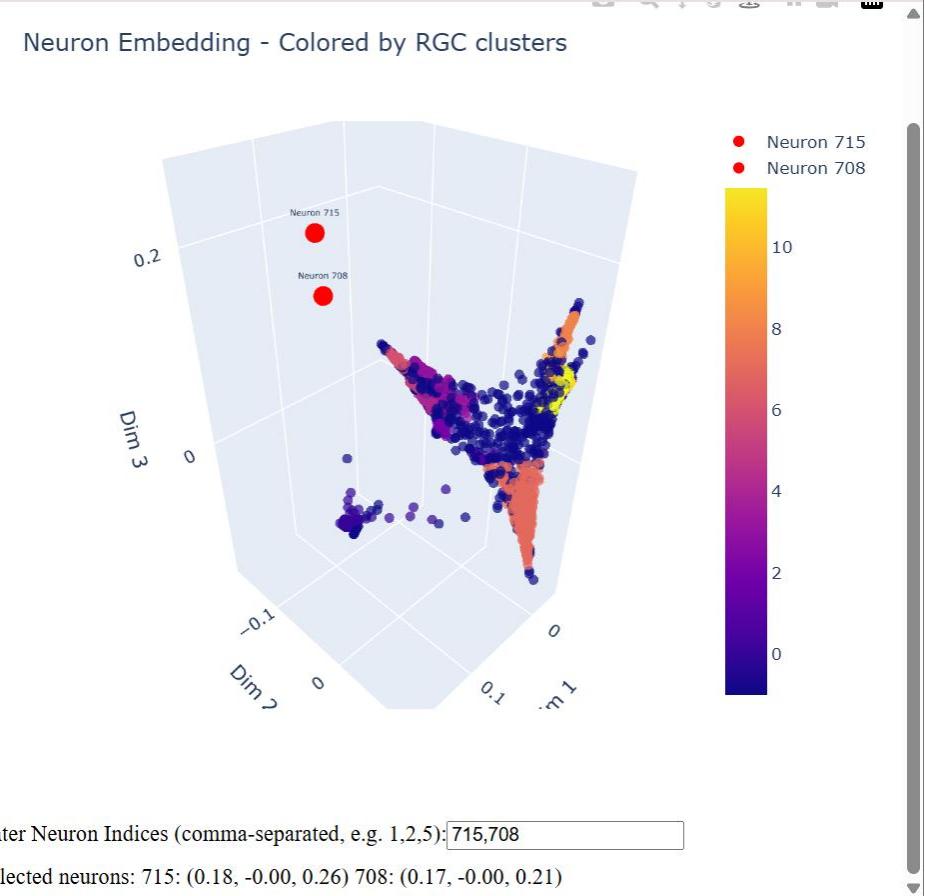


Class:-1

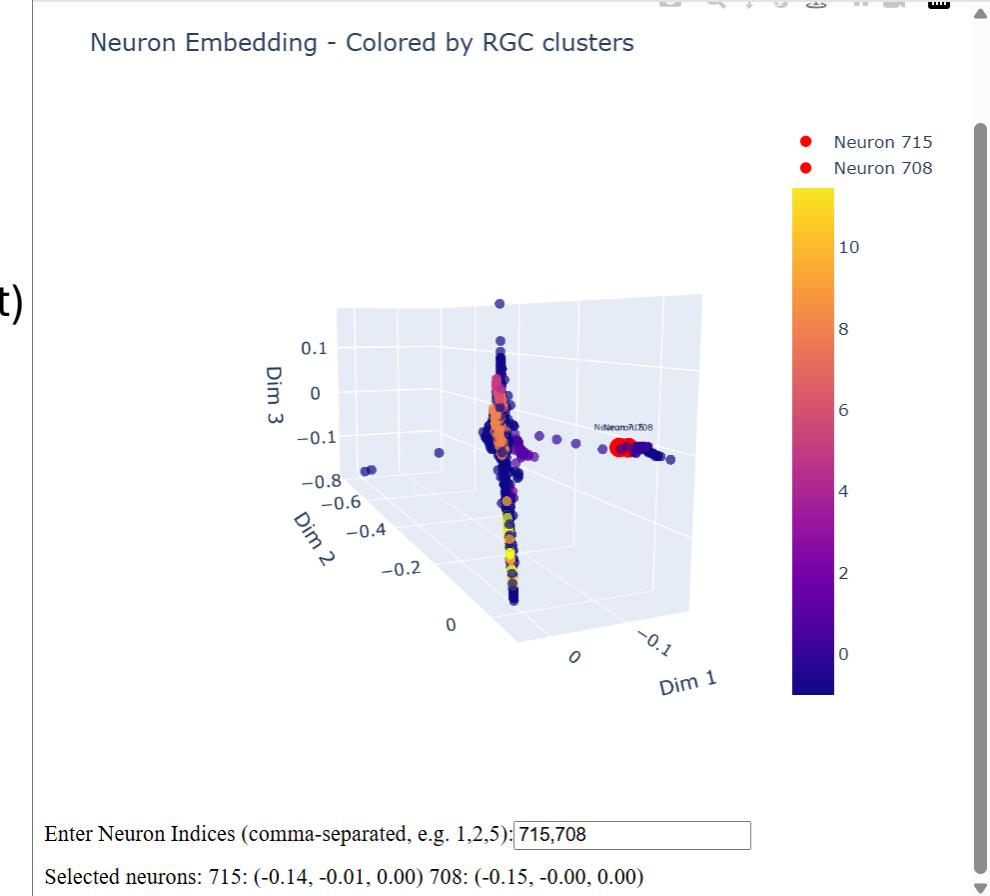


Neuron location comparison between the old clusters and new clusters.

Original cut: 0.5s pre+1.5s trial+1s post



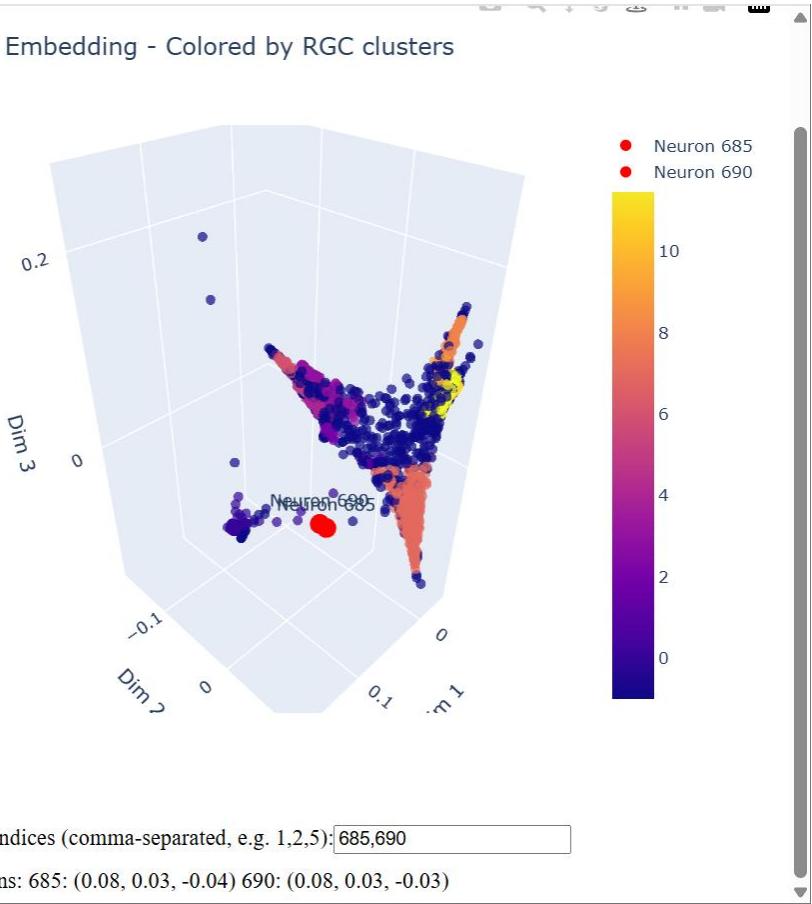
New cut: 0.5s pre+1.5s trial+2s post
dims: 1 2 3



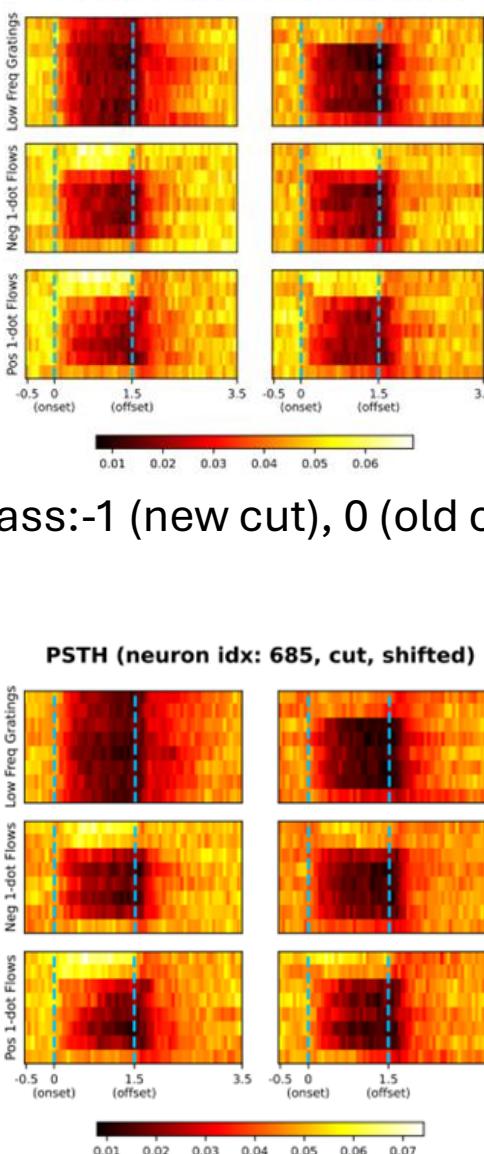
Class:0 (new cut), -1 (old cut)

Neuron location comparison between the old clusters and new clusters.

Neuron Embedding - Colored by RGC clusters

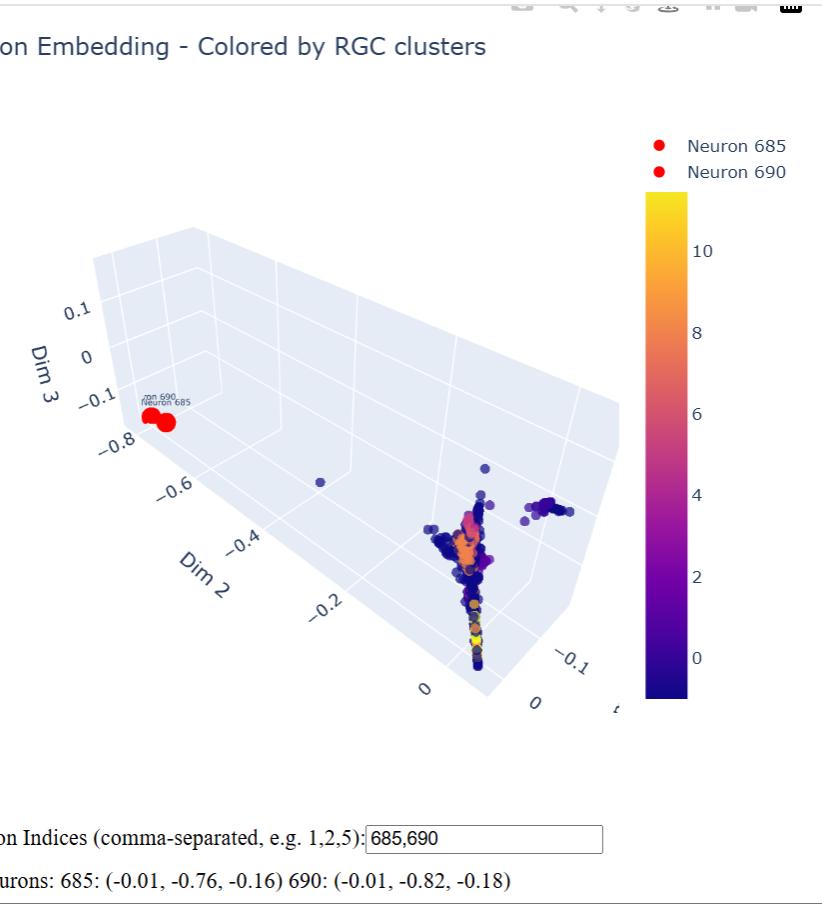


PSTH (neuron idx: 690, cut, shifted)



New cut: 0.5s pre+1.5s trial+2s post
dims: 1 2 3

Neuron Embedding - Colored by RGC clusters



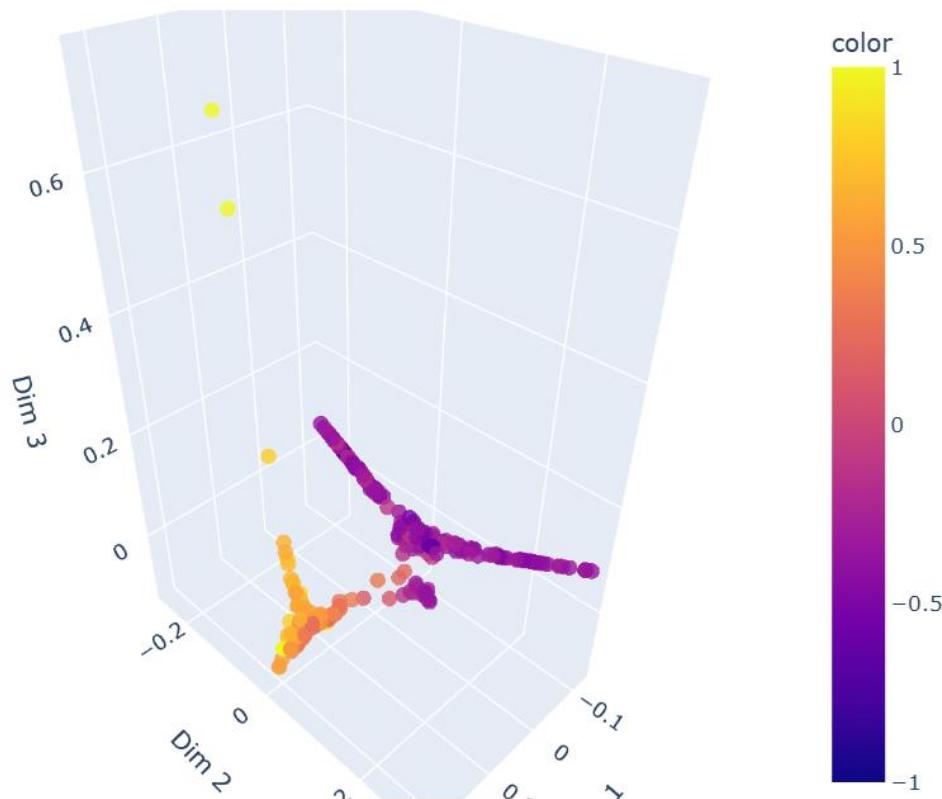
Class:-1 (new cut), -1 (old cut)

Superior Colliculus (SC)
2145 significant boutons

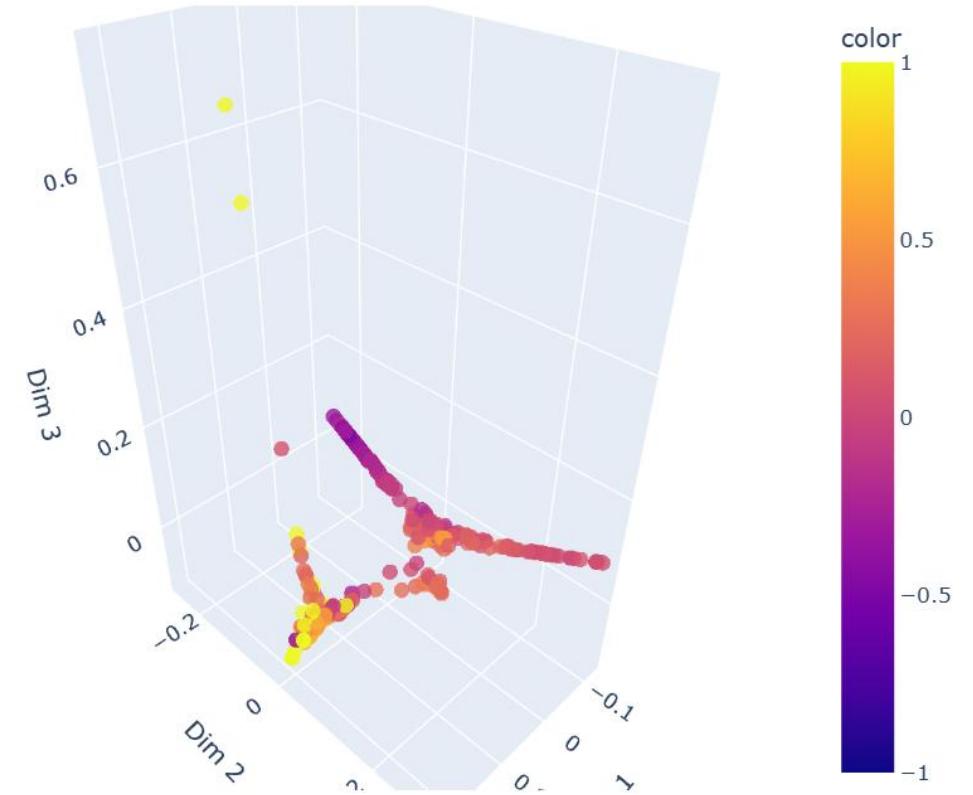
$$\text{Grating Selectivity Index} = \frac{\Delta R_g - \Delta R_f}{|\Delta R_g| + |\Delta R_f|}$$

$$\text{Flow Polarity Index} = \frac{\Delta R_{\text{pf}} - \Delta R_{\text{nf}}}{|\Delta R_{\text{pf}}| + |\Delta R_{\text{nf}}|}$$

Neuron Diffusion Map (Grating Selectivity Index)



Neuron Diffusion Map (Flow Polarity Index)



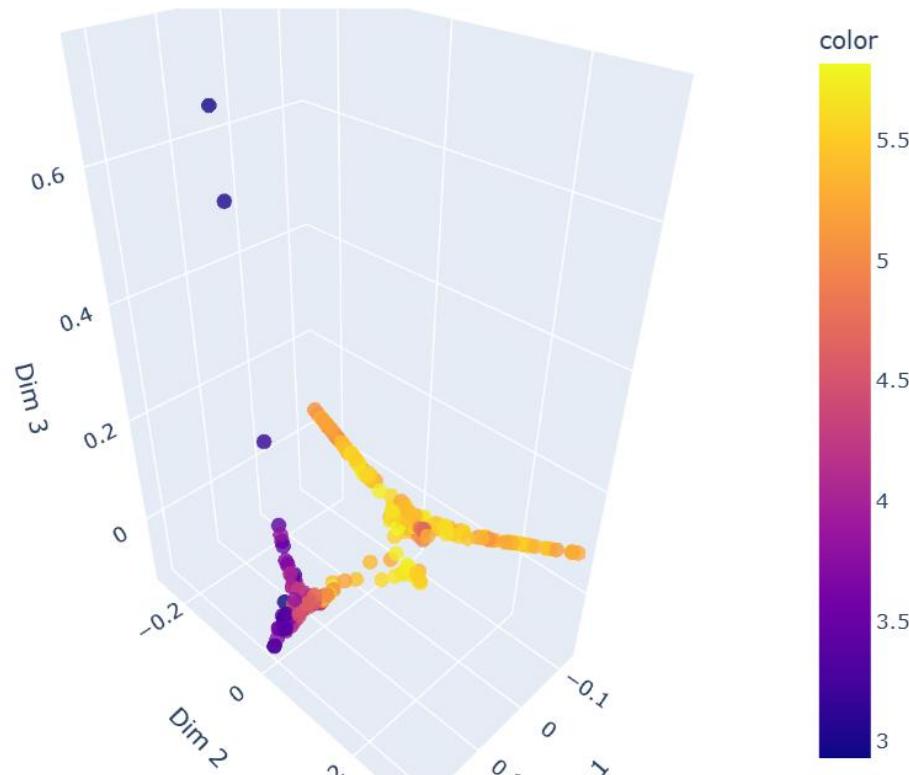
Higher stimulus specificity: An index close to 1 indicates strong selectivity — the neuron responds strongly to a specific stimulus and weakly (or not at all) to others.

Uniform responses: An index close to 6 indicates no selectivity — the neuron has similar amplitudes across all six stimuli.

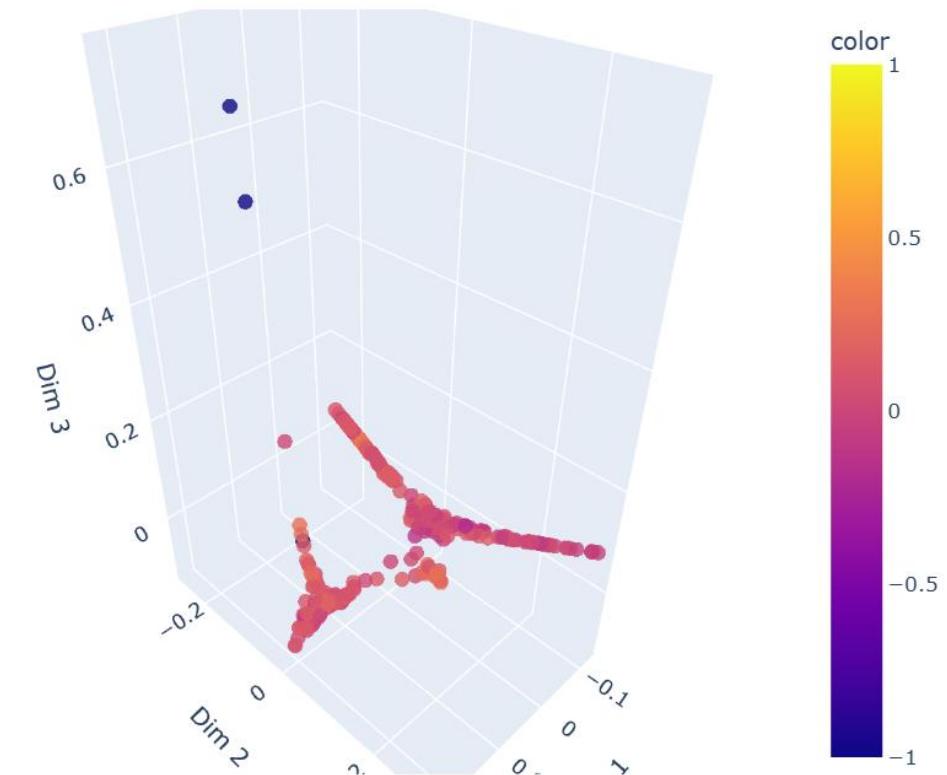
Note: the index only reflects the response magnitudes only. It does not distinguish the signs of responses.

$$\text{Dot Selectivity Index} = \frac{\Delta R_{1\text{dot}} - \Delta R_{3\text{dot}}}{|\Delta R_{1\text{dot}}| + |\Delta R_{3\text{dot}}|}$$

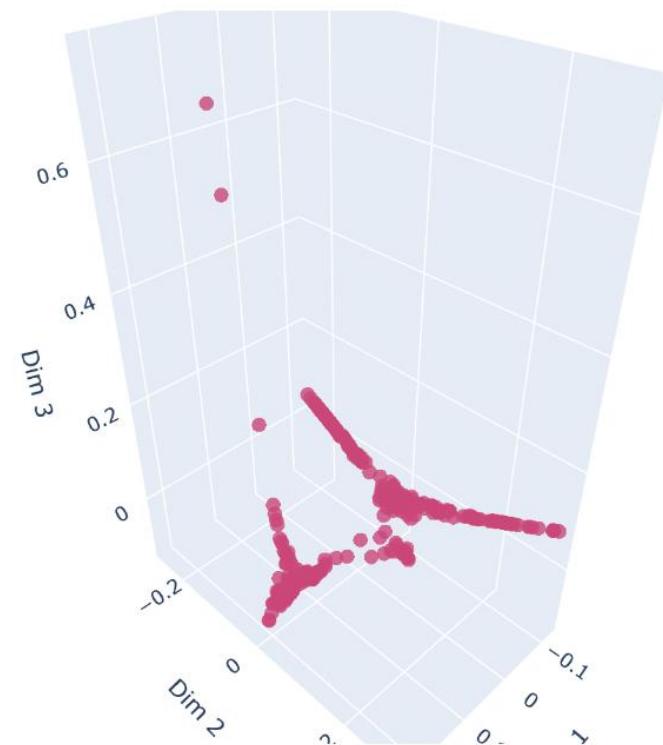
Neuron Diffusion Map (Stimulus Entropy Index)



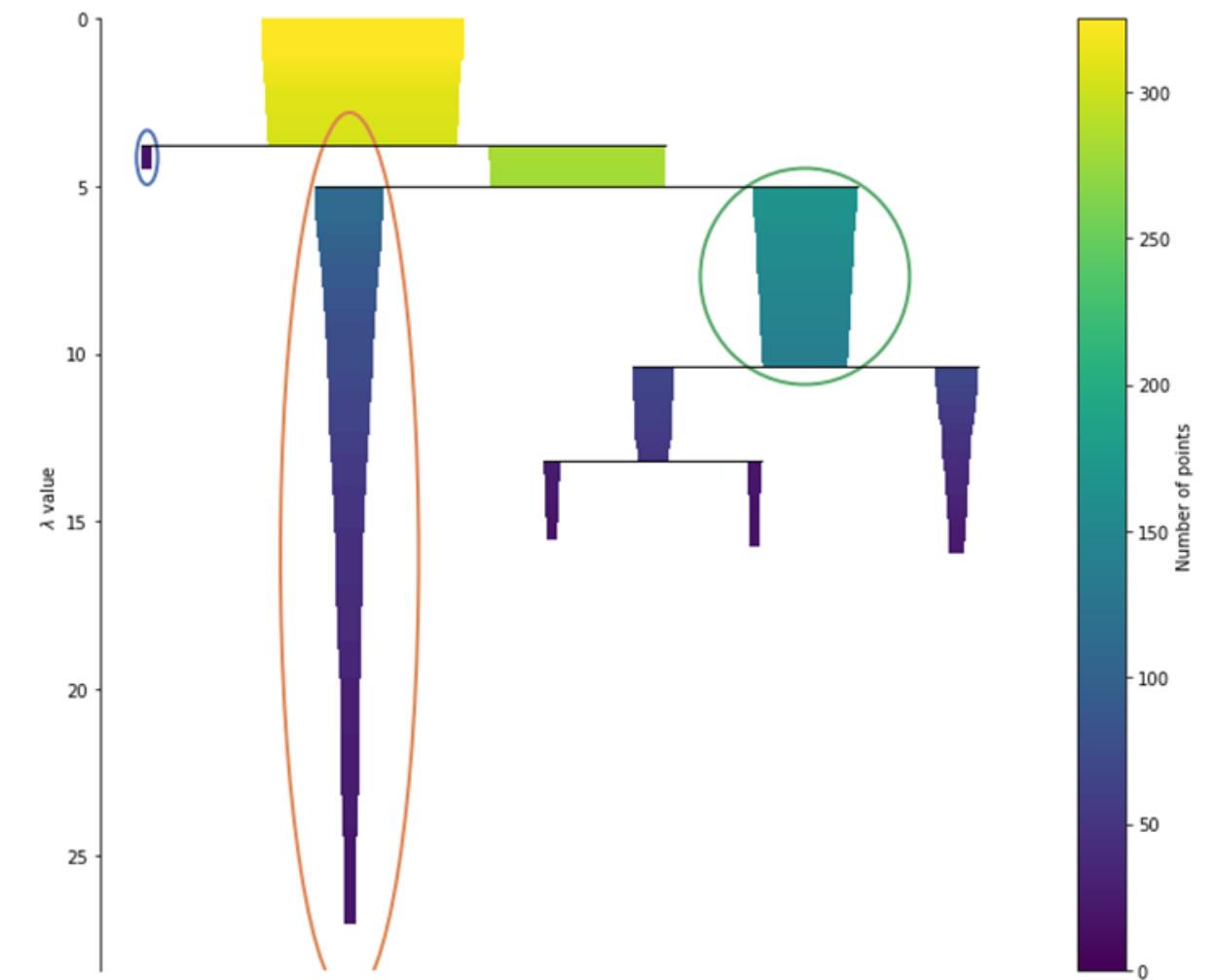
Neuron Diffusion Map (Dot Selectivity Index)



Neuron Diffusion Map (Negative Response Index)



Few suppressed cells in SC.



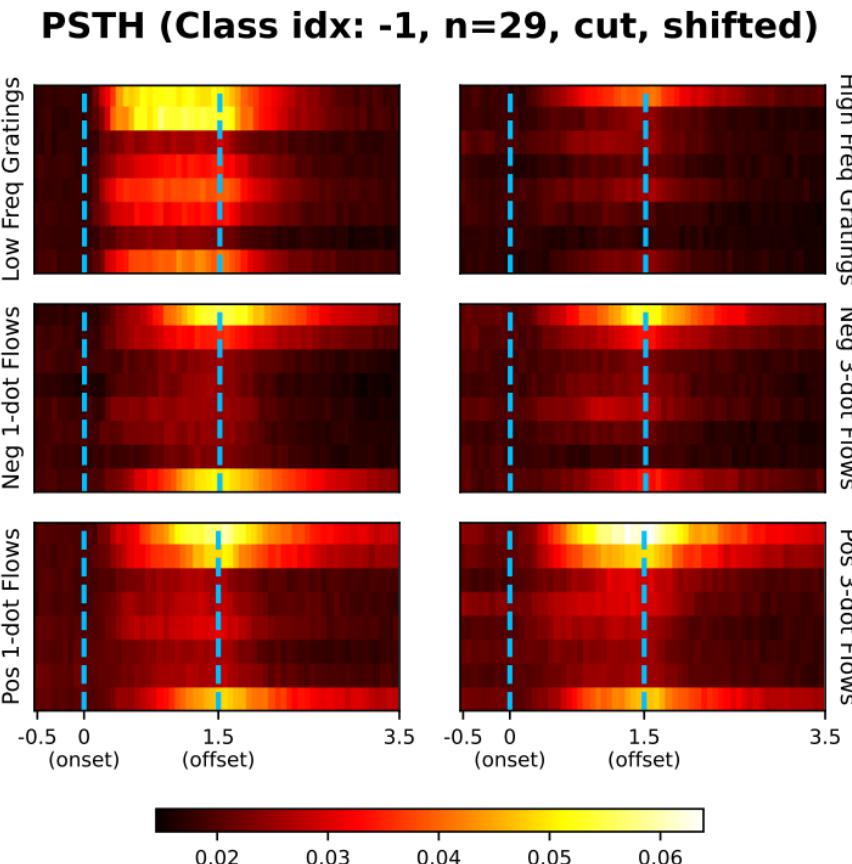
3 classes

`min_cluster_size=15`

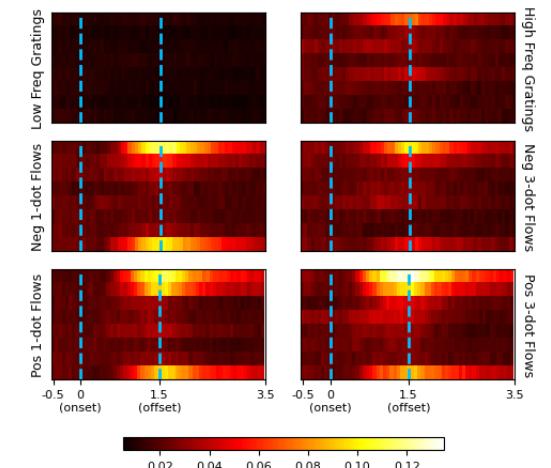
If `min_cluster_size=5, 8 clusters.`

Examples

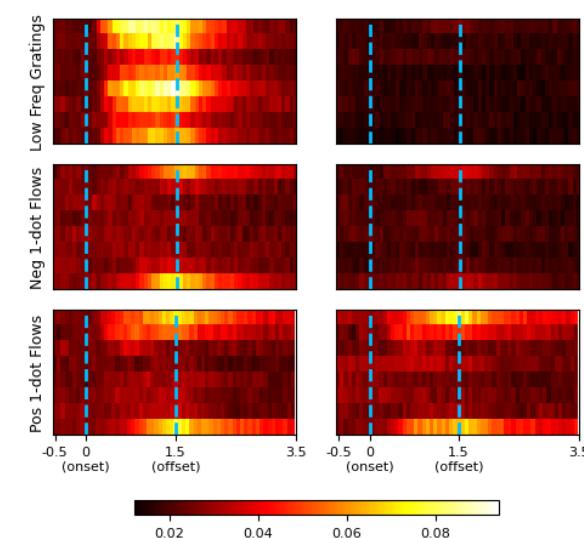
Class Avg PSTH



PSTH (Neuron idx: 230, Class idx: -1, cut, shifted)

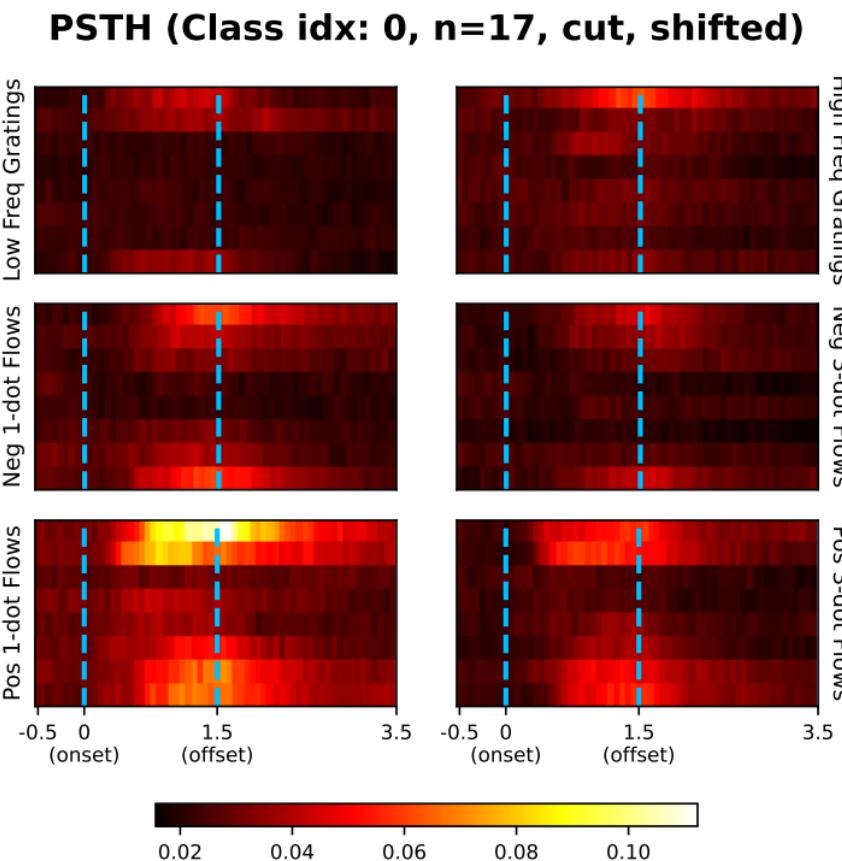


PSTH (Neuron idx: 102, Class idx: -1, cut, shifted)

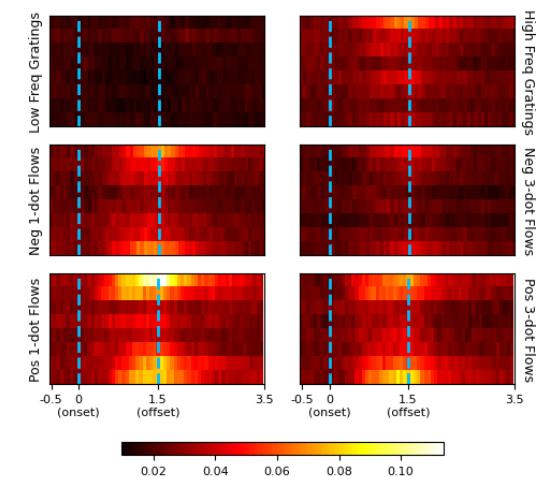


Examples

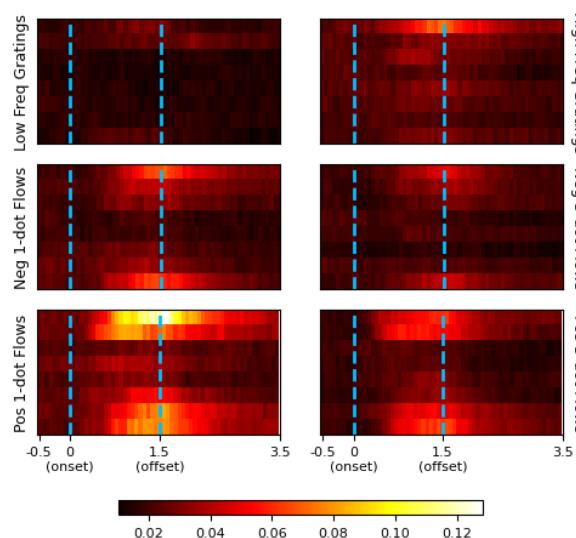
Class Avg PSTH



PSTH (Neuron idx: 315, Class idx: 0, cut, shifted)

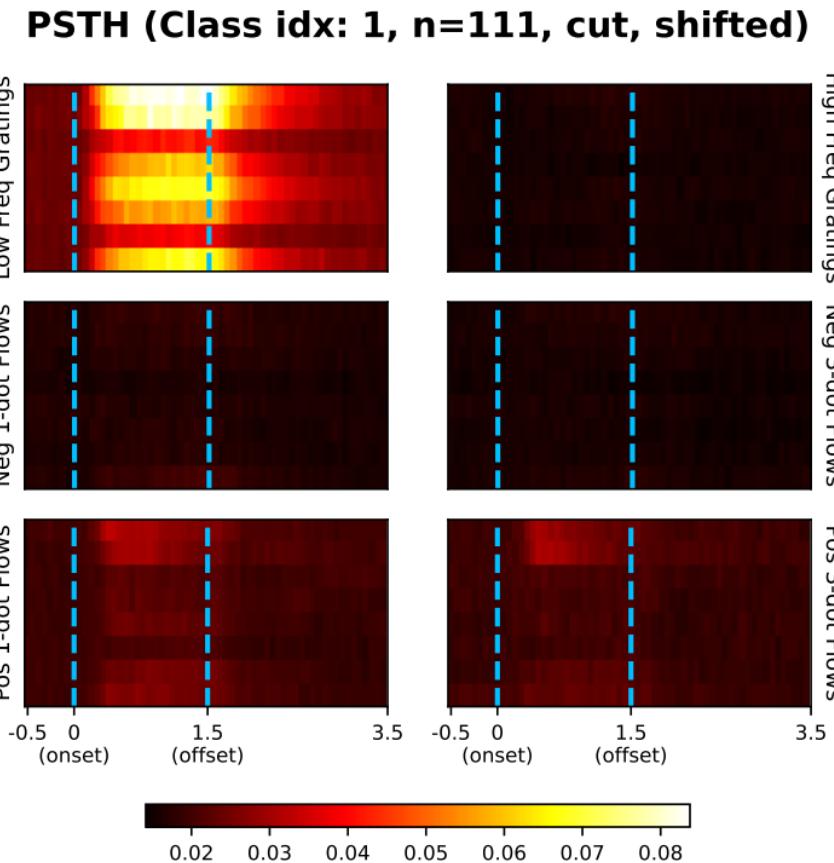


PSTH (Neuron idx: 310, Class idx: 0, cut, shifted)

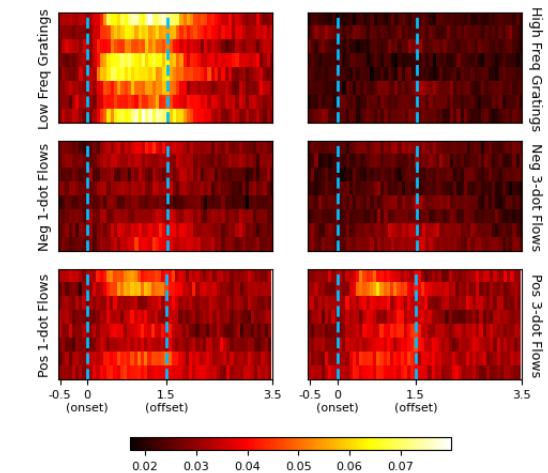


Examples

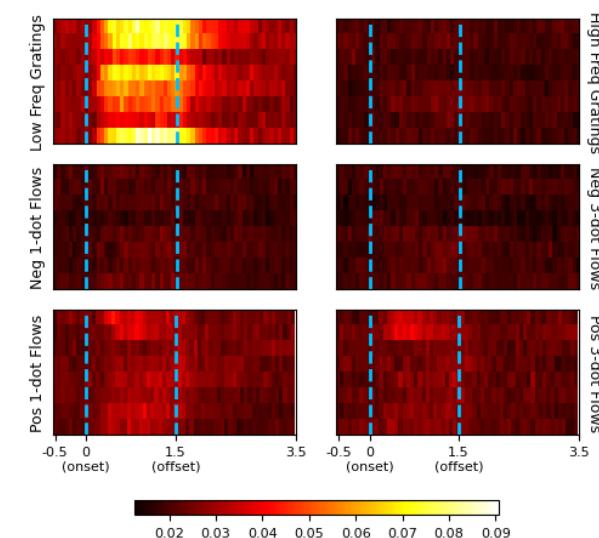
Class Avg PSTH



PSTH (Neuron idx: 178, Class idx: 1, cut, shifted)

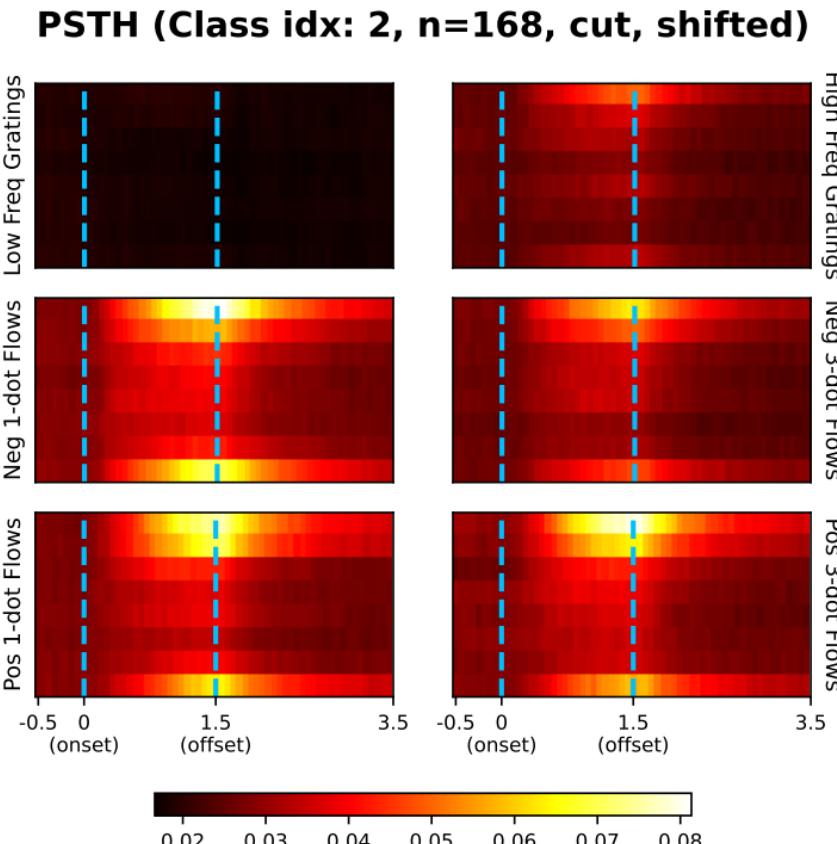


PSTH (Neuron idx: 101, Class idx: 1, cut, shifted)

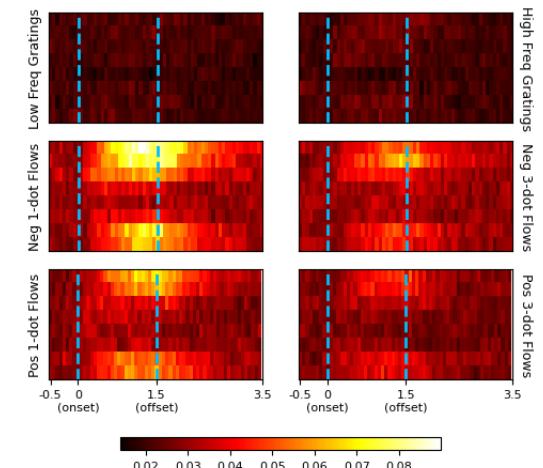


Examples

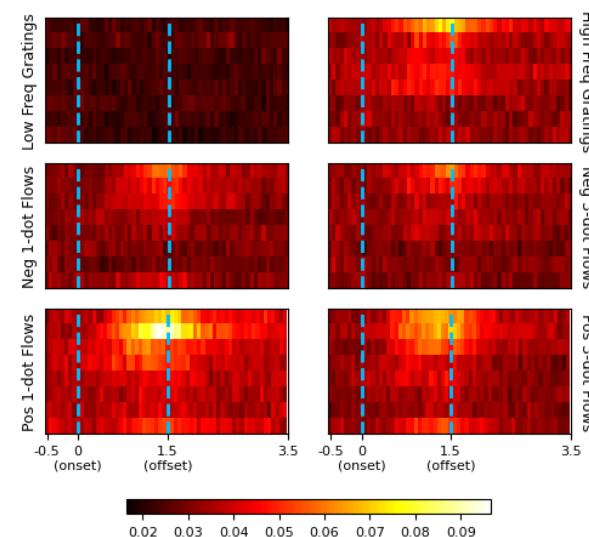
Class Avg PSTH



PSTH (Neuron idx: 79, Class idx: 2, cut, shifted)

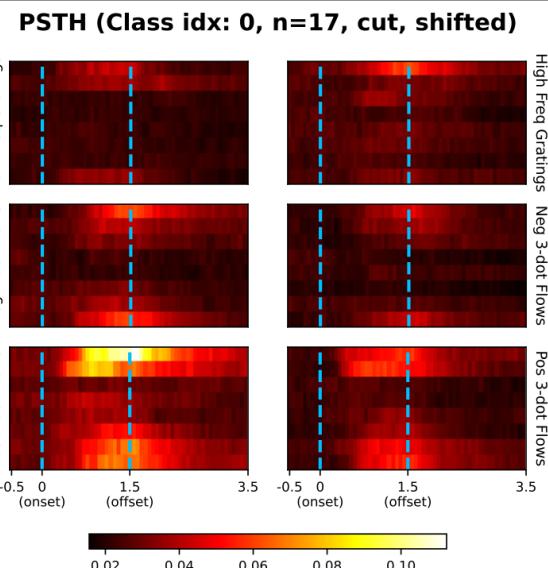


PSTH (Neuron idx: 202, Class idx: 2, cut, shifted)

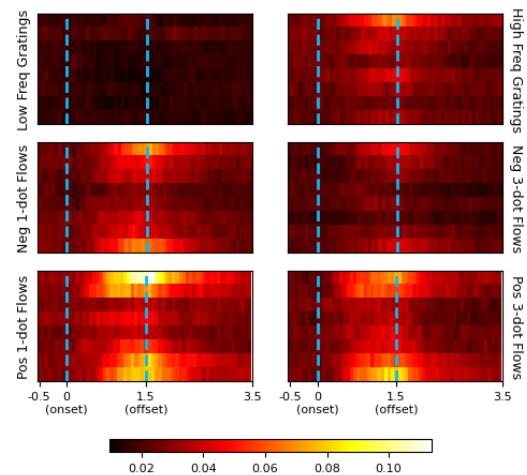


Examples

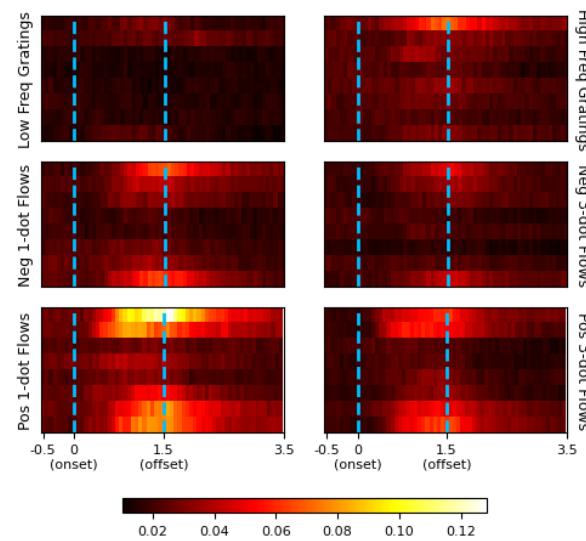
Class Avg PSTH (SC)



PSTH (Neuron idx: 315, Class idx: 0, cut, shifted)



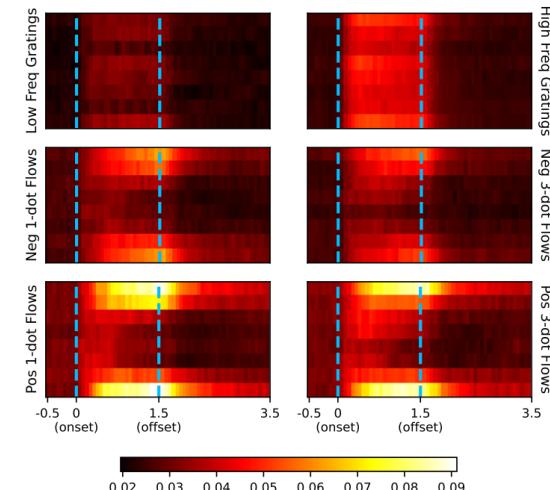
PSTH (Neuron idx: 310, Class idx: 0, cut, shifted)



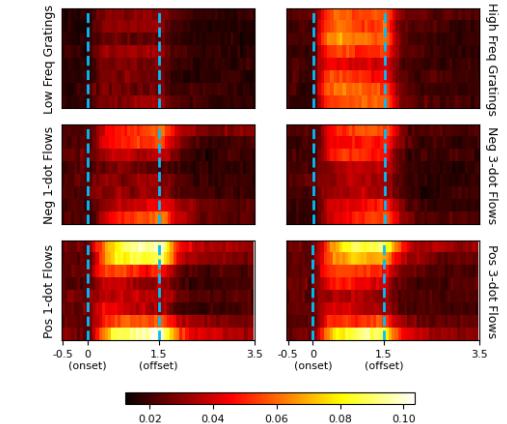
Most similar RGC class

Class Avg PSTH (RGC)

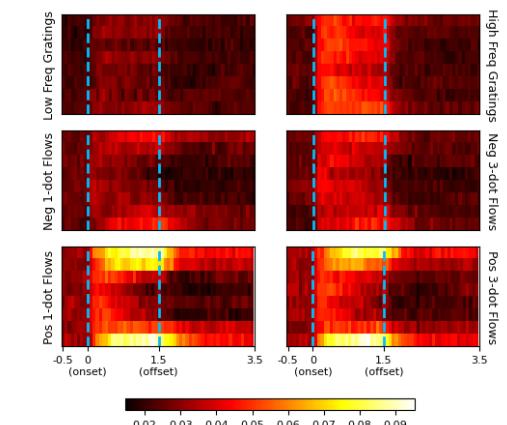
PSTH (Class idx: 3, n=23, cut, shifted)



PSTH (Neuron idx: 1124, Class idx: 3, cut, shifted)



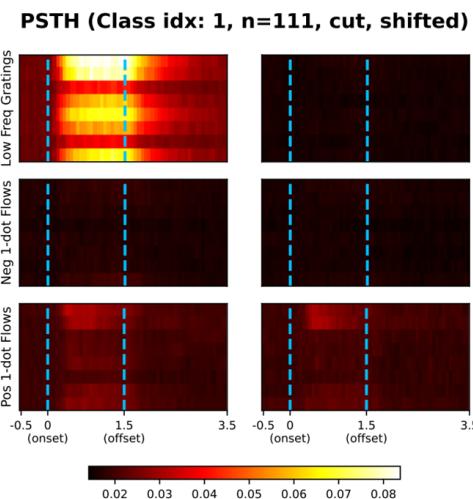
PSTH (Neuron idx: 1207, Class idx: 3, cut, shifted)



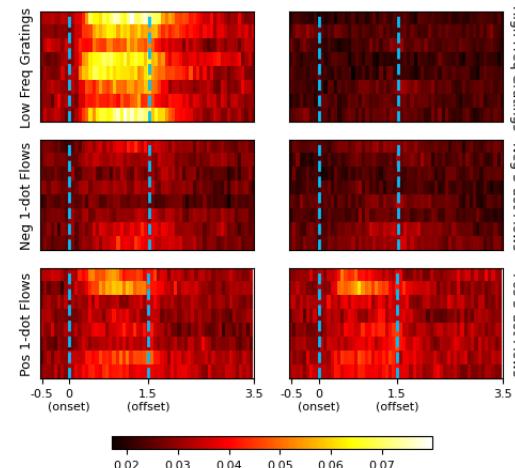
Examples

Examples

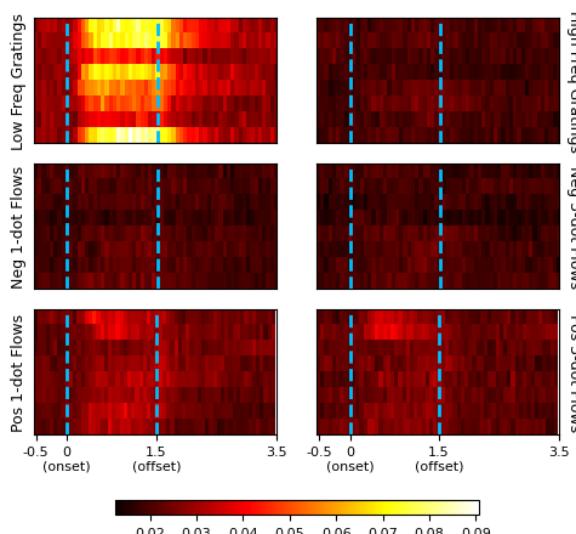
Class Avg PSTH (SC)



PSTH (Neuron idx: 178, Class idx: 1, cut, shifted)

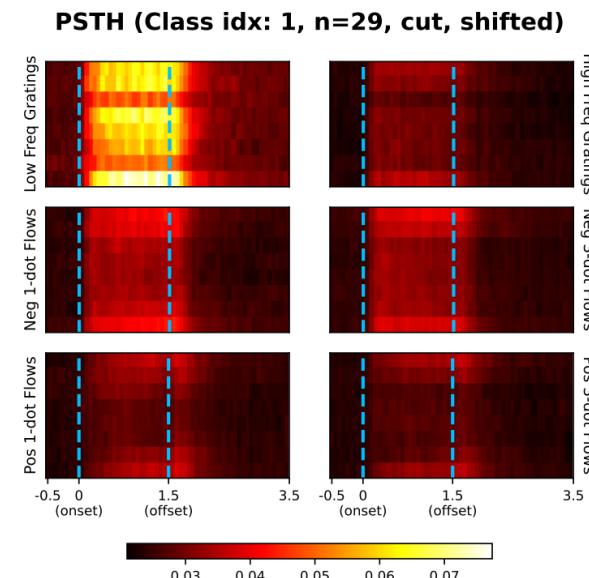


PSTH (Neuron idx: 101, Class idx: 1, cut, shifted)

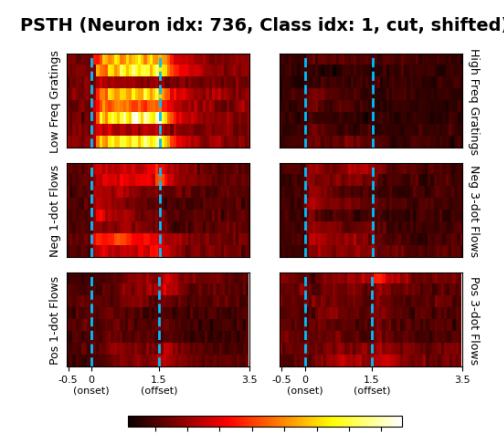
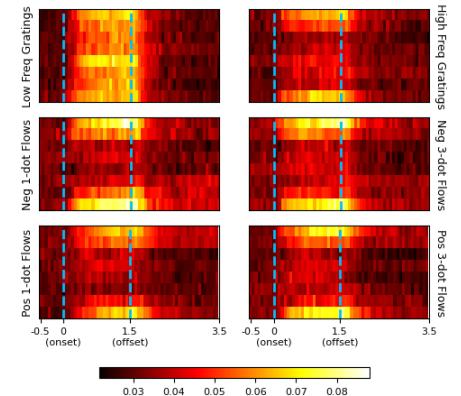


Most similar RGC class

Class Avg PSTH (RGC)



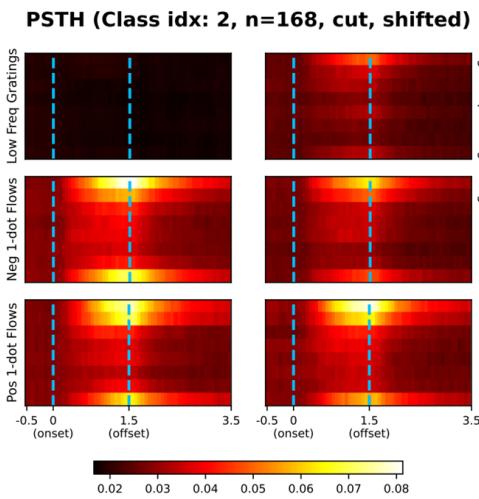
PSTH (Neuron idx: 228, Class idx: 1, cut, shifted)



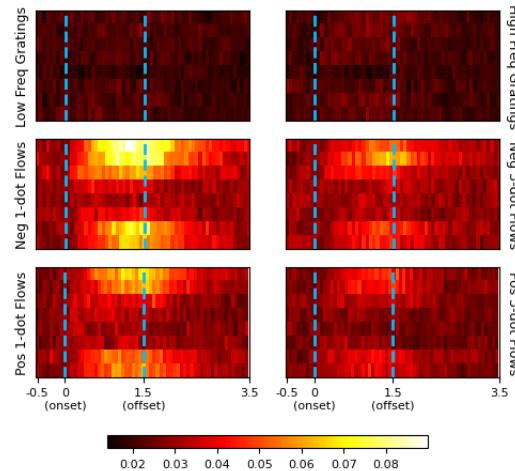
Examples

Examples

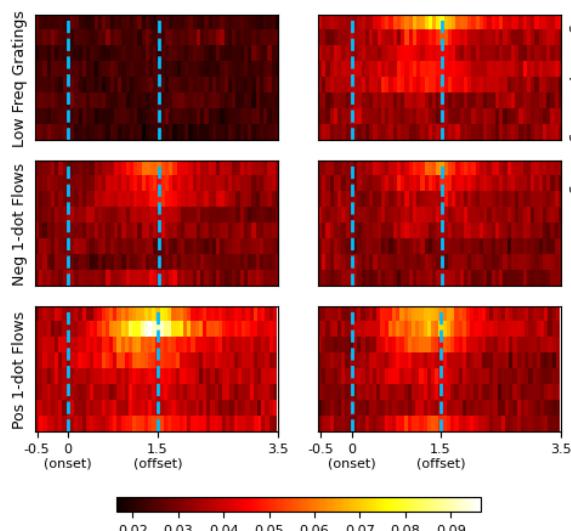
Class Avg PSTH (SC)



PSTH (Neuron idx: 79, Class idx: 2, cut, shifted)



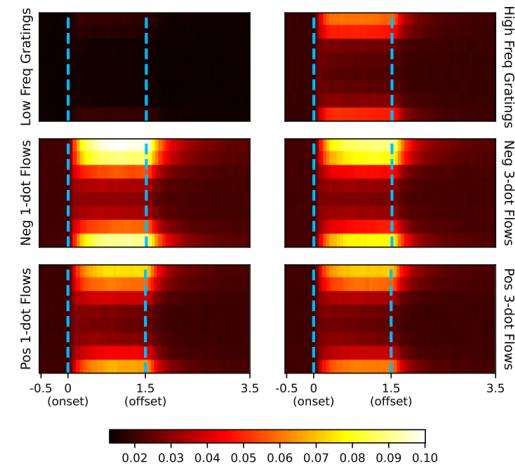
PSTH (Neuron idx: 202, Class idx: 2, cut, shifted)



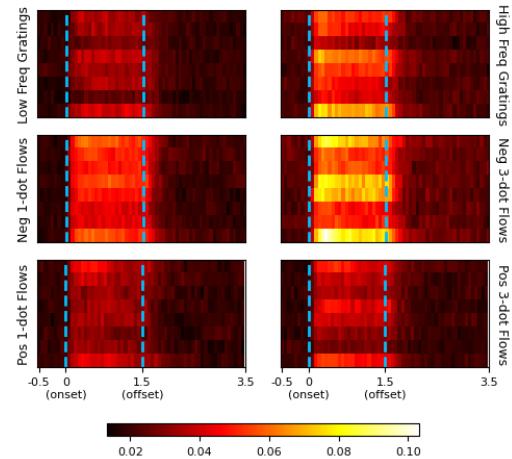
Most similar RGC class

Class Avg PSTH (RGC)

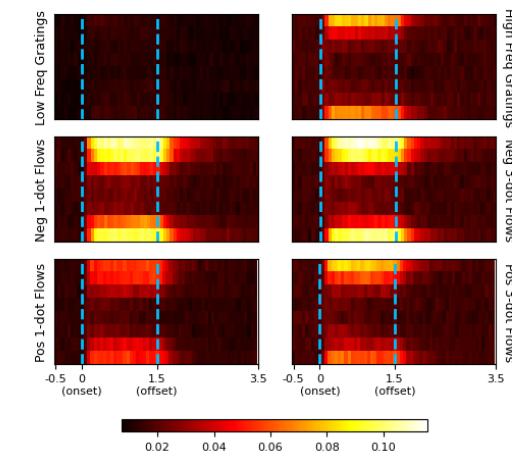
PSTH (Class idx: 8, n=536, cut, shifted)



PSTH (Neuron idx: 56, Class idx: 8, cut, shifted)



PSTH (Neuron idx: 1714, Class idx: 8, cut, shifted)



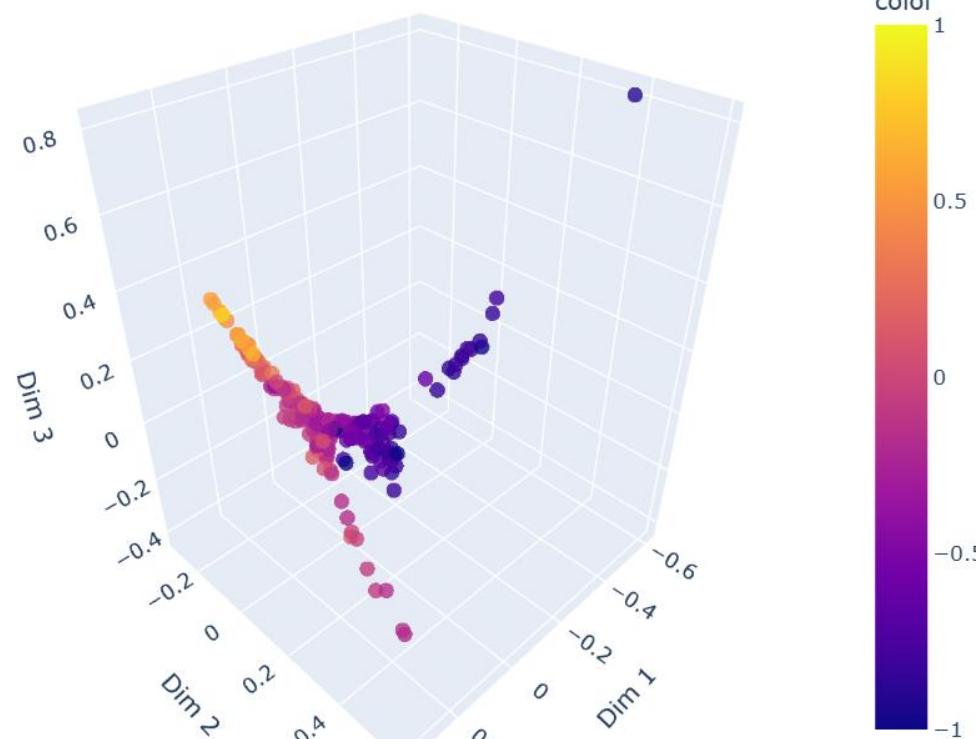
Examples

dLGN
229 significant neurons

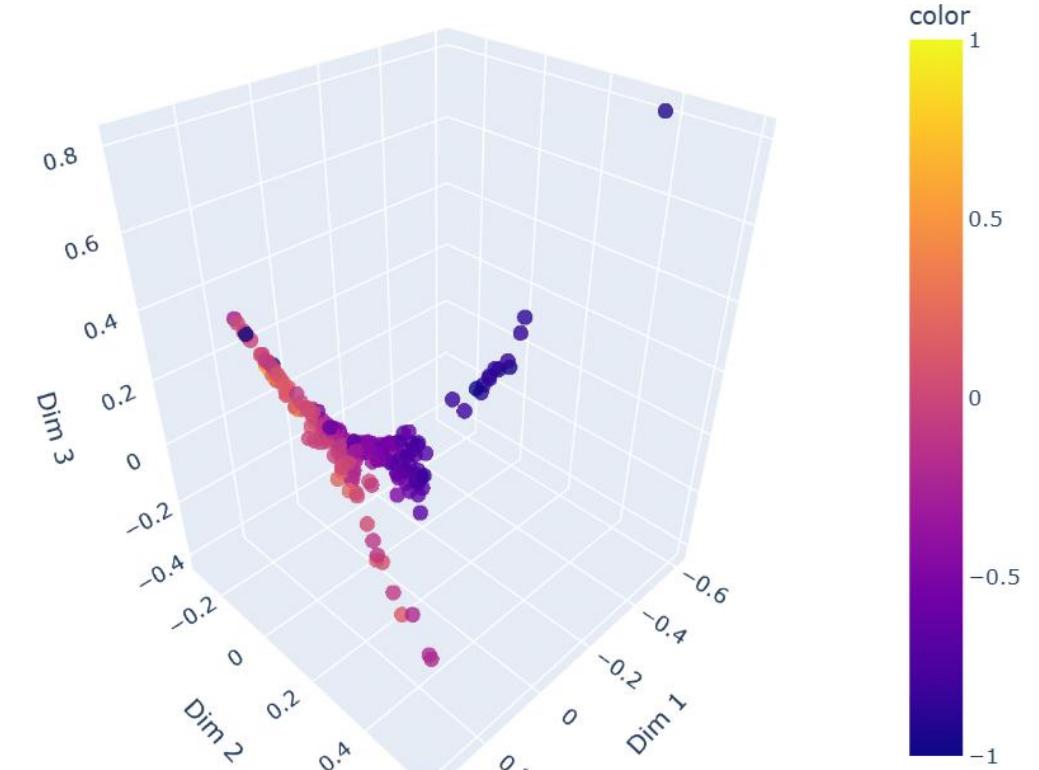
$$\text{Grating Selectivity Index} = \frac{\Delta R_g - \Delta R_f}{|\Delta R_g| + |\Delta R_f|}$$

$$\text{Flow Polarity Index} = \frac{\Delta R_{\text{pf}} - \Delta R_{\text{nf}}}{|\Delta R_{\text{pf}}| + |\Delta R_{\text{nf}}|}$$

Neuron Diffusion Map (Grating Selectivity Index)



Neuron Diffusion Map (Flow Polarity Index)



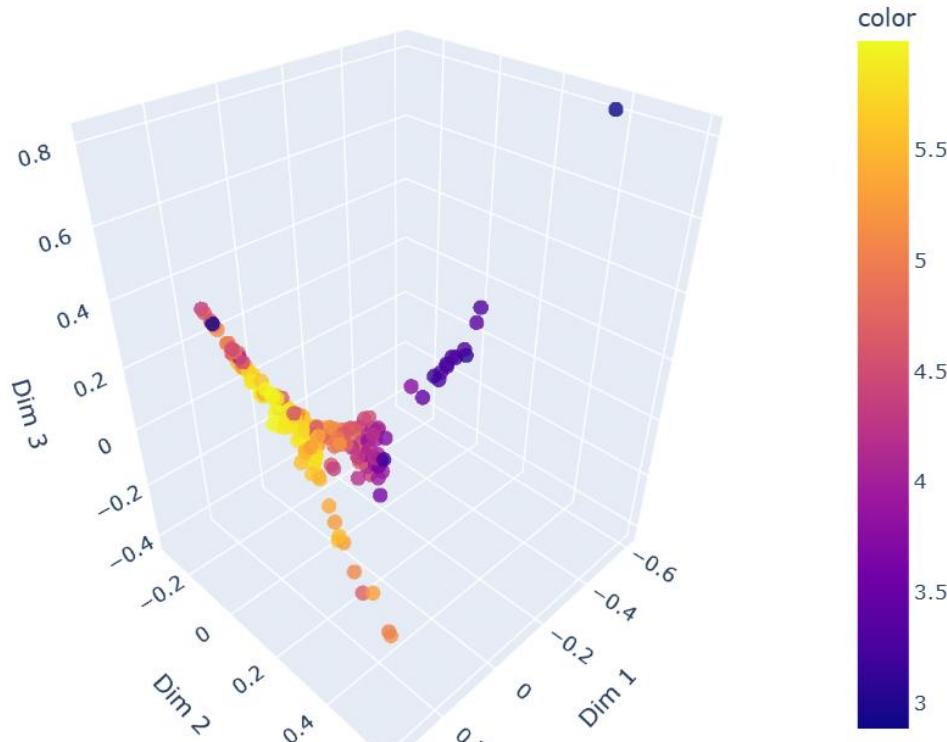
Higher stimulus specificity: An index close to 1 indicates strong selectivity — the neuron responds strongly to a specific stimulus and weakly (or not at all) to others.

Uniform responses: An index close to 6 indicates no selectivity — the neuron has similar amplitudes across all six stimuli.

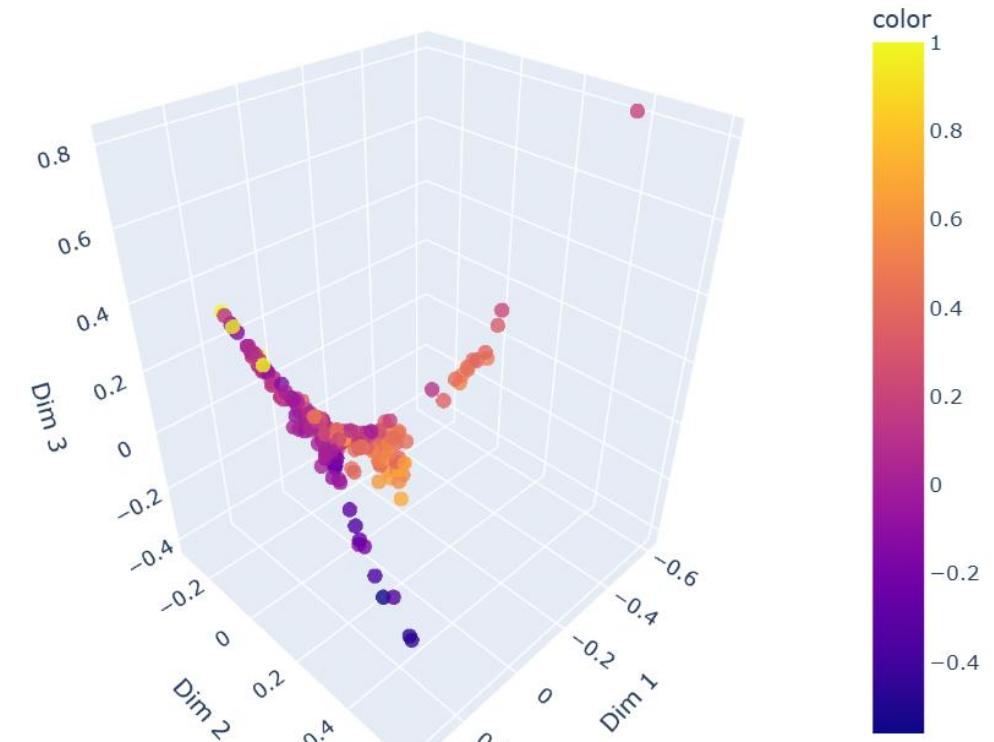
Note: the index only reflects the response magnitudes only. It does not distinguish the signs of responses.

$$\text{Dot Selectivity Index} = \frac{\Delta R_{1\text{dot}} - \Delta R_{3\text{dot}}}{|\Delta R_{1\text{dot}}| + |\Delta R_{3\text{dot}}|}$$

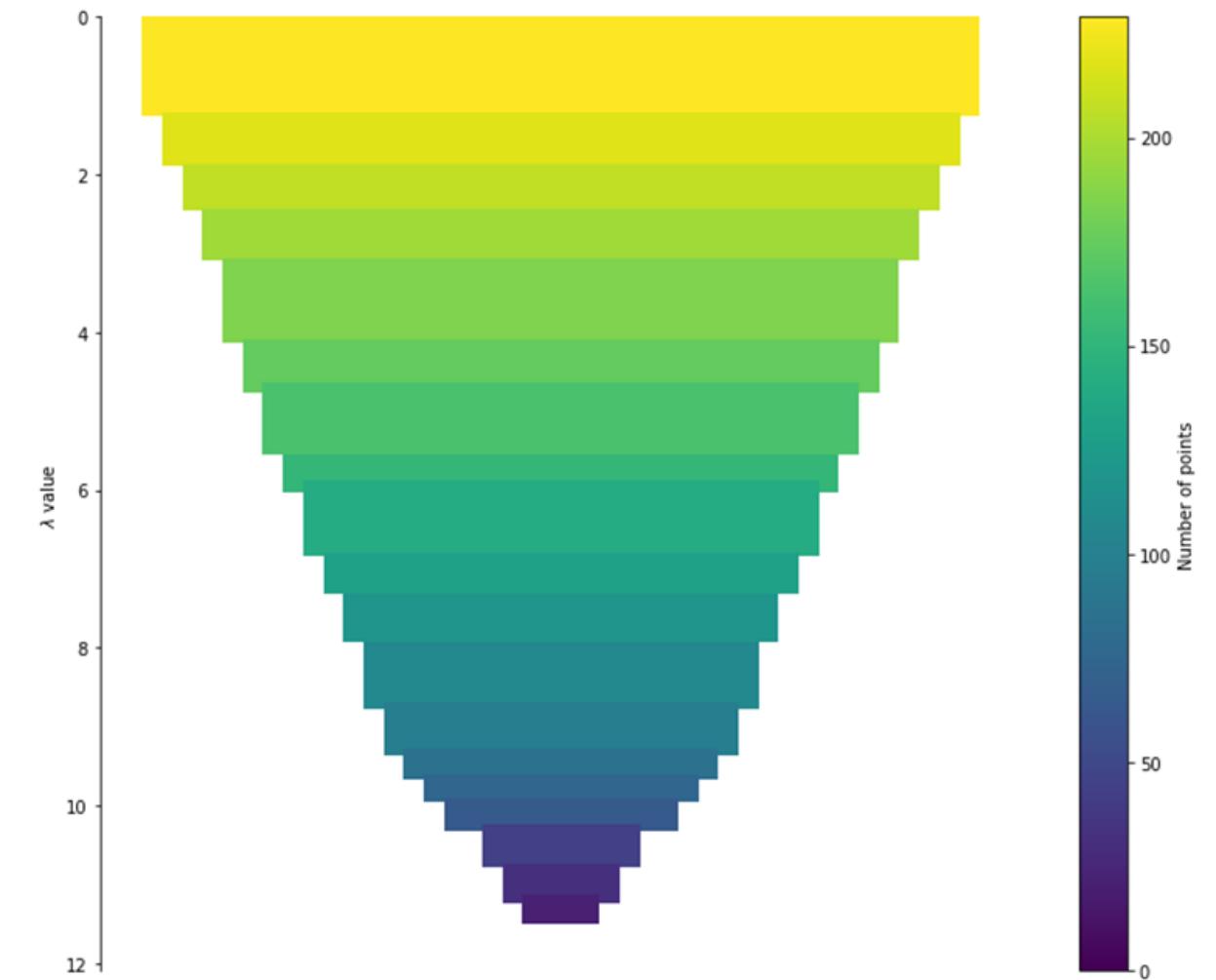
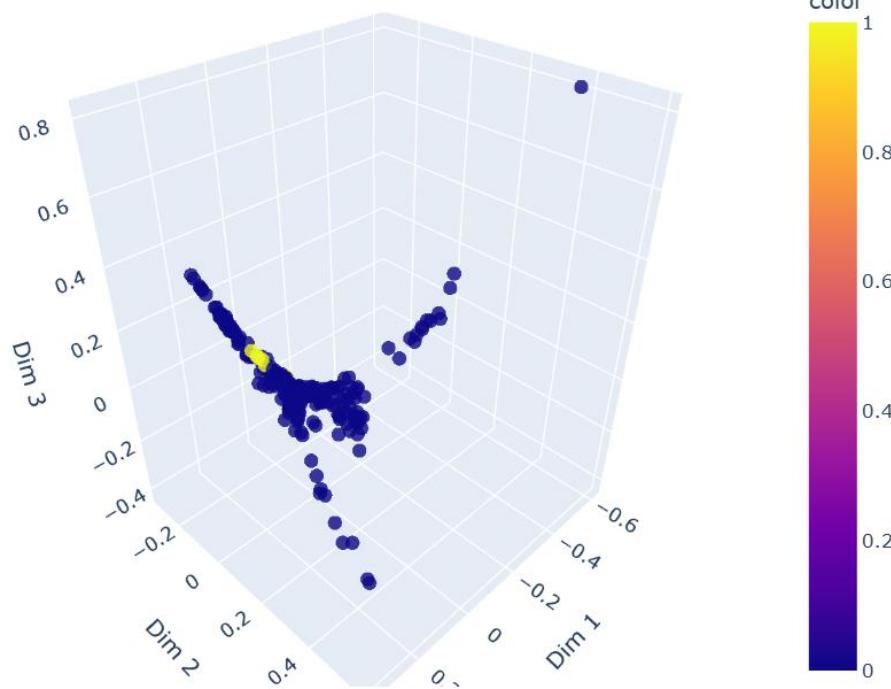
Neuron Diffusion Map (Stimulus Entropy Index)



Neuron Diffusion Map (Dot Selectivity Index)



Neuron Diffusion Map (Negative Response Index)



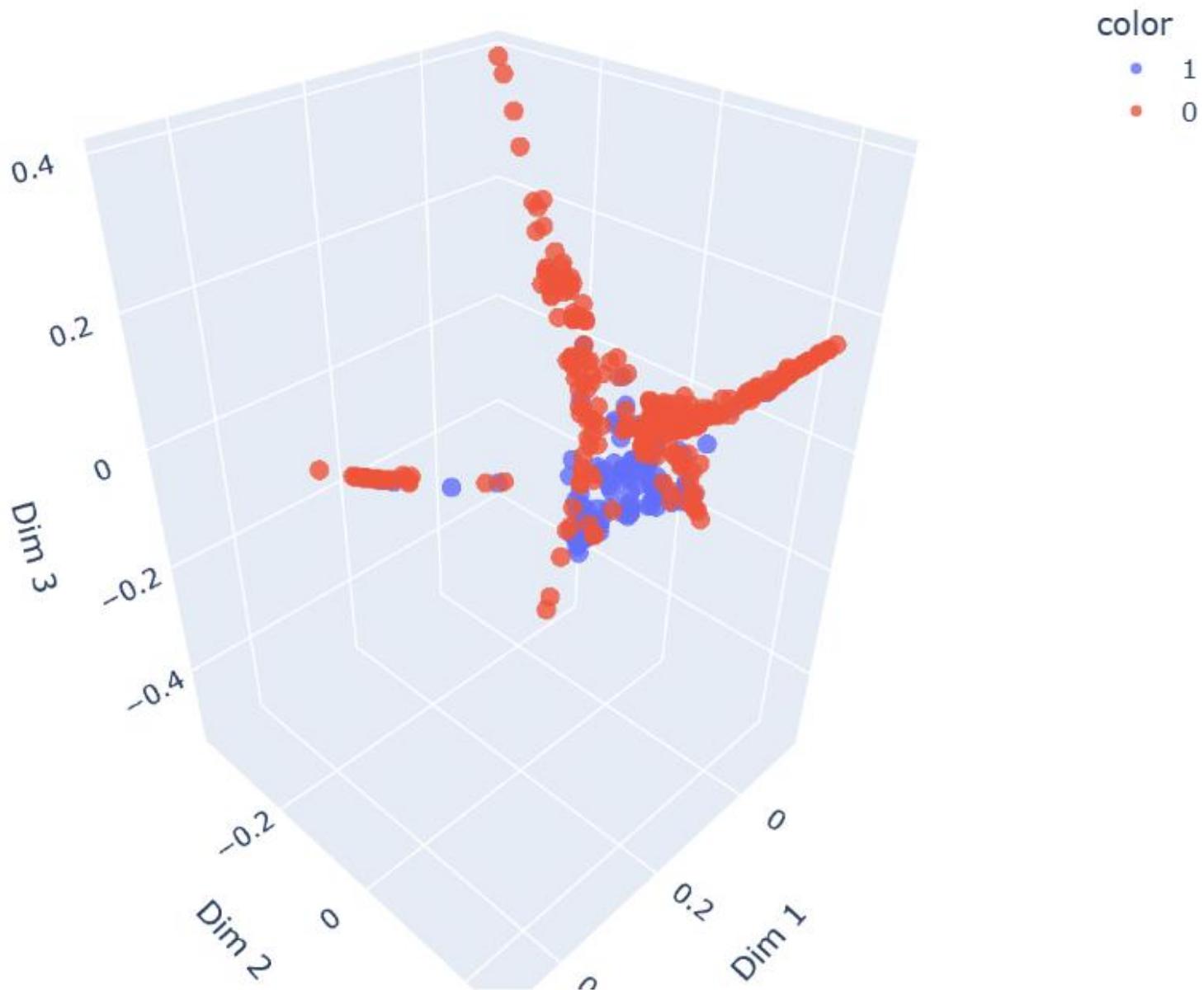
continuous

`min_cluster_size=15`

If `min_cluster_size=5`, 2 clusters.

dLGN+RGC
(117 neurons + 300 boutons, both significant)

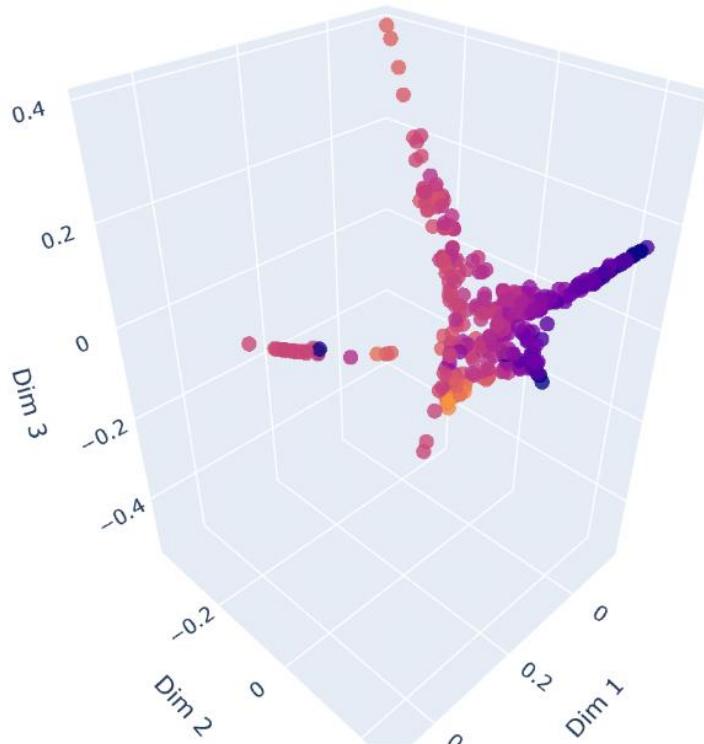
Neuron Diffusion Map (dLGN_RGC_labels (1:dLGN, 0:RGC))



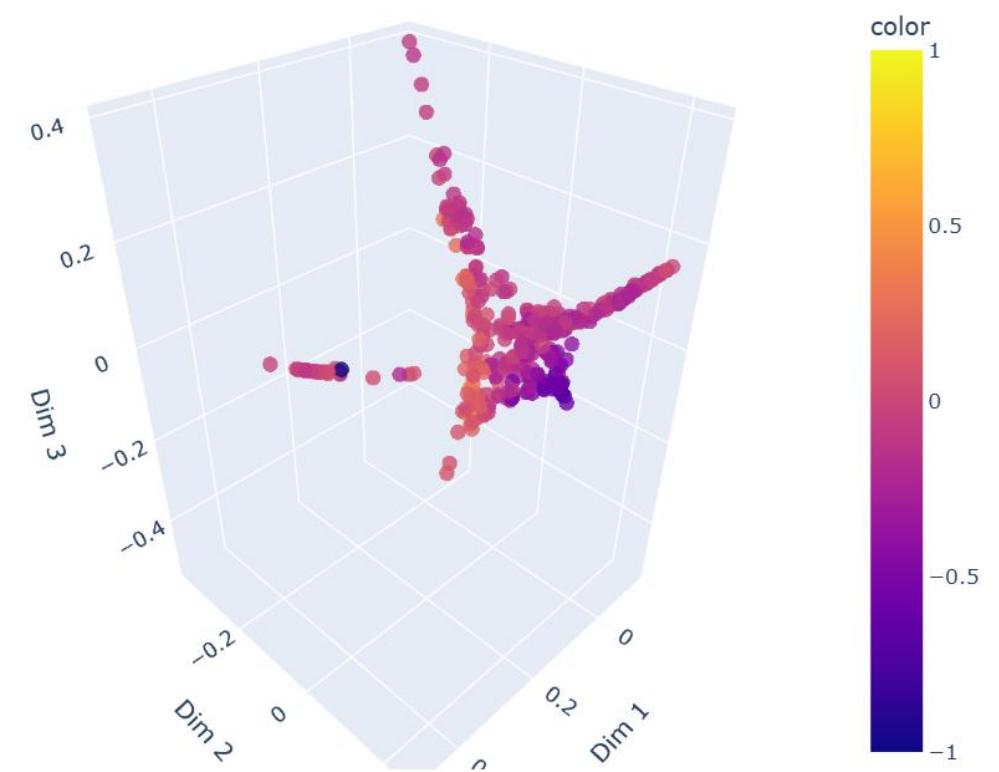
$$\text{Grating Selectivity Index} = \frac{\Delta R_g - \Delta R_f}{|\Delta R_g| + |\Delta R_f|}$$

$$\text{Flow Polarity Index} = \frac{\Delta R_{\text{pf}} - \Delta R_{\text{nf}}}{|\Delta R_{\text{pf}}| + |\Delta R_{\text{nf}}|}$$

Neuron Diffusion Map (Grating Selectivity Index)



Neuron Diffusion Map (Flow Polarity Index)



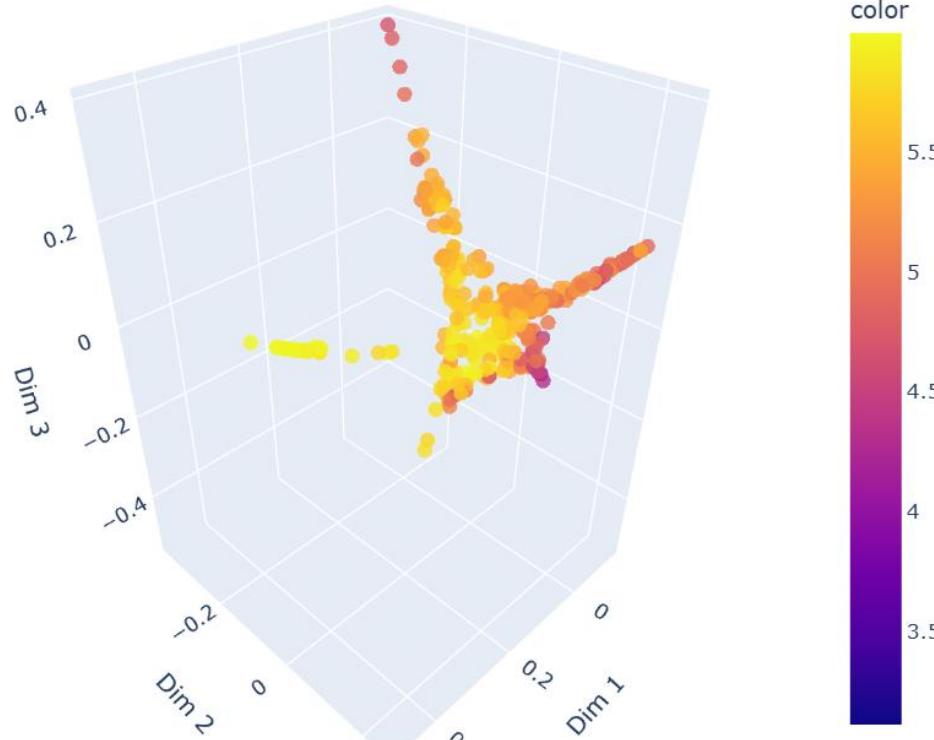
Higher stimulus specificity: An index close to 1 indicates strong selectivity — the neuron responds strongly to a specific stimulus and weakly (or not at all) to others.

Uniform responses: An index close to 6 indicates no selectivity — the neuron has similar amplitudes across all six stimuli.

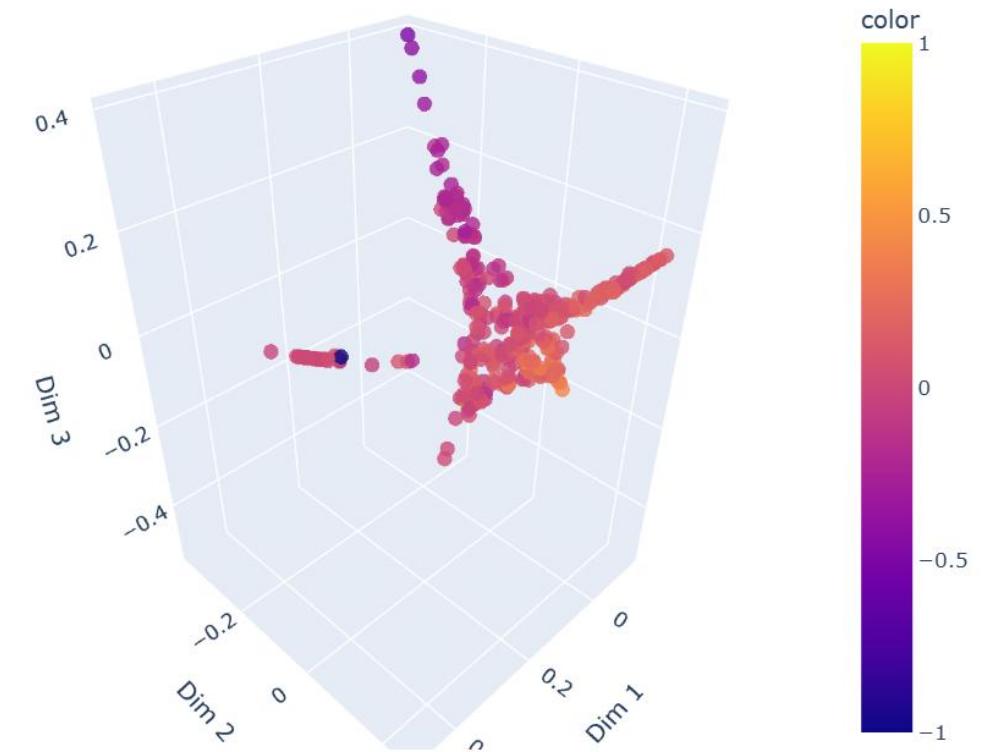
Note: the index only reflects the response magnitudes only. It does not distinguish the signs of responses.

$$\text{Dot Selectivity Index} = \frac{\Delta R_{1\text{dot}} - \Delta R_{3\text{dot}}}{|\Delta R_{1\text{dot}}| + |\Delta R_{3\text{dot}}|}$$

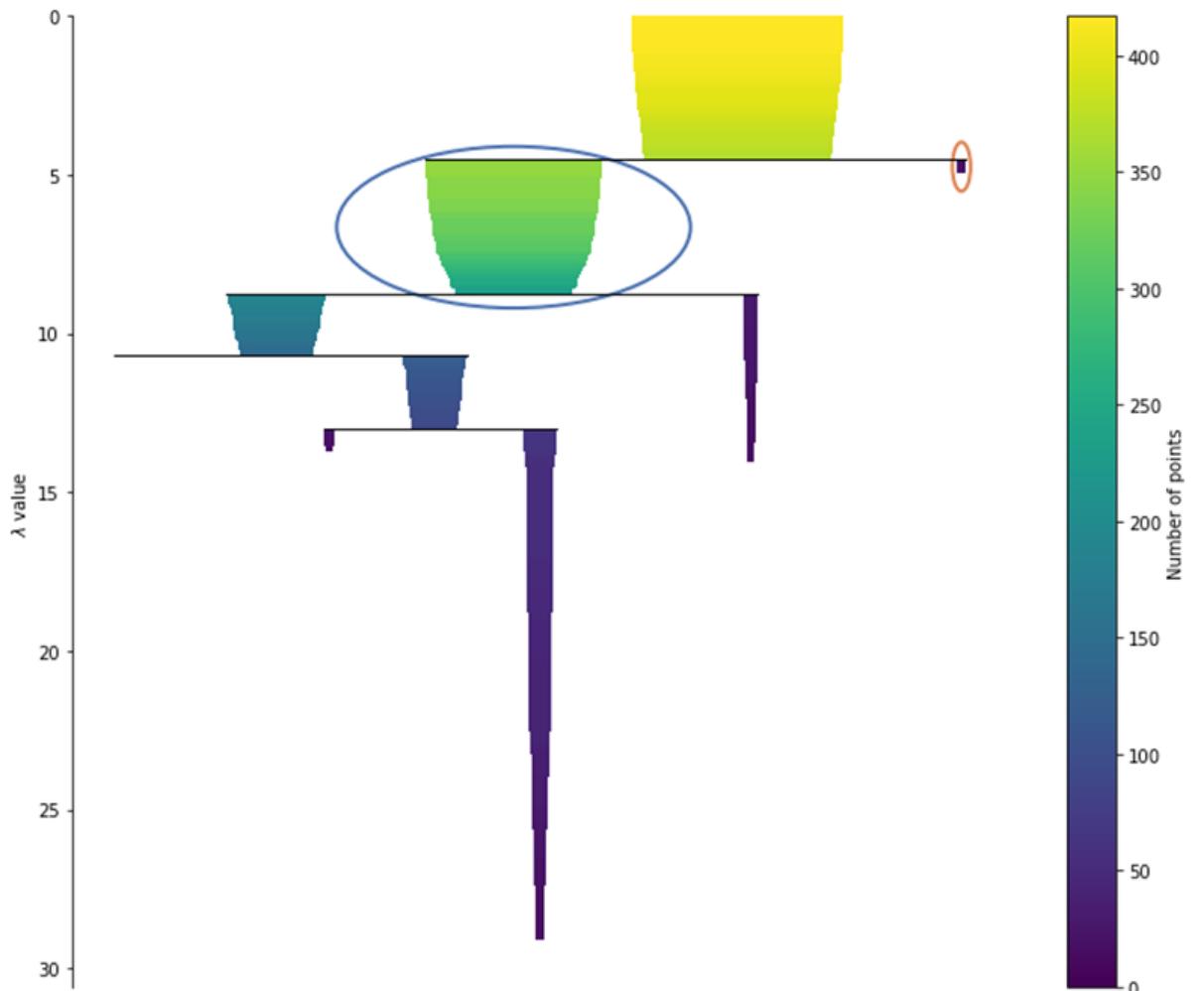
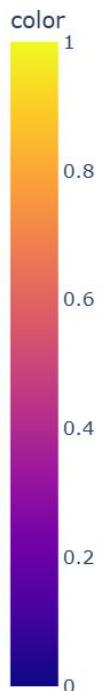
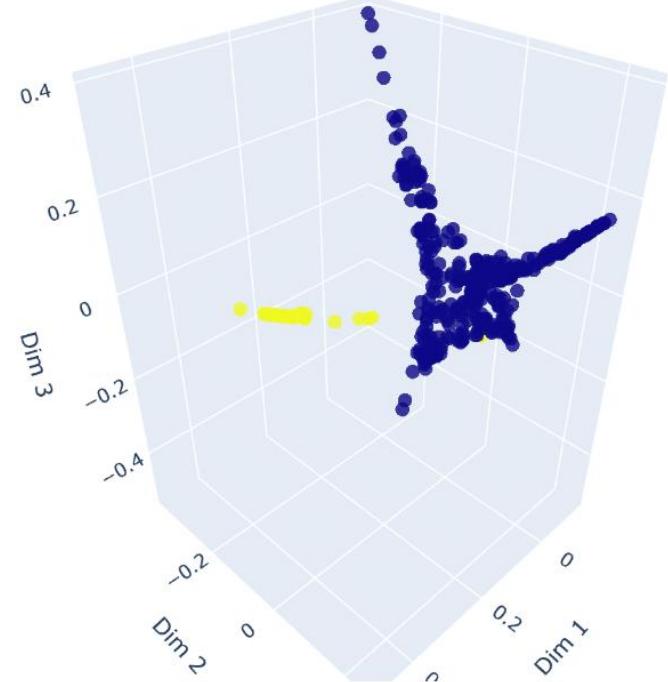
Neuron Diffusion Map (Stimulus Entropy Index)



Neuron Diffusion Map (Dot Selectivity Index)



Neuron Diffusion Map (Negative Response Index)



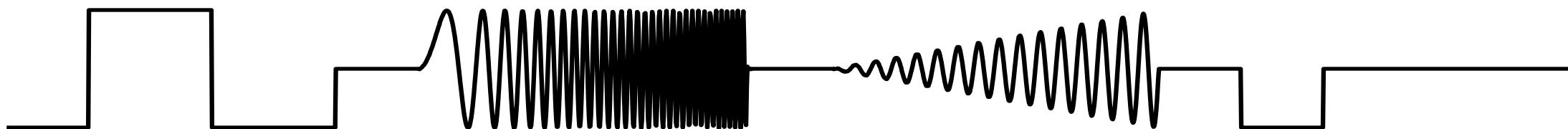
2 clusters

`min_cluster_size=15`

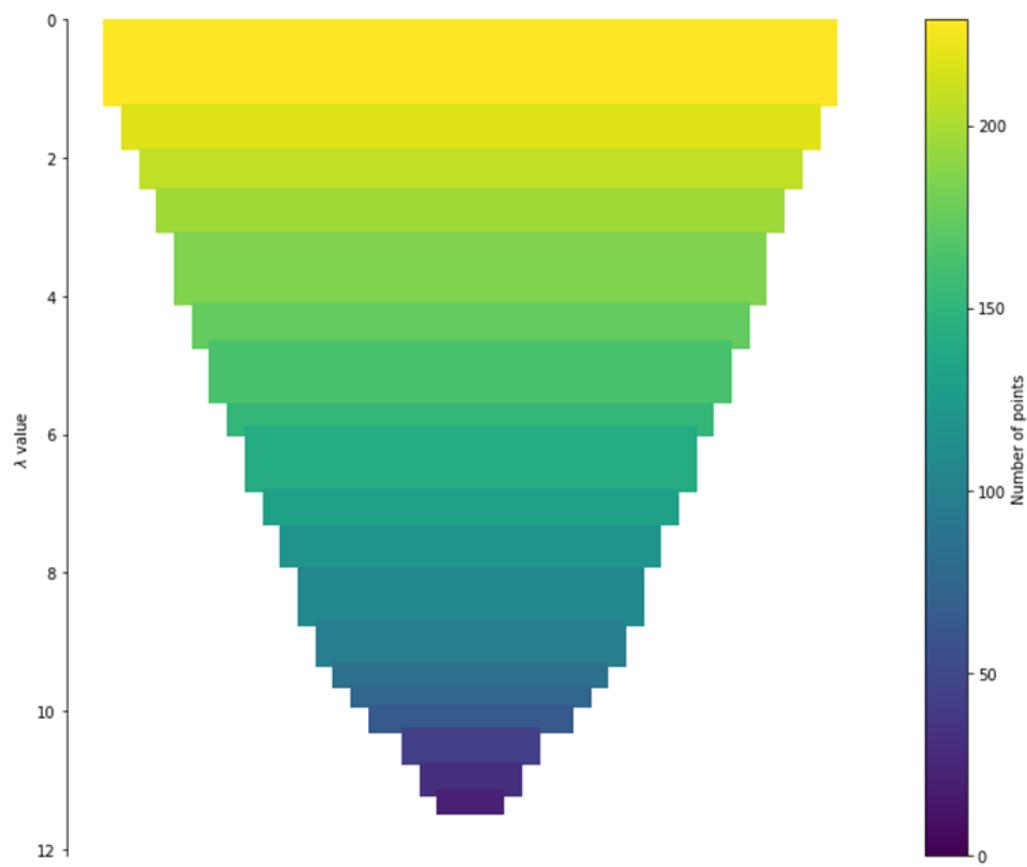
If `min_cluster_size=5`, 16 clusters.

Chirp based analysis (dLGN and RGC)

Our chirp

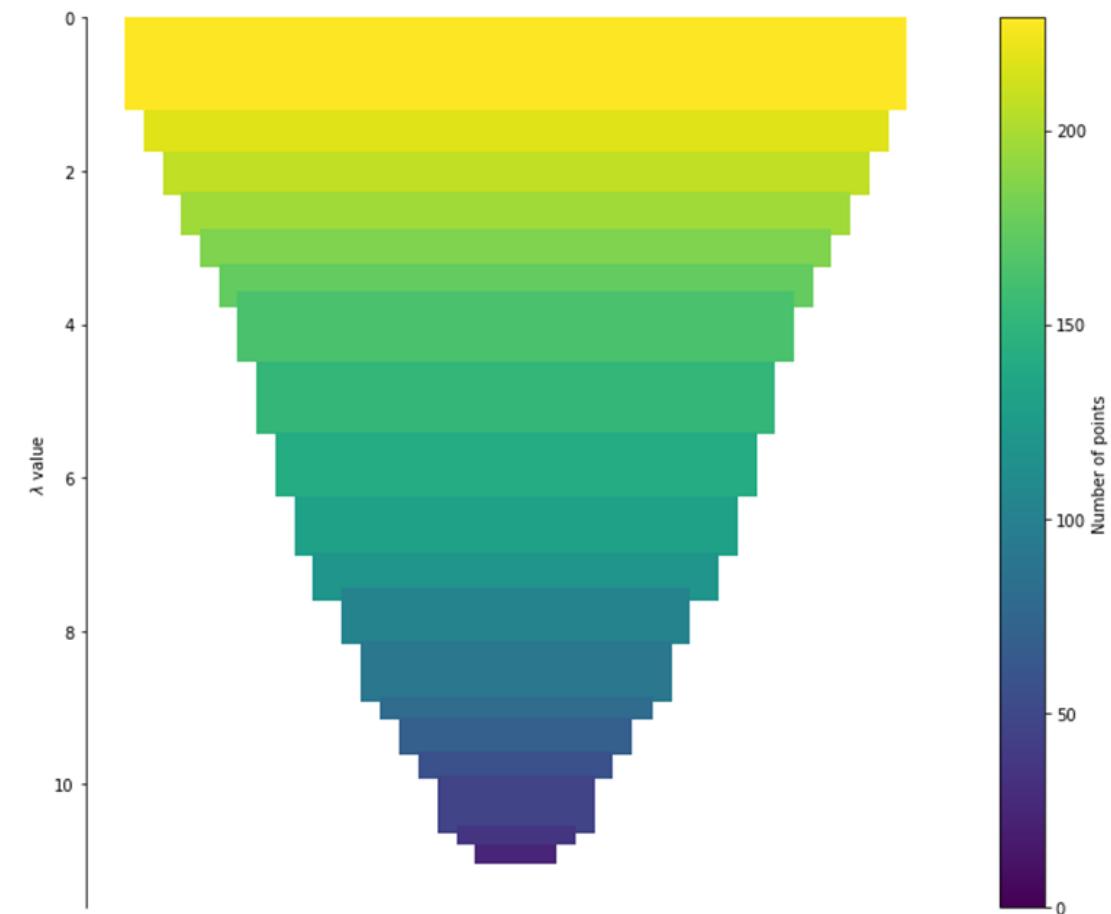


48-stim based dLGN results



If `min_cluster_size=5`, 2 clusters.

Chirp based dLGN results
(min-max normalization)



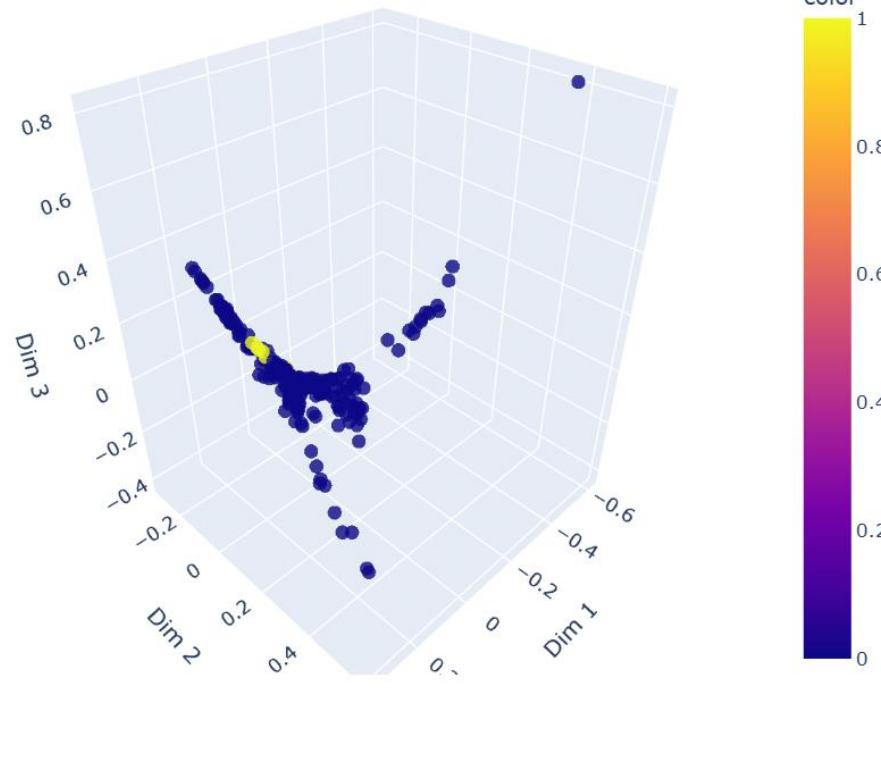
`min_cluster_size=15`

If `min_cluster_size=5`, 2 clusters.

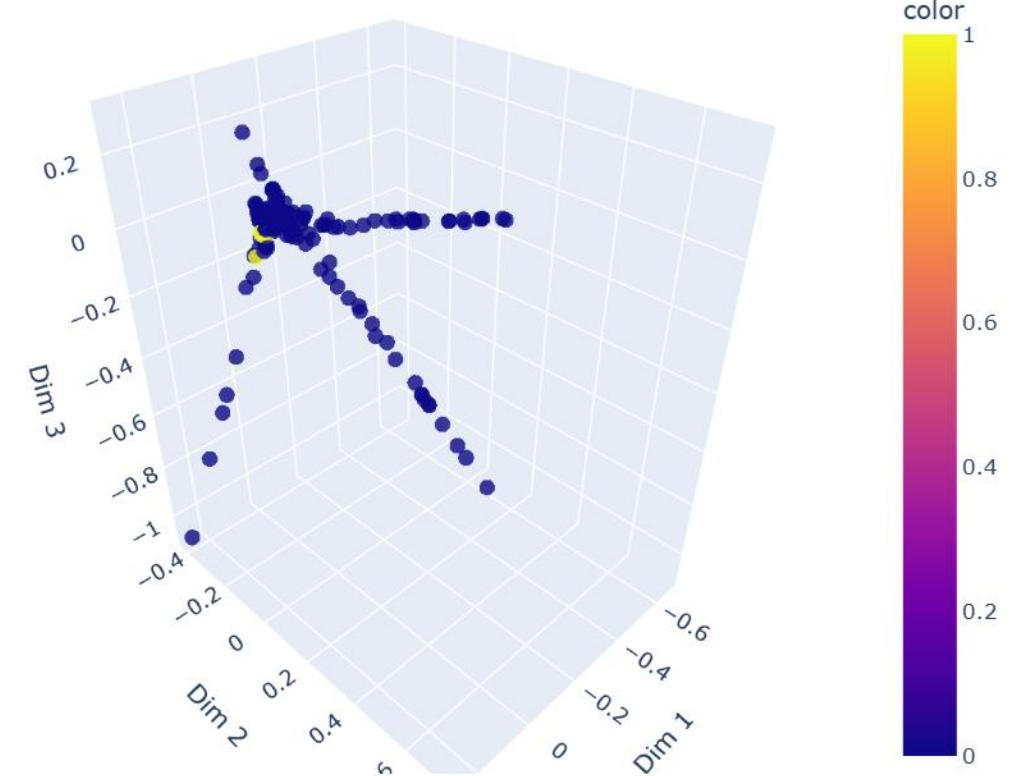
48-stim based dLGN results

Chirp based dLGN results
(min-max normalization)

Neuron Diffusion Map (Negative Response Index)



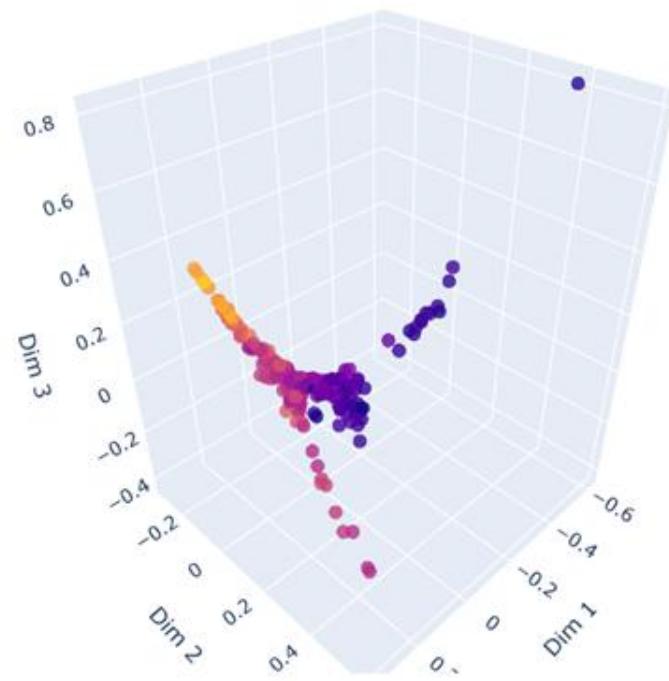
Neuron Diffusion Map (Negative Response Index)



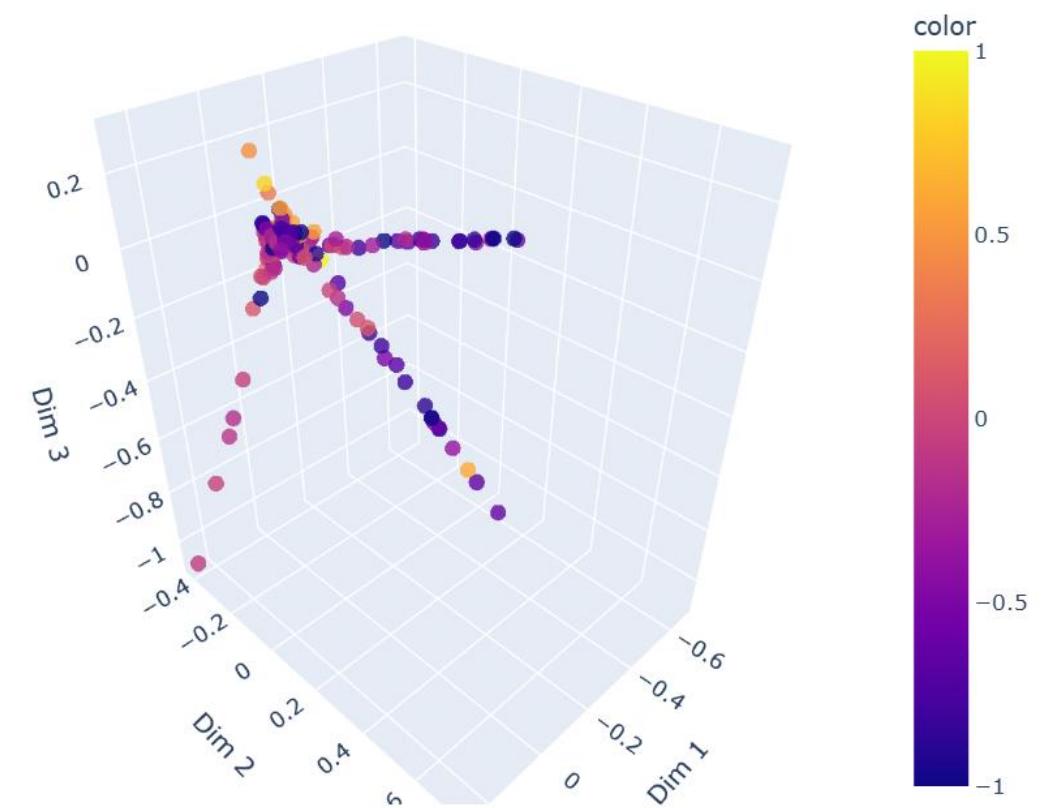
48-stim based dLGN results

Chirp based dLGN results
(min-max normalization)

Neuron Diffusion Map (Grating Selectivity Index)

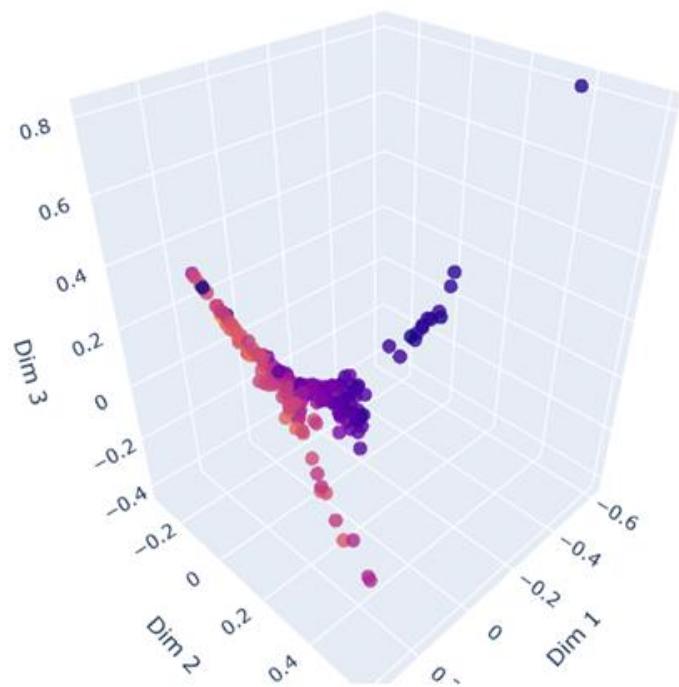


Neuron Diffusion Map (Grating Selectivity Index)



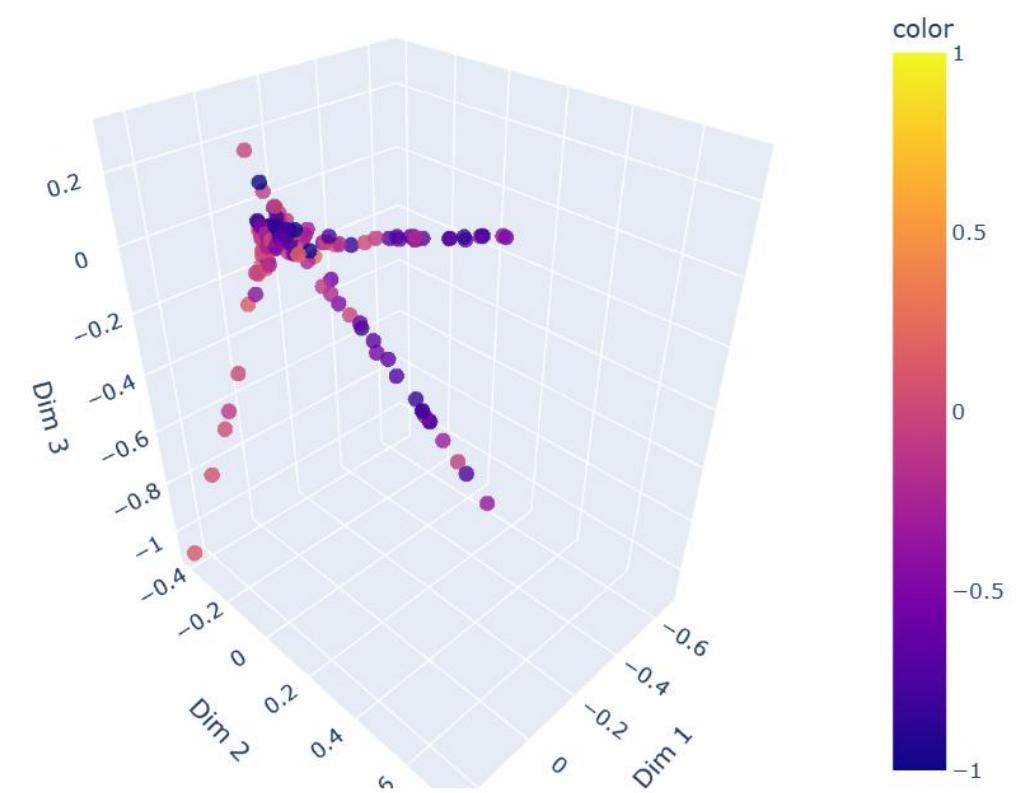
48-stim based dLGN results

Neuron Diffusion Map (Flow Polarity Index)



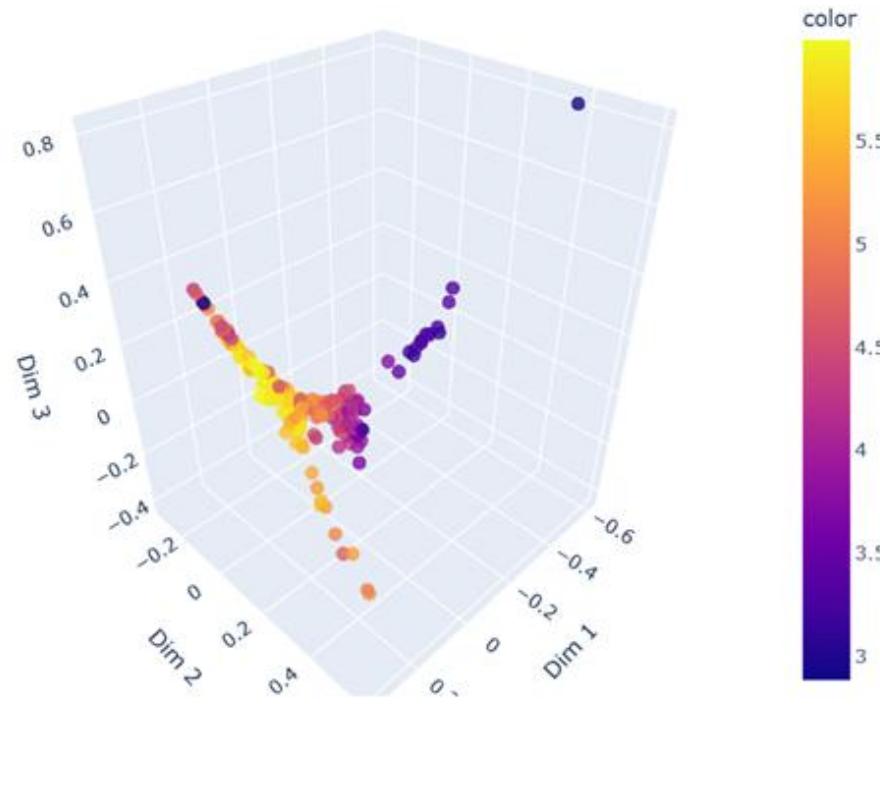
Chirp based dLGN results
(min-max normalization)

Neuron Diffusion Map (Flow Polarity Index)



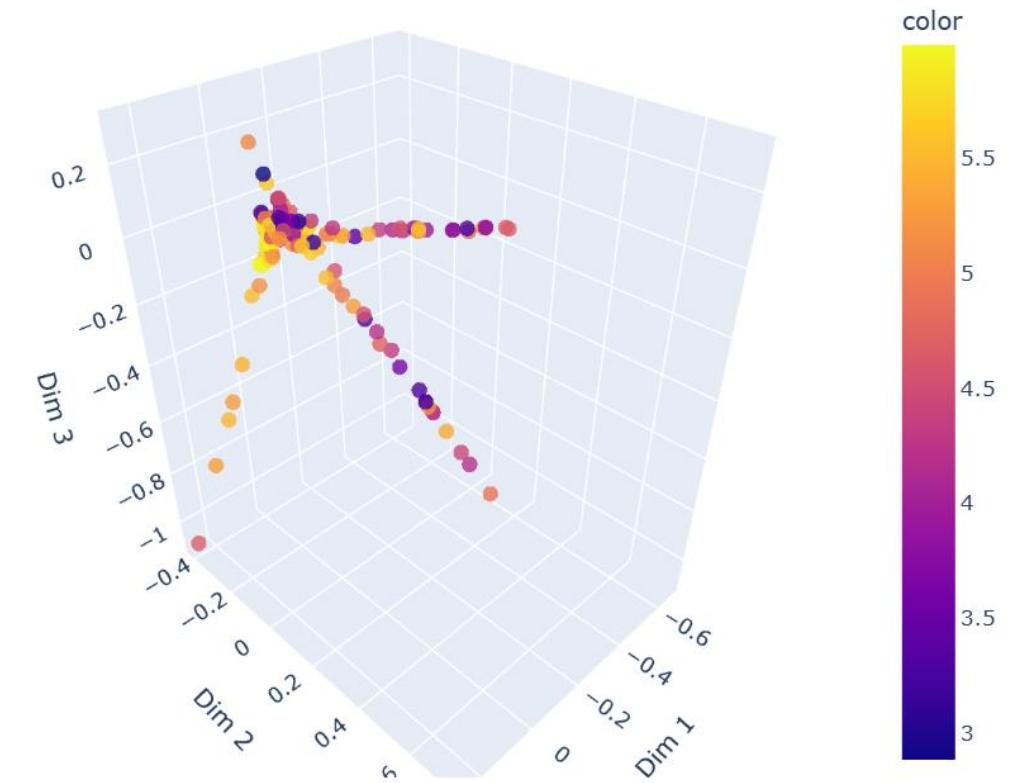
48-stim based dLGN results

Neuron Diffusion Map (Stimulus Entropy Index)



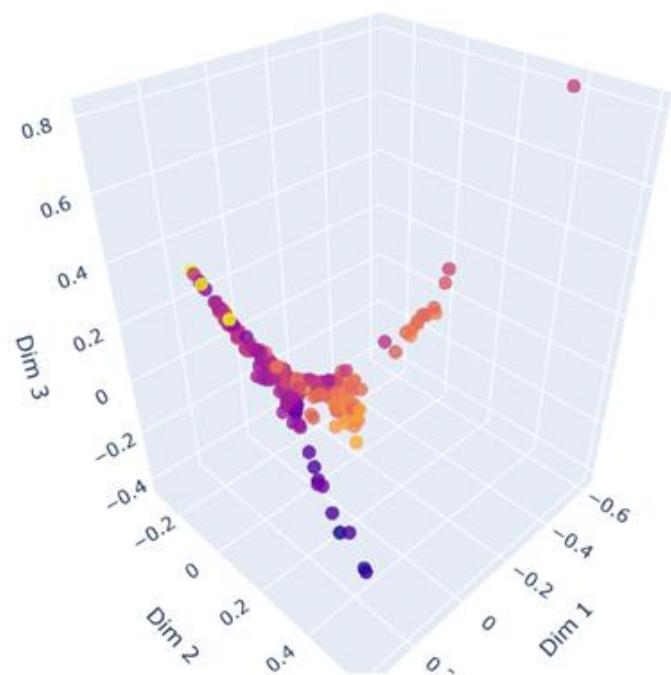
Chirp based dLGN results
(min-max normalization)

Neuron Diffusion Map (Stimulus Entropy Index)



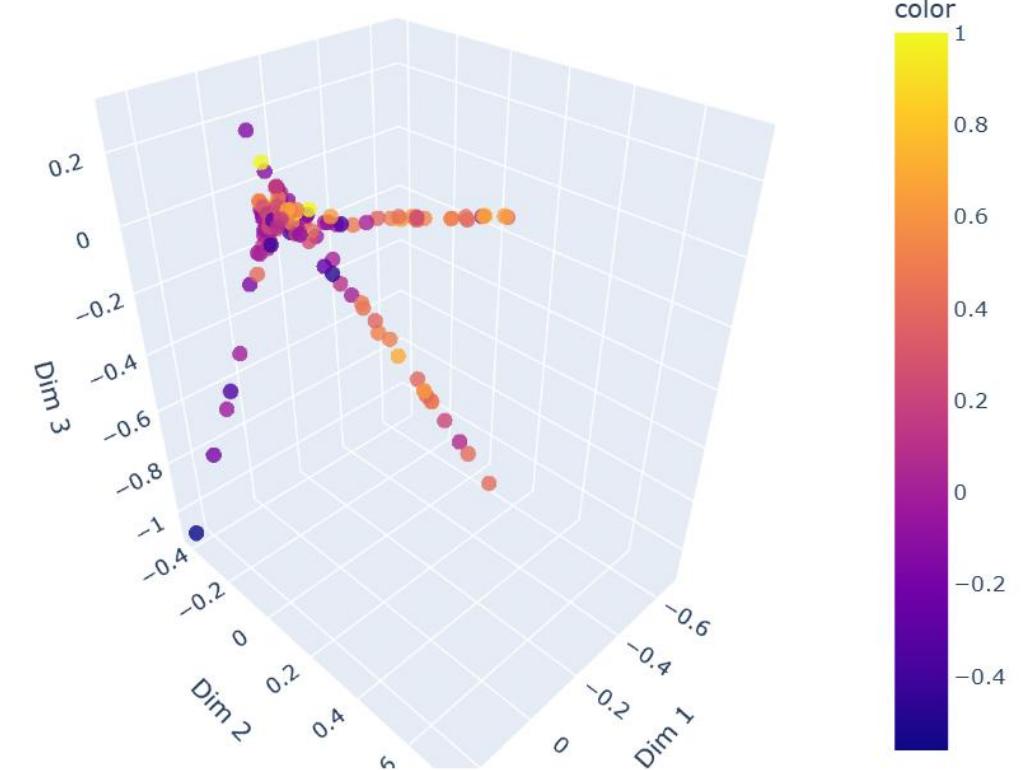
48-stim based dLGN results

Neuron Diffusion Map (Dot Selectivity Index)



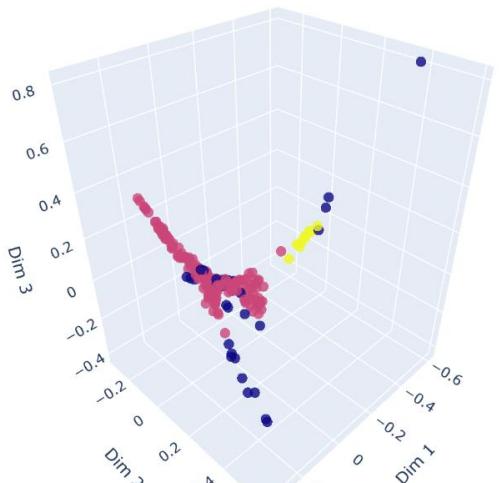
Chirp based dLGN results
(min-max normalization)

Neuron Diffusion Map (Dot Selectivity Index)



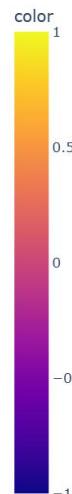
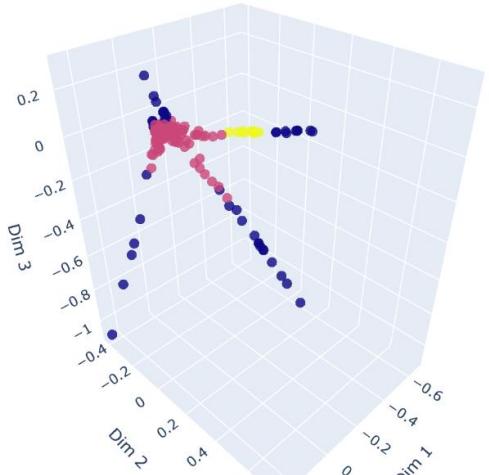
48-stim based dLGN results

Neuron Diffusion Map (HDBSCAN Cluster Index)

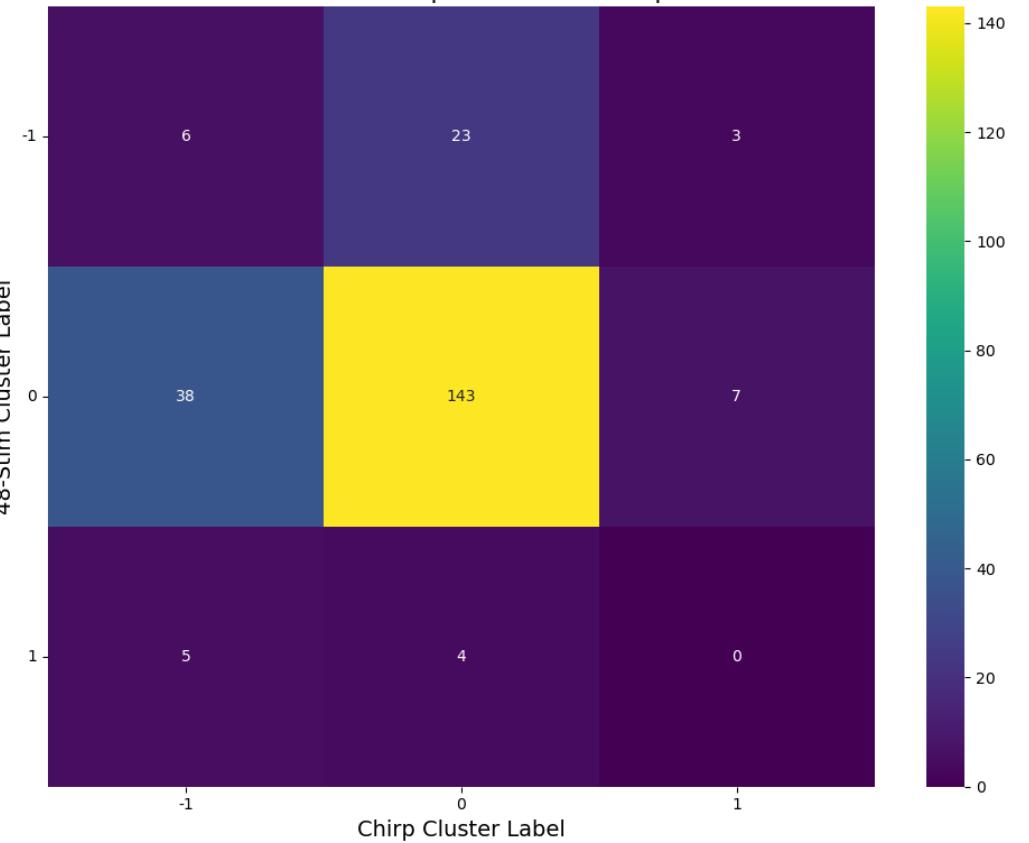


Chirp based dLGN results (min-max normalization)

Neuron Diffusion Map (HDBSCAN Cluster Index)

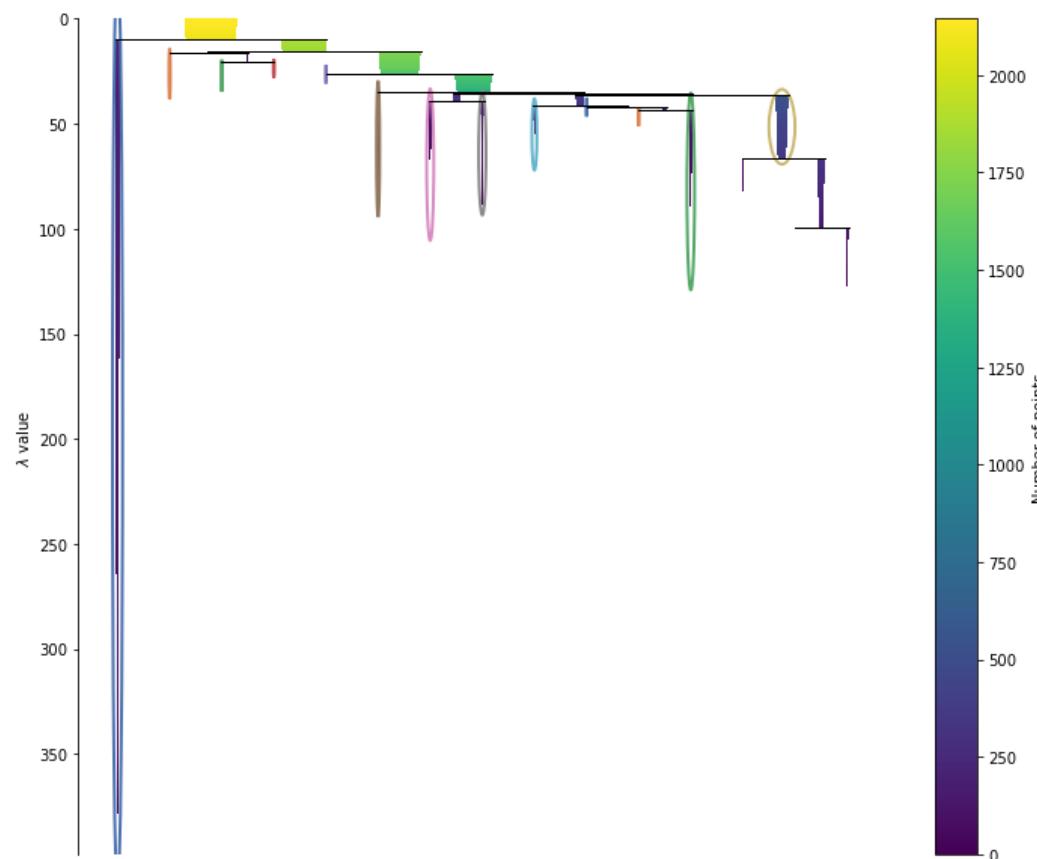


Cluster Overlap: 48-Stim vs Chirp



min_cluster_size=5

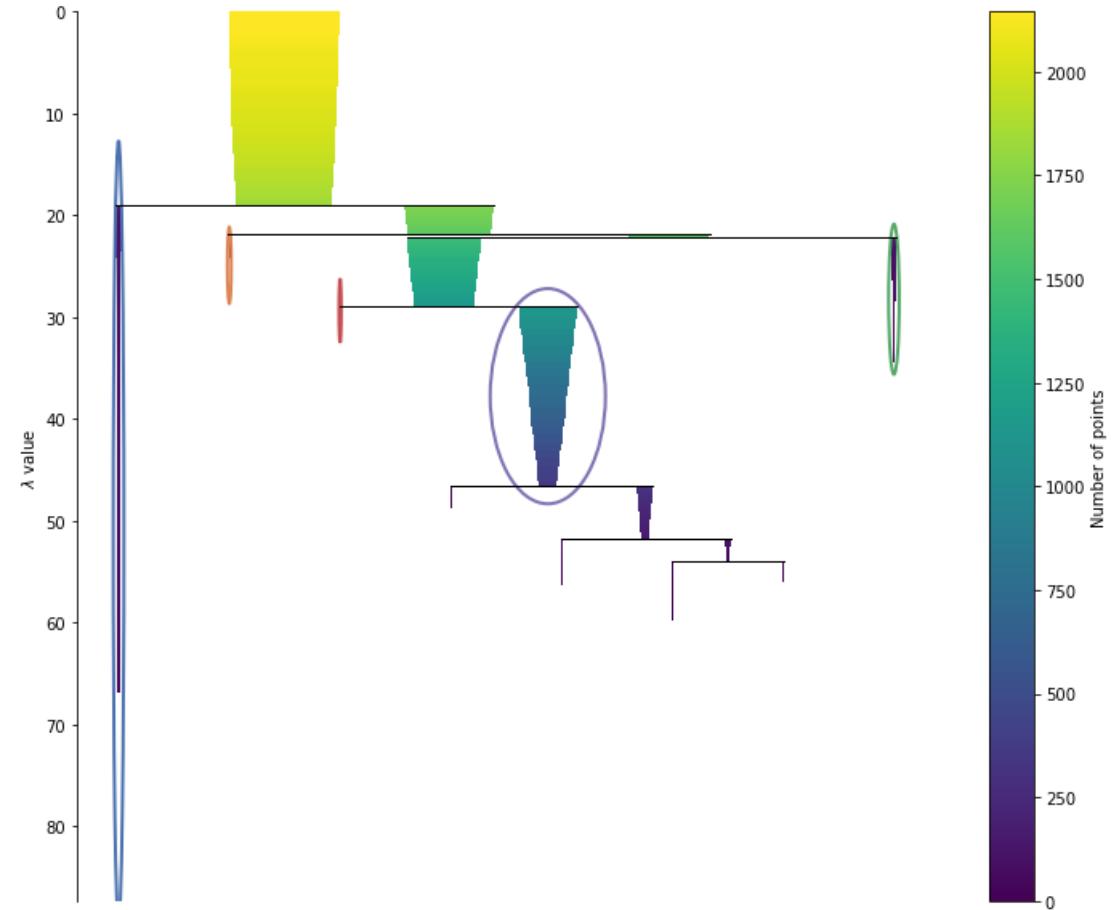
48-stim based RGC results



13 clusters

If min_cluster_size=5, 36 clusters.

Chirp based RGC results
(min-max normalization)



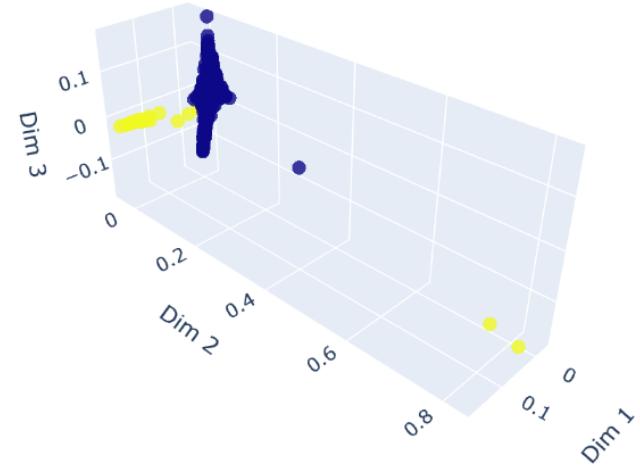
5 clusters

min_cluster_size=15

If min_cluster_size=5, 4 clusters. ???

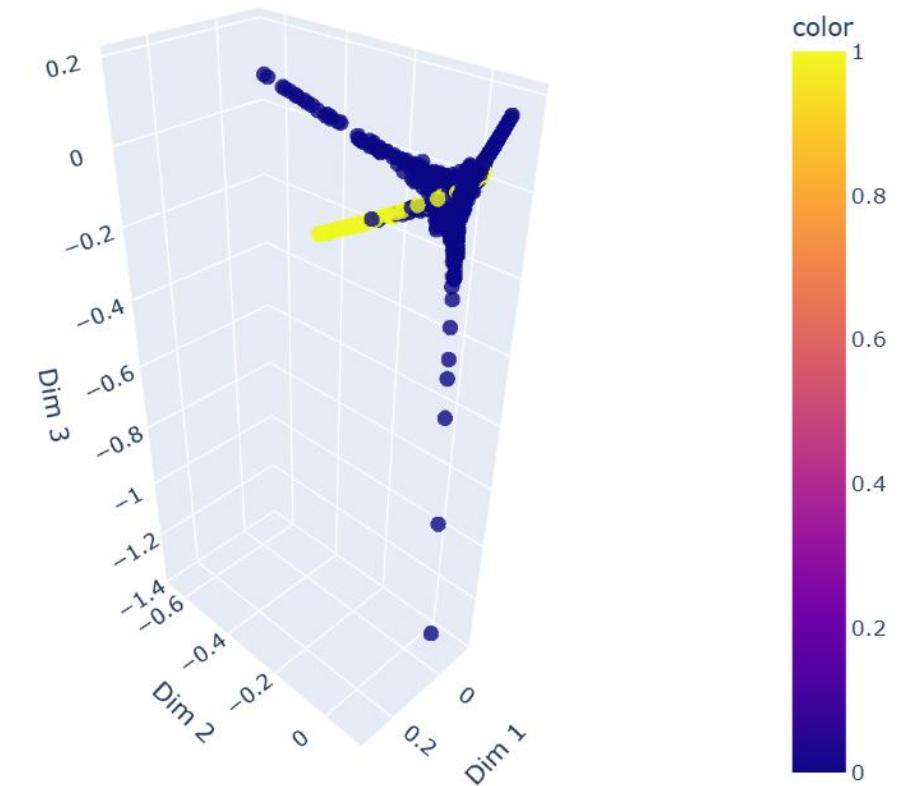
48-stim based RGC results

Neuron Diffusion Map (Negative Response Index)



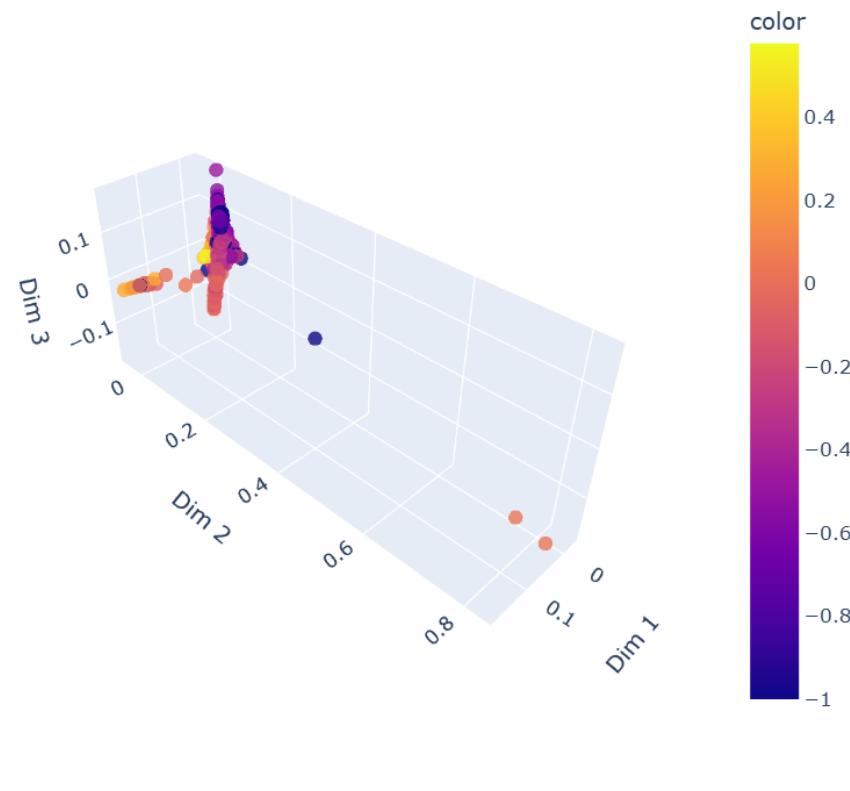
Chirp based RGC results (min-max normalization)

Neuron Diffusion Map (Negative Response Index)



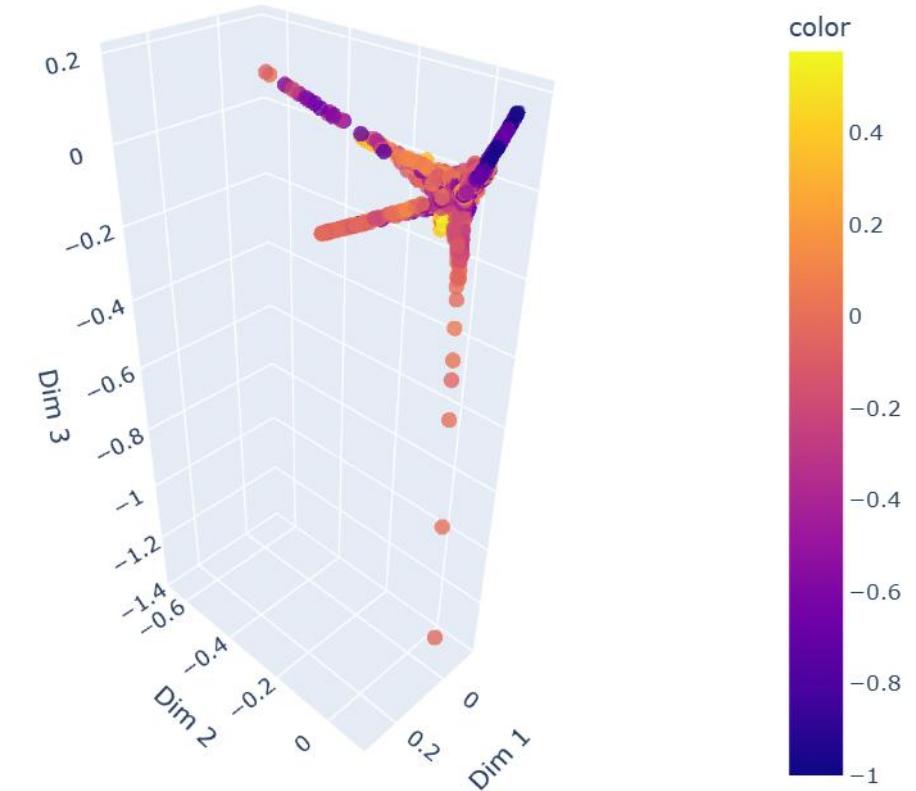
48-stim based RGC results

Neuron Diffusion Map (Grating Selectivity Index)



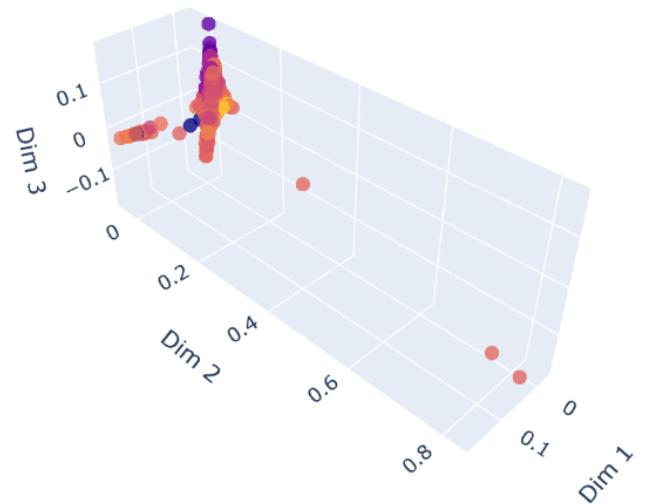
Chirp based RGC results
(min-max normalization)

Neuron Diffusion Map (Grating Selectivity Index)



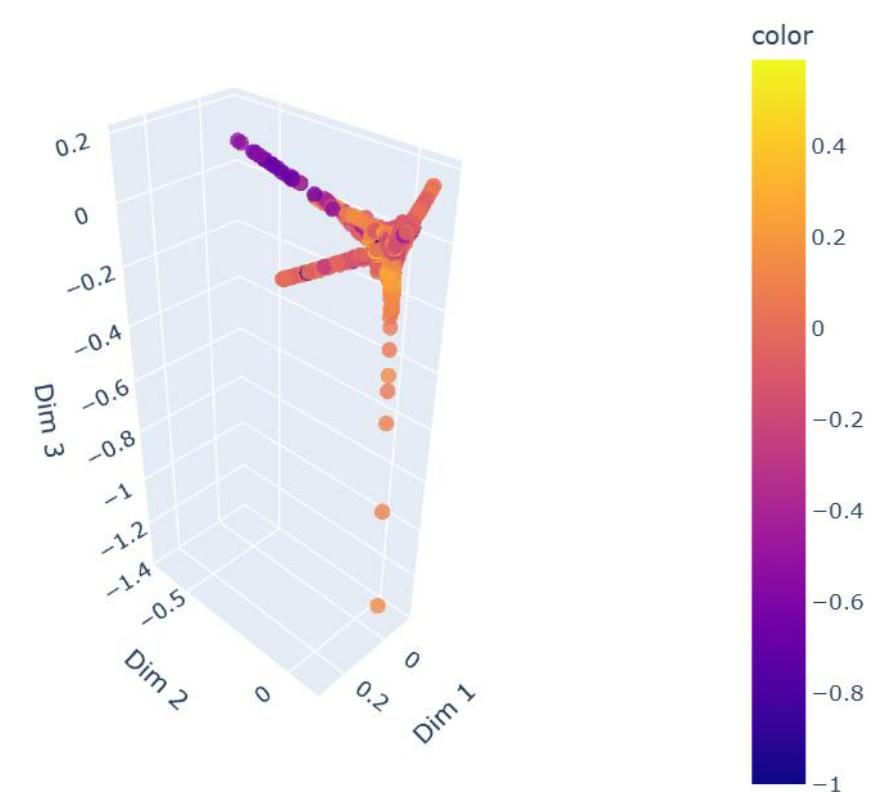
48-stim based RGC results

Neuron Diffusion Map (Flow Polarity Index)



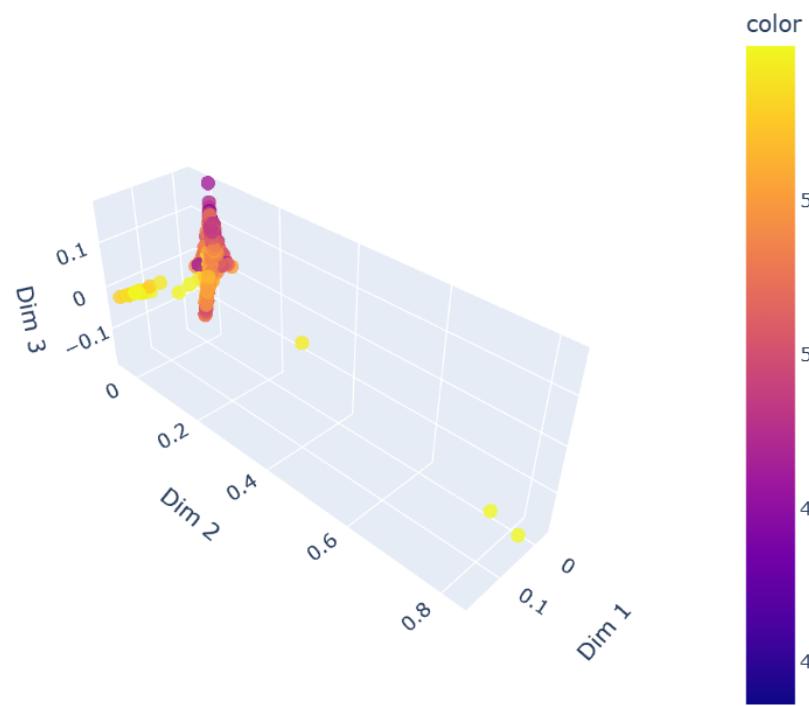
Chirp based RGC results
(min-max normalization)

Neuron Diffusion Map (Flow Polarity Index)



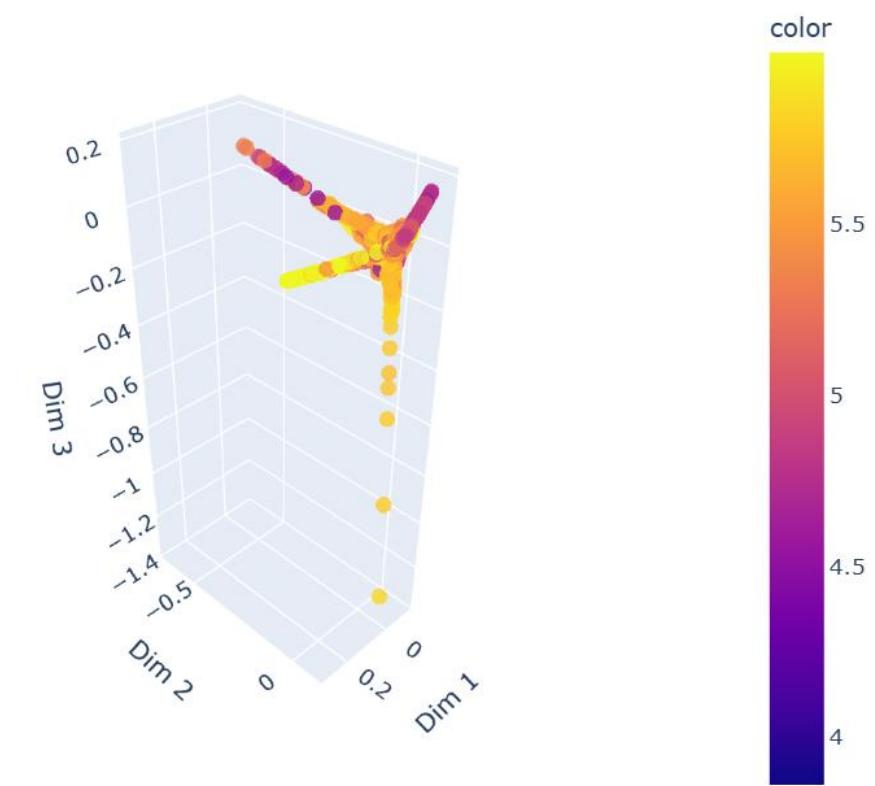
48-stim based RGC results

Neuron Diffusion Map (Stimulus Entropy Index)



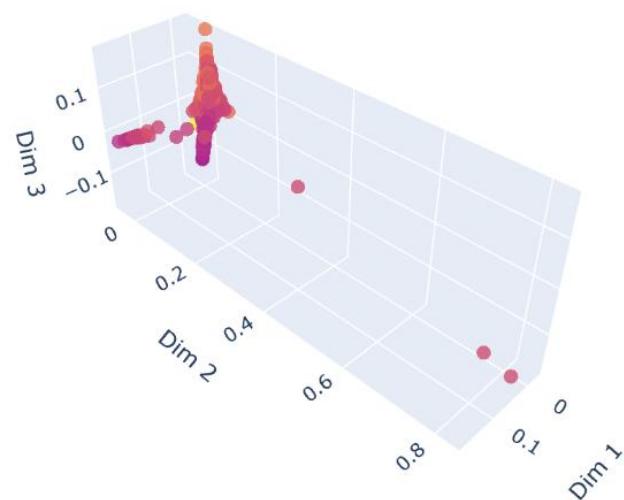
Chirp based RGC results
(min-max normalization)

Neuron Diffusion Map (Stimulus Entropy Index)



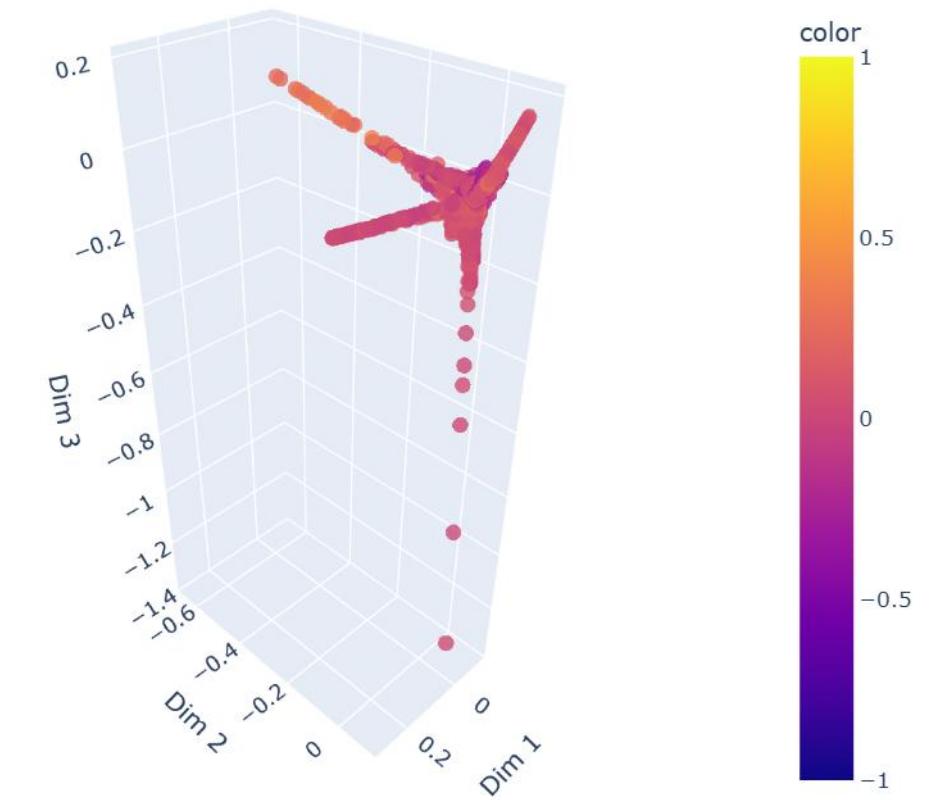
48-stim based RGC results

Neuron Diffusion Map (Dot Selectivity Index)

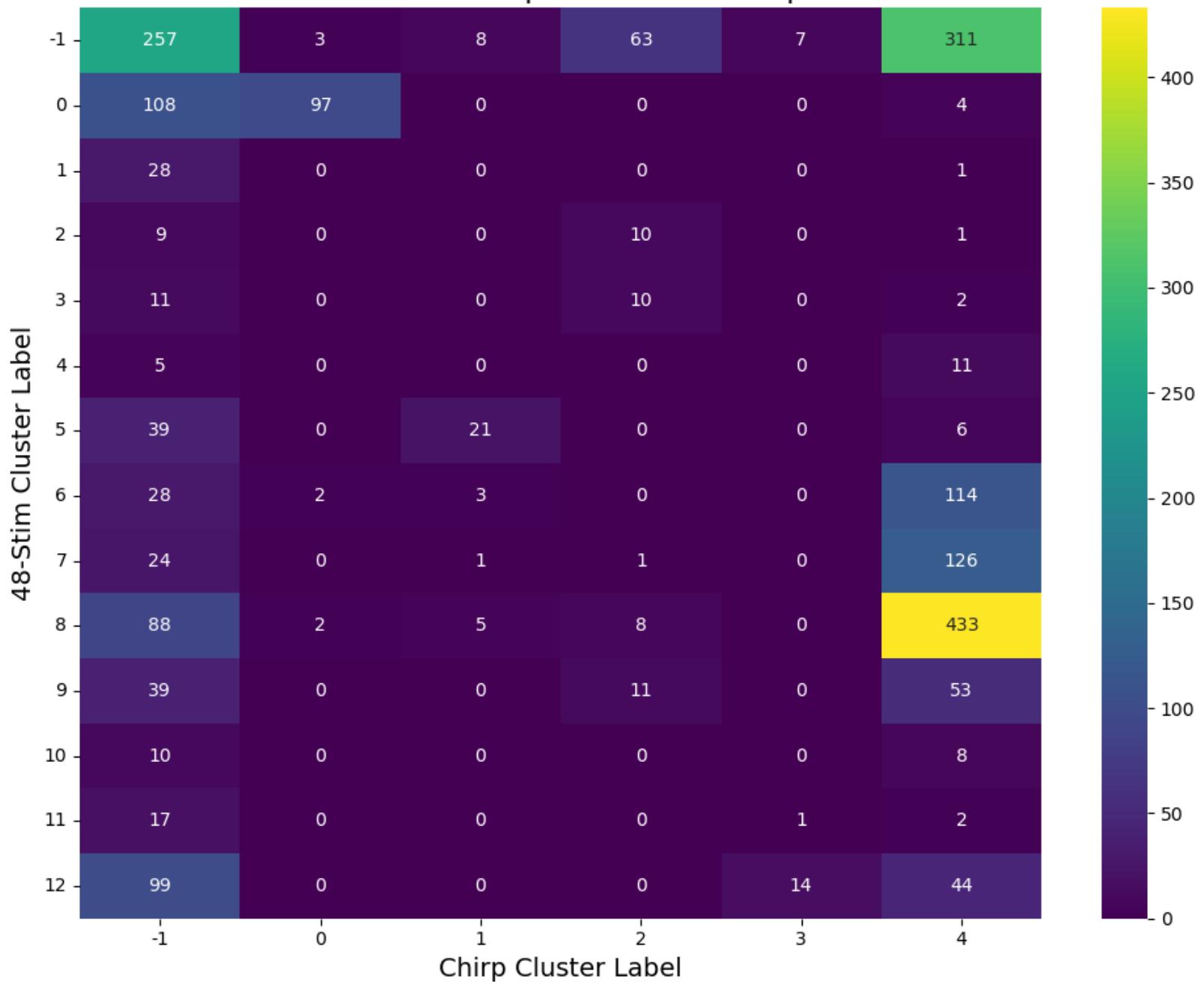


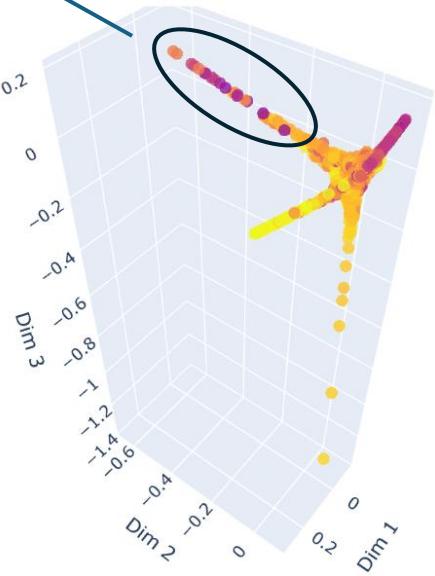
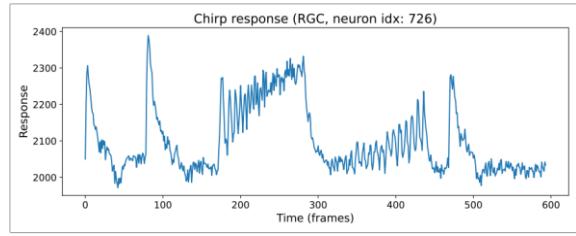
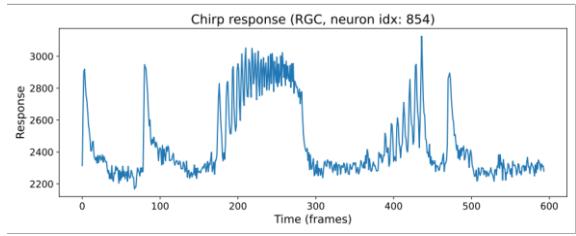
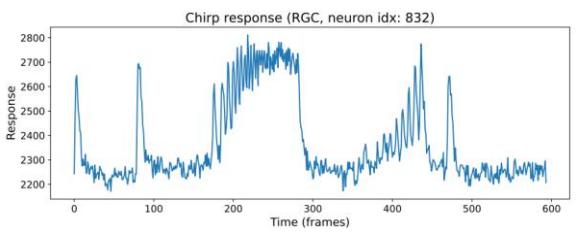
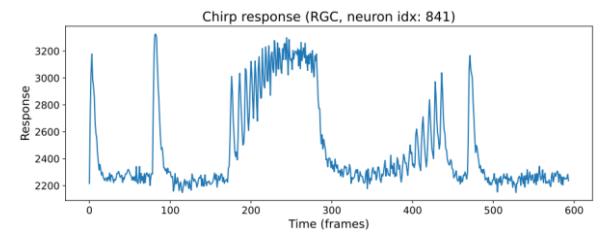
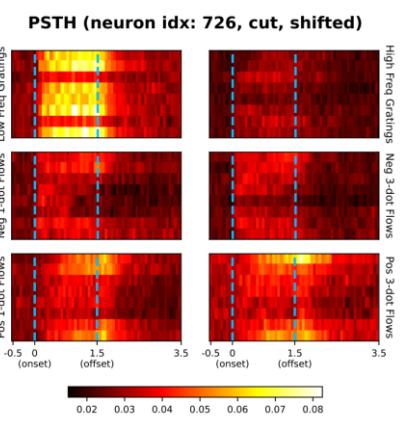
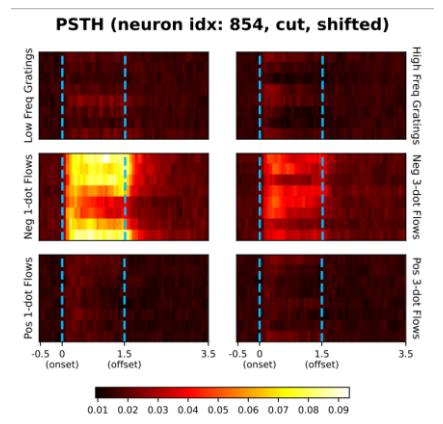
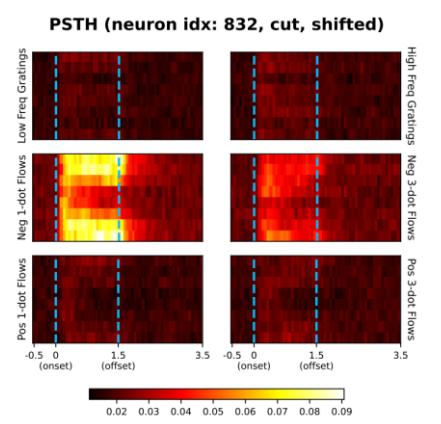
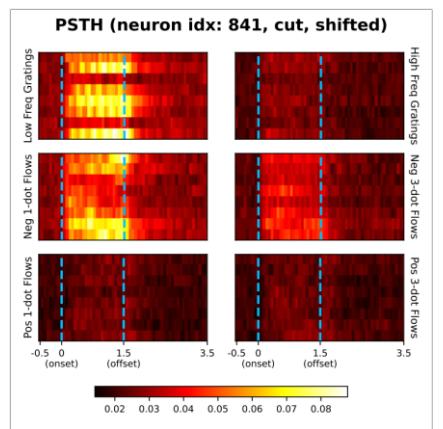
Chirp based RGC results
(min-max normalization)

Neuron Diffusion Map (Dot Selectivity Index)

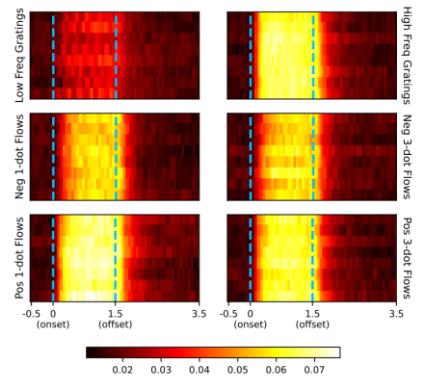


Cluster Overlap: 48-Stim vs Chirp

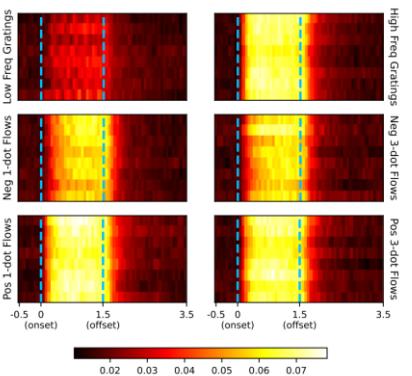




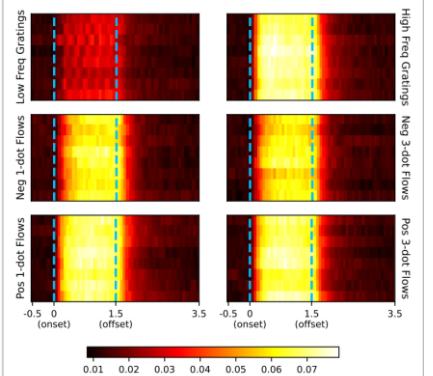
PSTH (neuron idx: 272, cut, shifted)



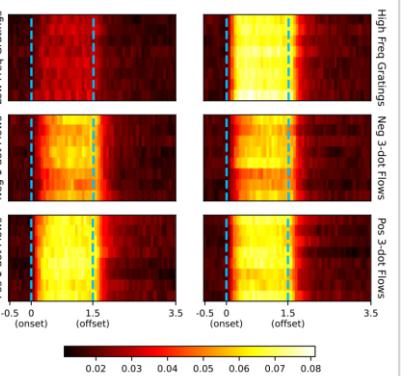
PSTH (neuron idx: 253, cut, shifted)



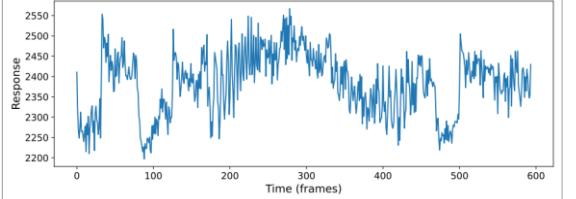
PSTH (neuron idx: 238, cut, shifted)



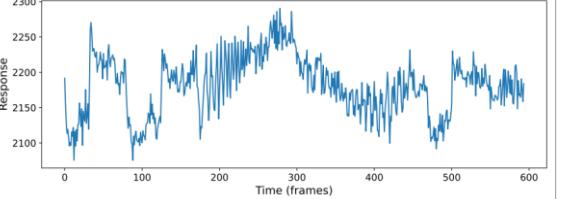
PSTH (neuron idx: 268, cut, shifted)



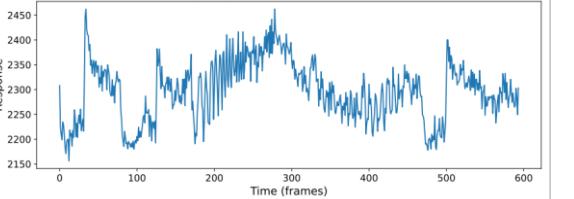
Chirp response (RGC, neuron idx: 272)



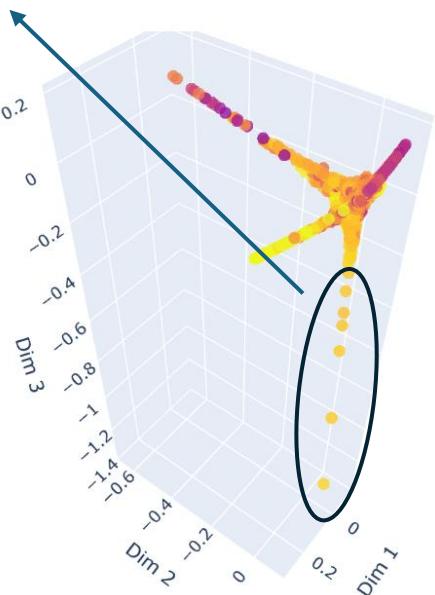
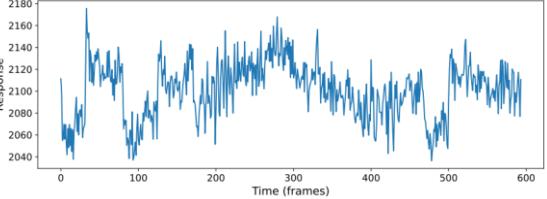
Chirp response (RGC, neuron idx: 253)



Chirp response (RGC, neuron idx: 238)



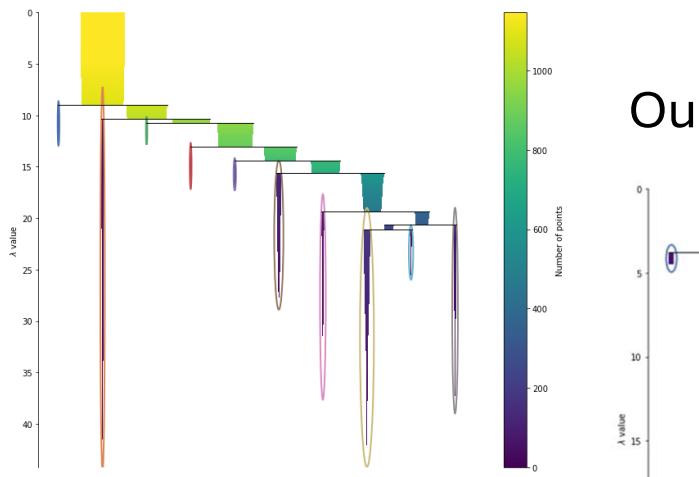
Chirp response (RGC, neuron idx: 268)



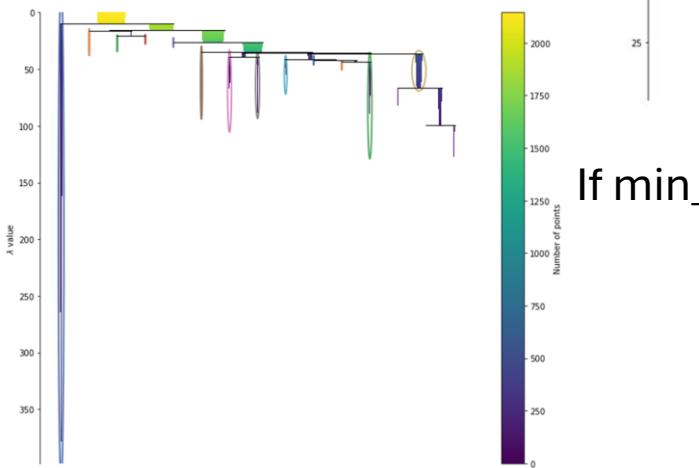
Comparison

Retina

Public retina

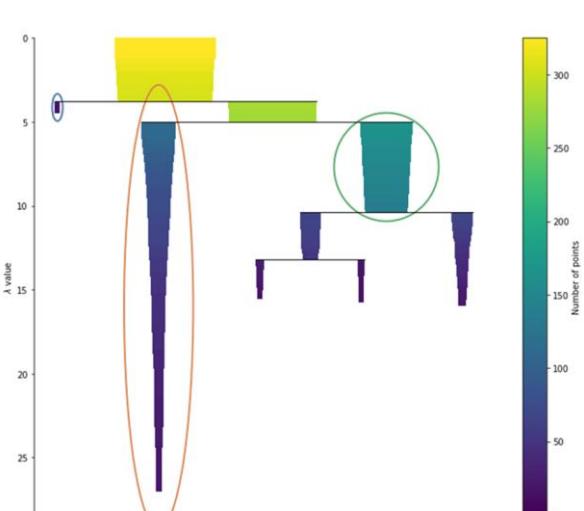


Our RGC



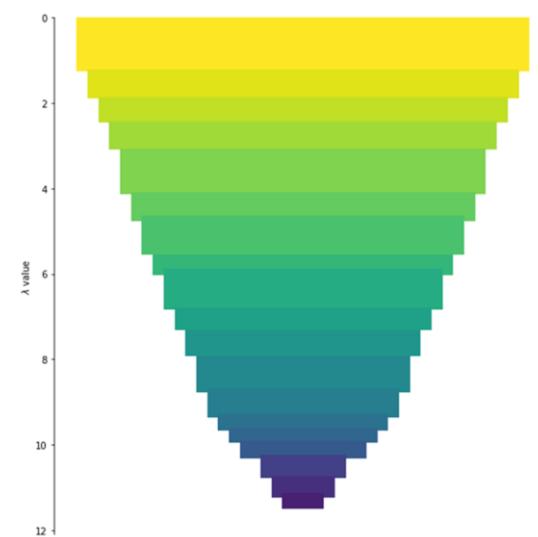
SC

Our



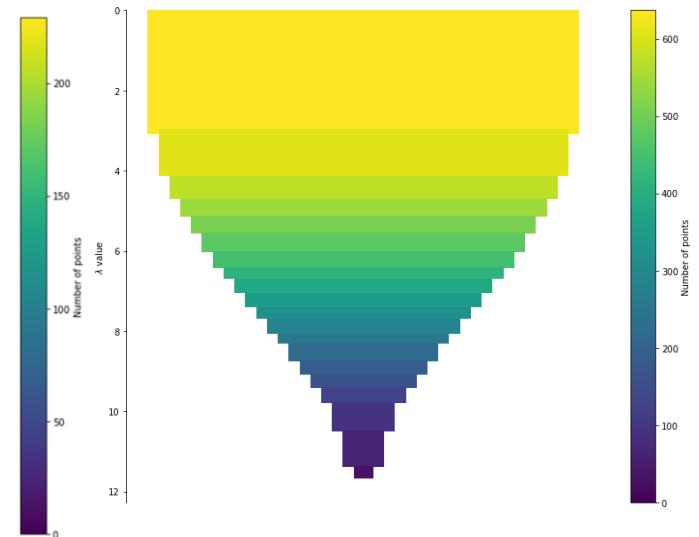
dLGN

Our



V1

Public



If min_cluster_size=5, 8 clusters.

If min_cluster_size=5, 2 clusters.

If min_cluster_size=5, 36 clusters.