Embedding Analysis of Neuron Responses under Various Stimuli in Vision Systems

Huimiao Chen

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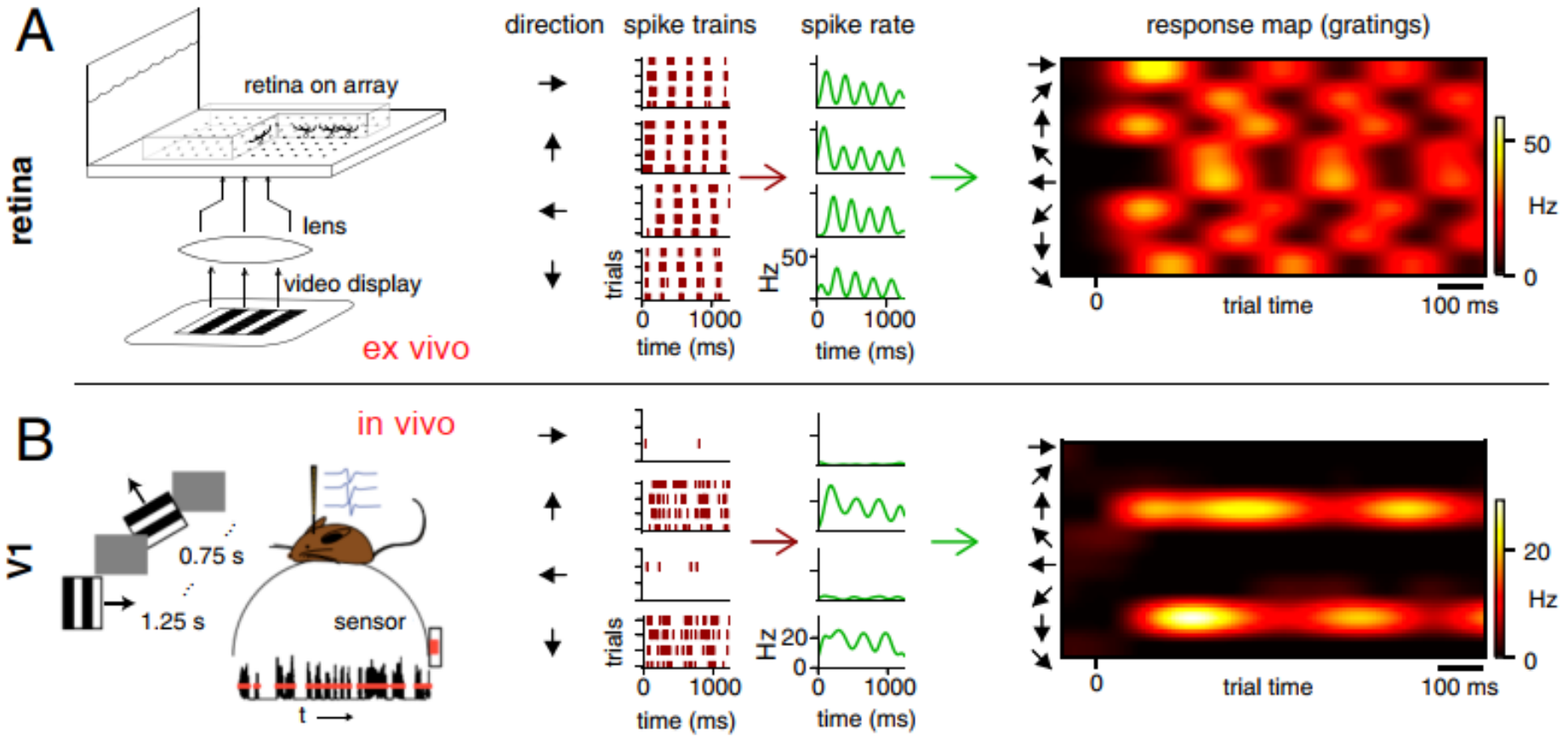
Background

Retinal and cortical population encodings differ

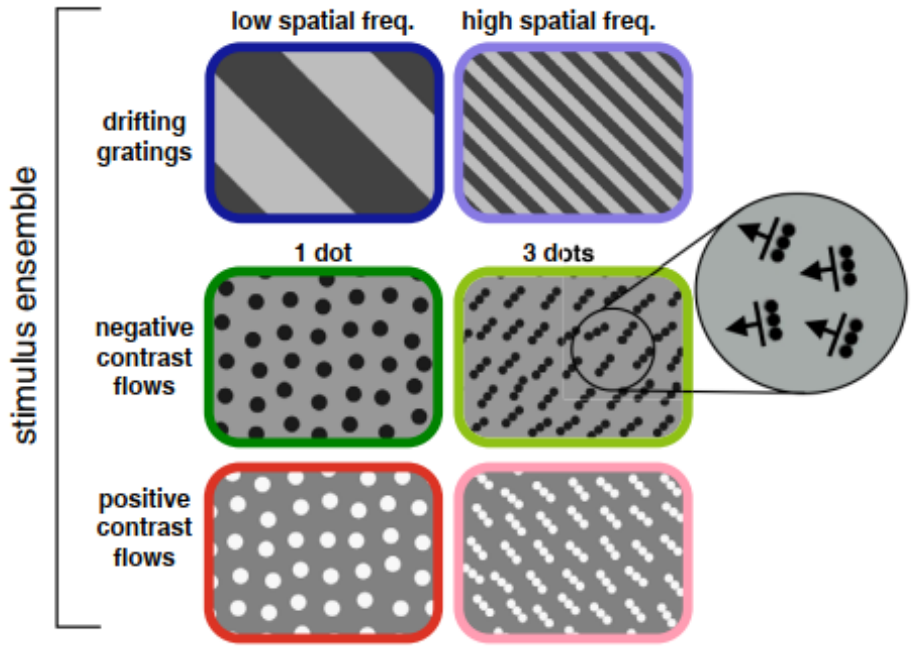
Use multi-electrode array (MEA) recordings.

Data: Spike trains.



Luciano et al., 2024

Retinal and cortical population encodings differ

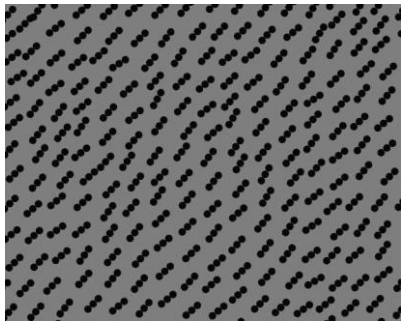


Stimuli and Data

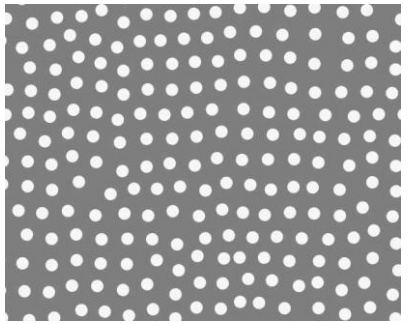
```
# dir: 0, 45, 90, 135, 180, 225, 270

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

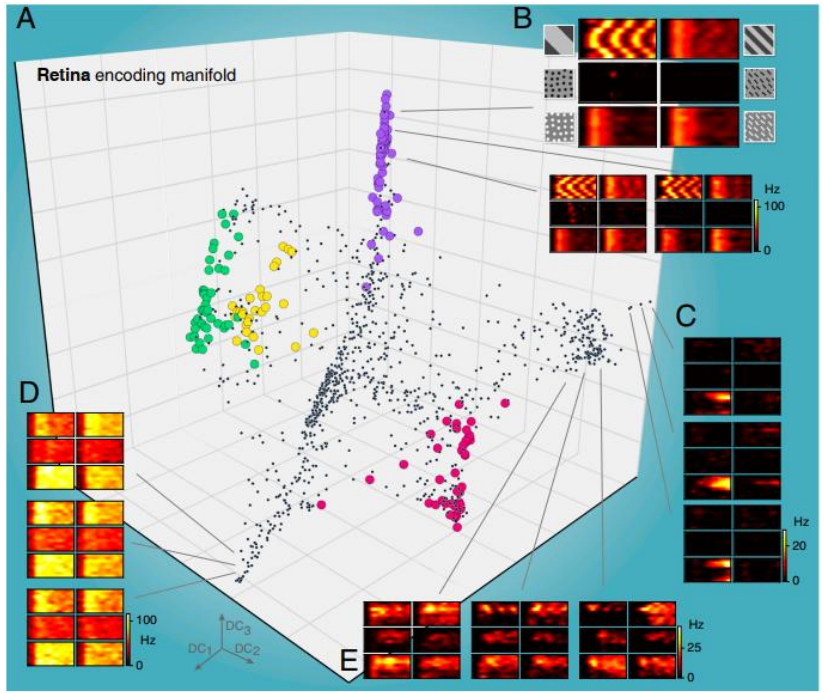


pos_1flows_225

gratings_lf_45

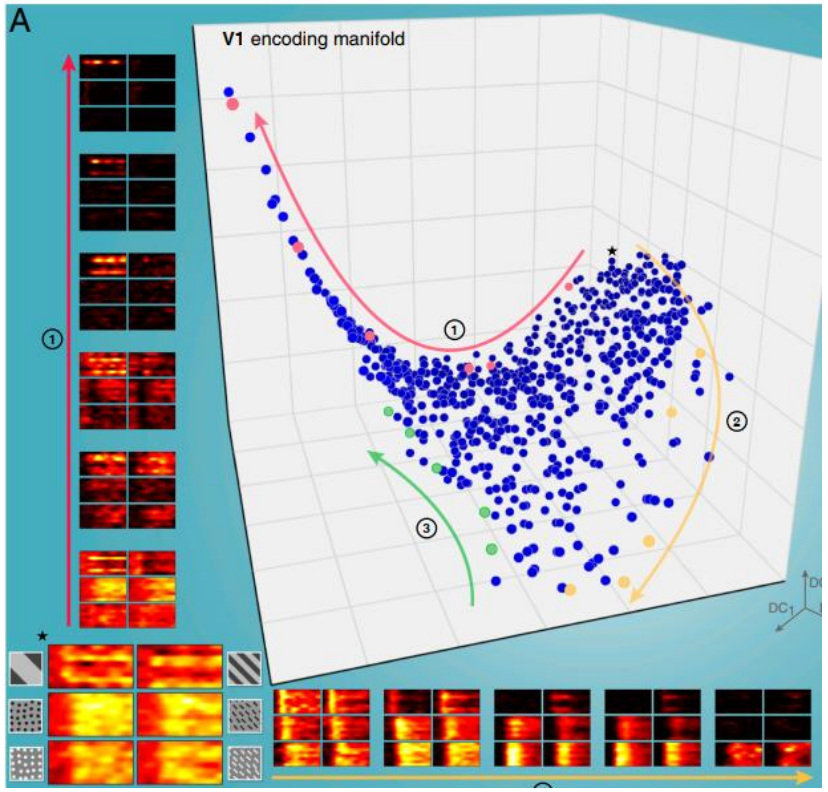
Luciano et al., 2024

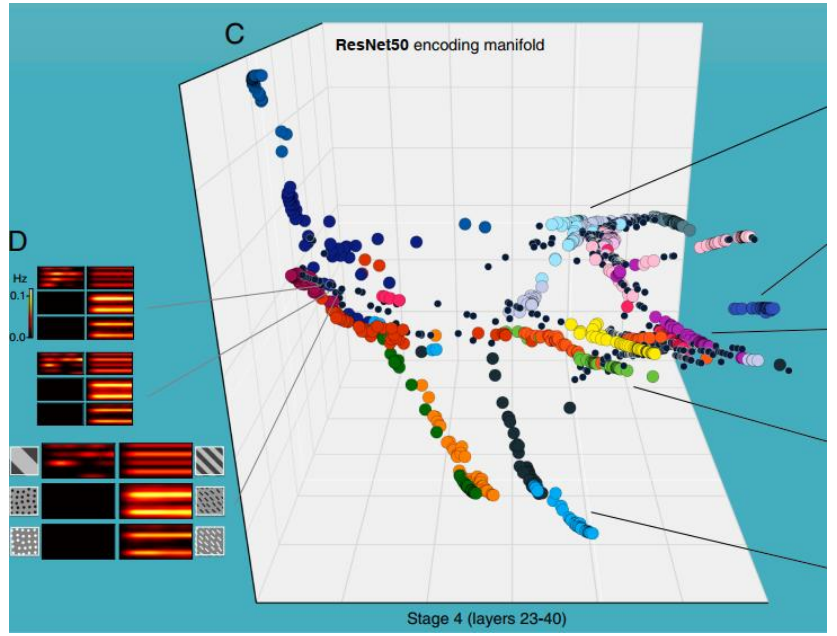
Retina: Discrete clusters; V1: Continuous encoding



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.



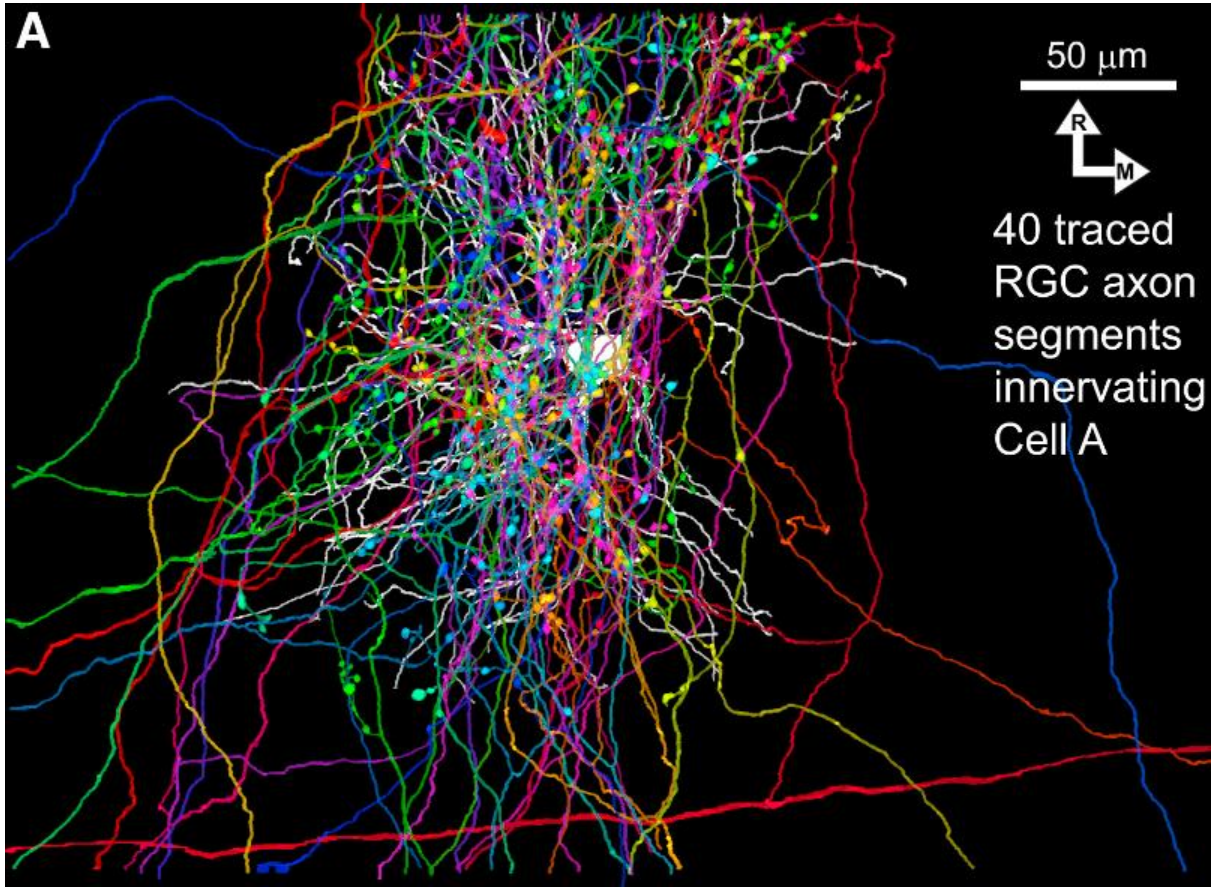


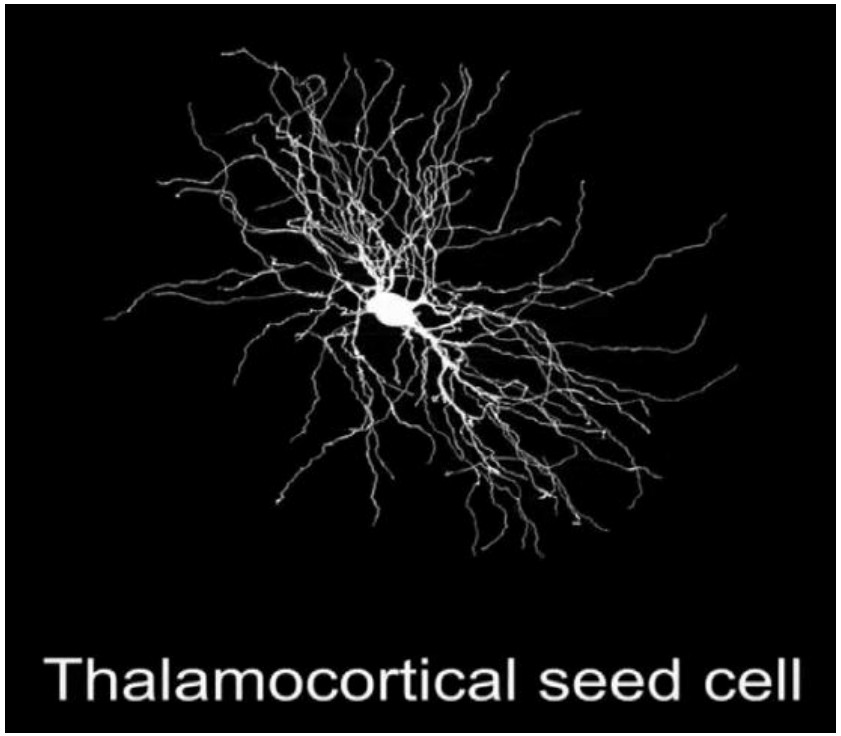
ResNet50 (CNN) network's encoding manifold showing **strong clustering**: more discrete than the retina, and unlike V1.

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

Luciano et al., 2024

Tens of RGCs can converge to a single dLGN neuron



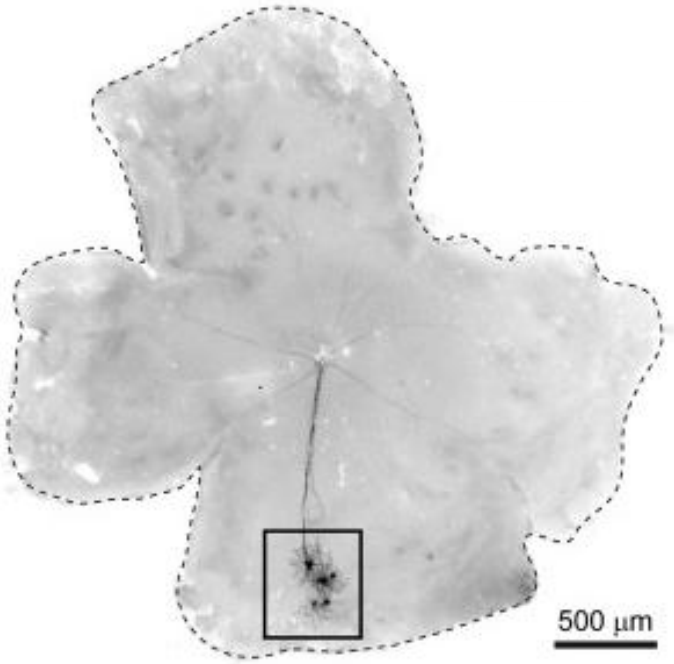


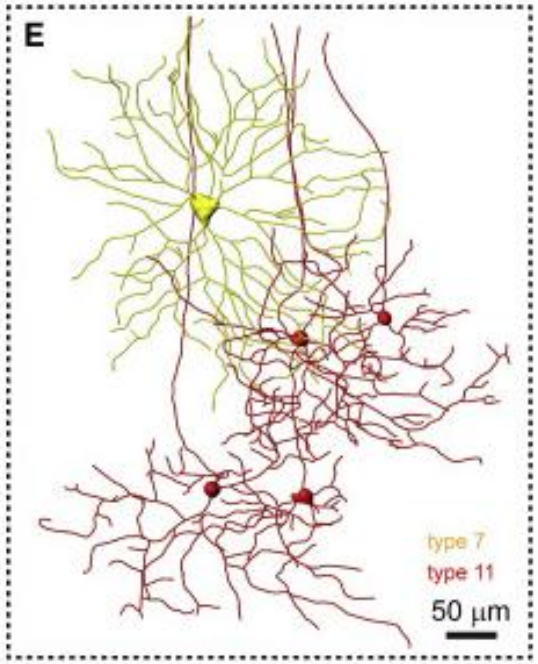
A single dLGN neuron (white) receives input from ~40 RGC axon segments (different colors).

Retrograde tracing shows inputs from multiple morphologically distinct RGC types.

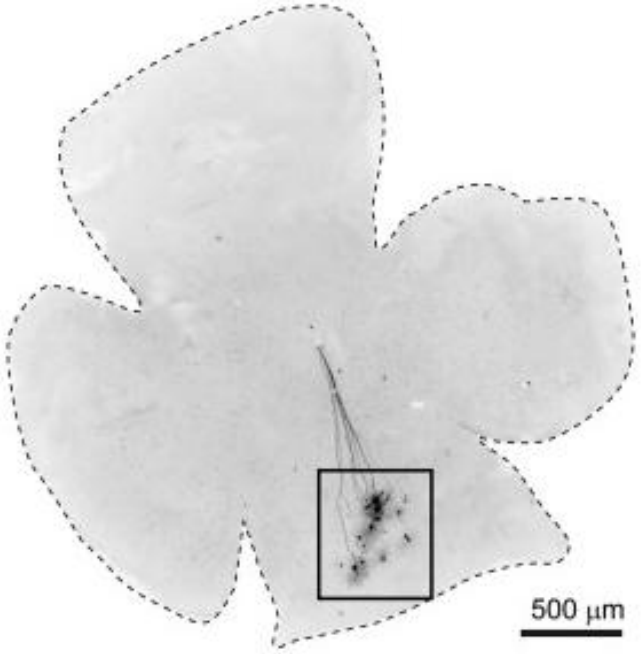
Morgan et. al, 2016

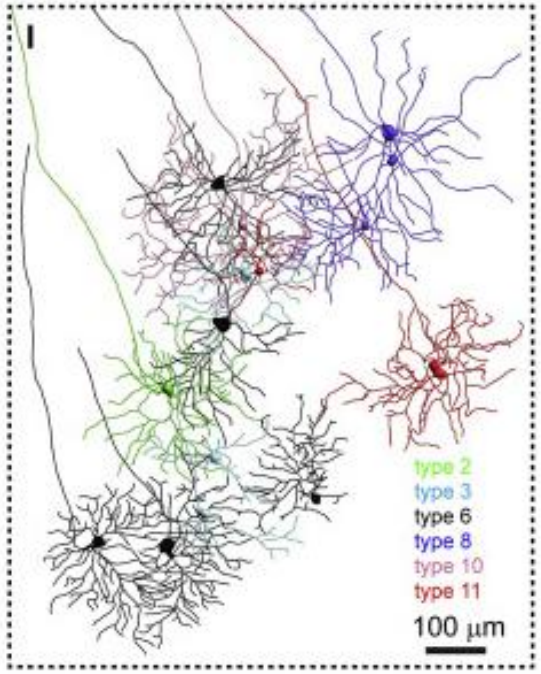
dLGN cells integrate retinal inputs in relay and combination mode





Relay-mode cluster





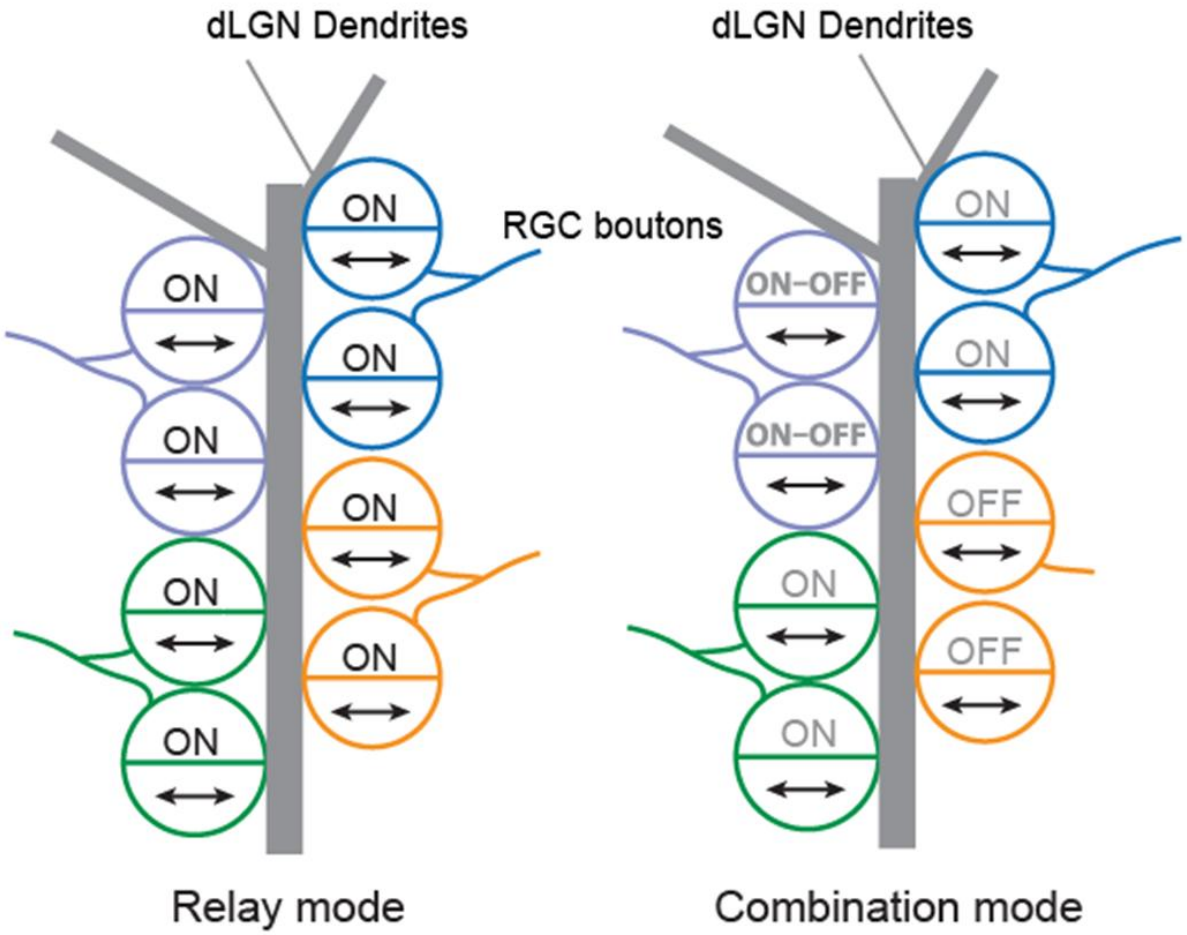
Combination-mode cluster

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.

Rompani et al., 2017

Nearby RGC boutons share one or several similar visual feature preference

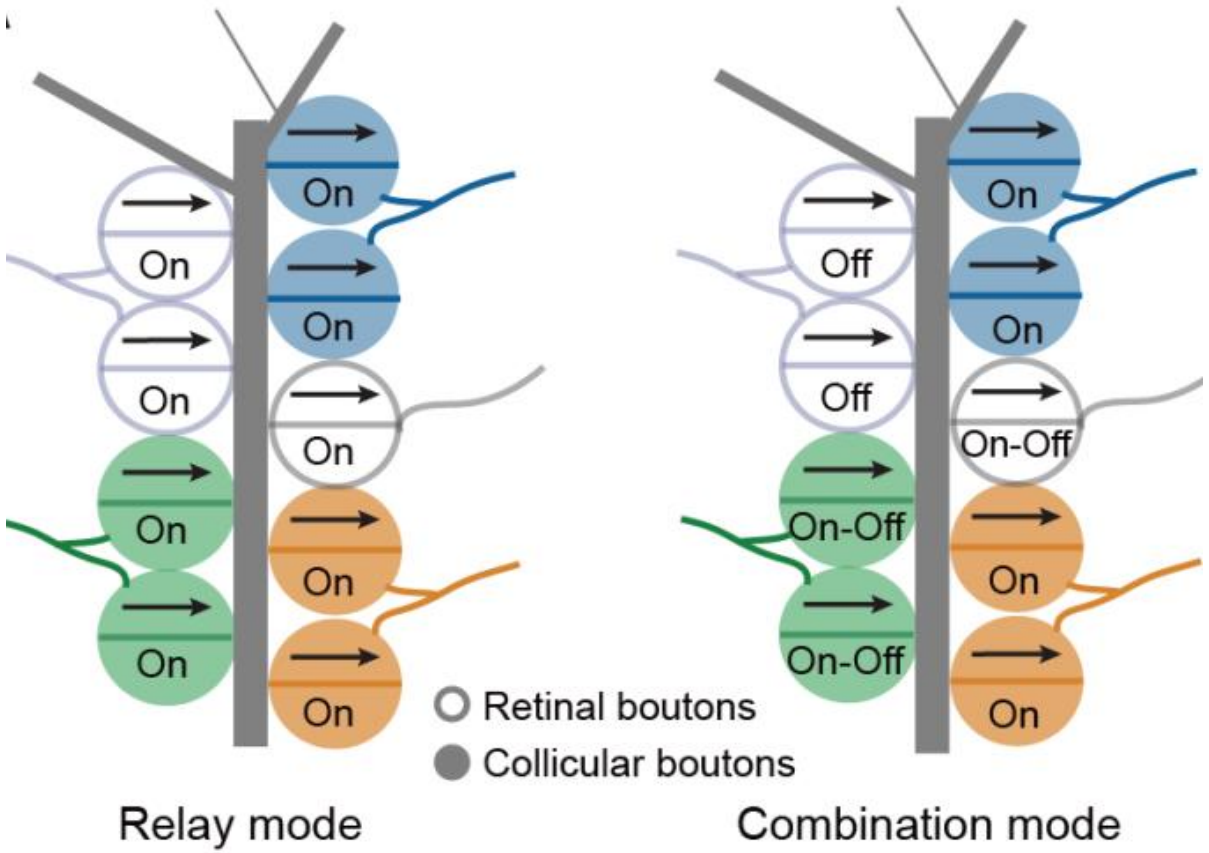


Visual responses of RGC boutons in dLGN show local clustering by feature preference.

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

Liang et. al, 2018

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



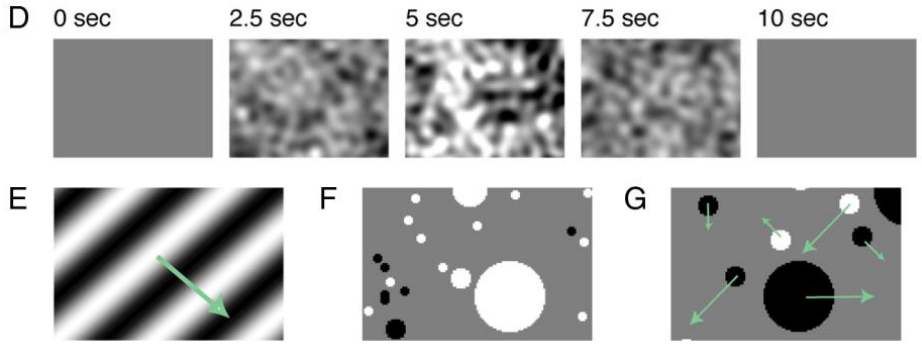
Relay mode: nearby boutons share preferences for a single feature

Combination mode: nearby boutons exhibit similar preferences for multiple features

between retinal and collicular boutons.

Yue et. al, 2025

Functional Diversity of dLGN Neurons



Four stimulus sets used.
D, Contrast modulated band-limited noise.
E, Drifting sinusoidal gratings.
F, Flashing spots.
G, Moving spots.

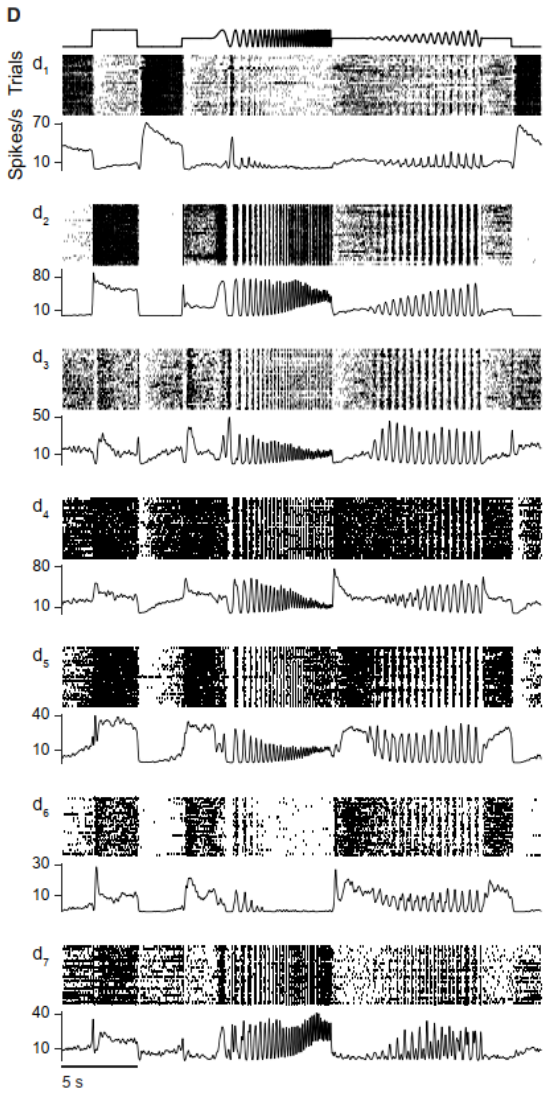
Unsupervised clustering (k-means) based on responses to flashes, drifting gratings, and noise movies.

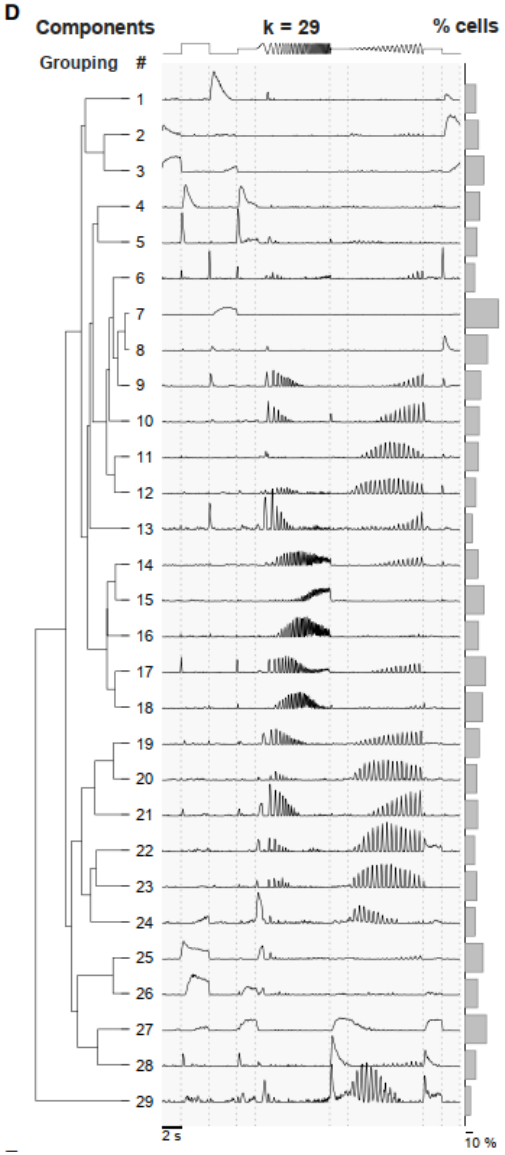
7 Discrete Cell Types Identified:

- **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

Denise et al., 2013

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 .

Miroslav et al., 2019

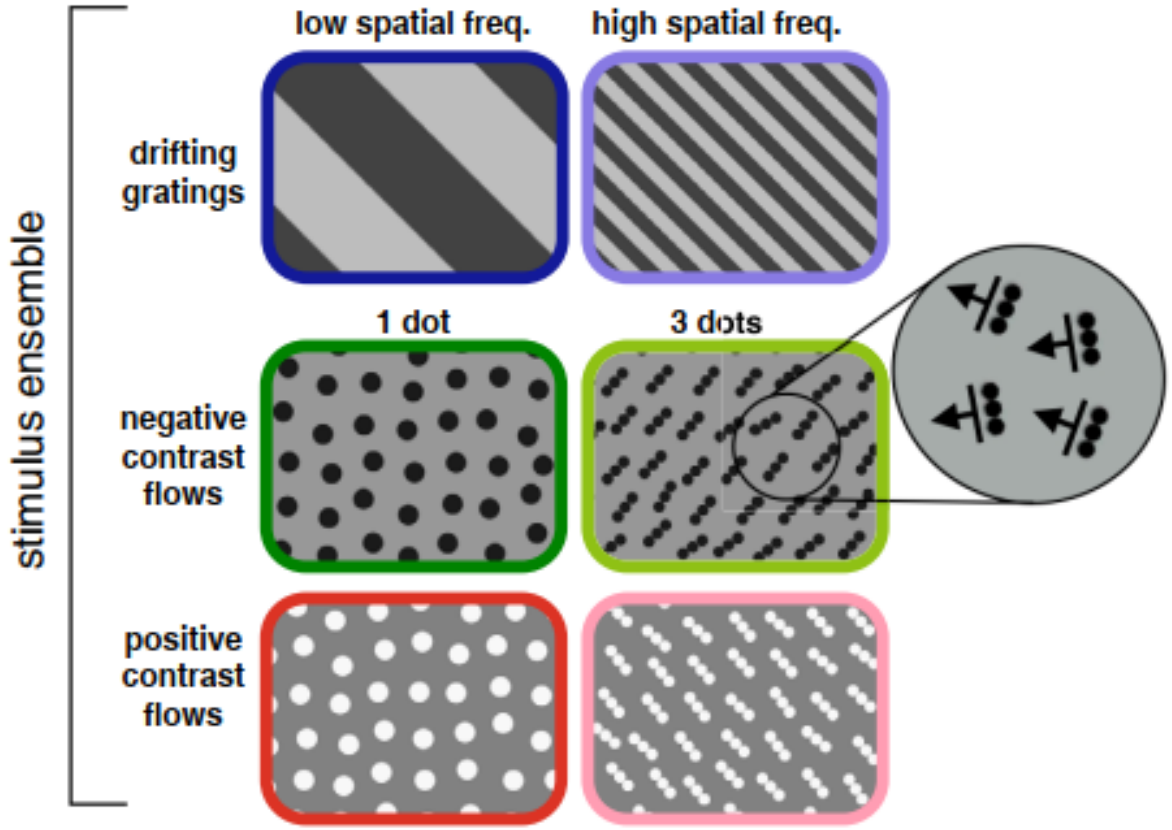
Hypothesis on dLGN Cell Type Organization

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

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

Low Freq Gratings
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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**

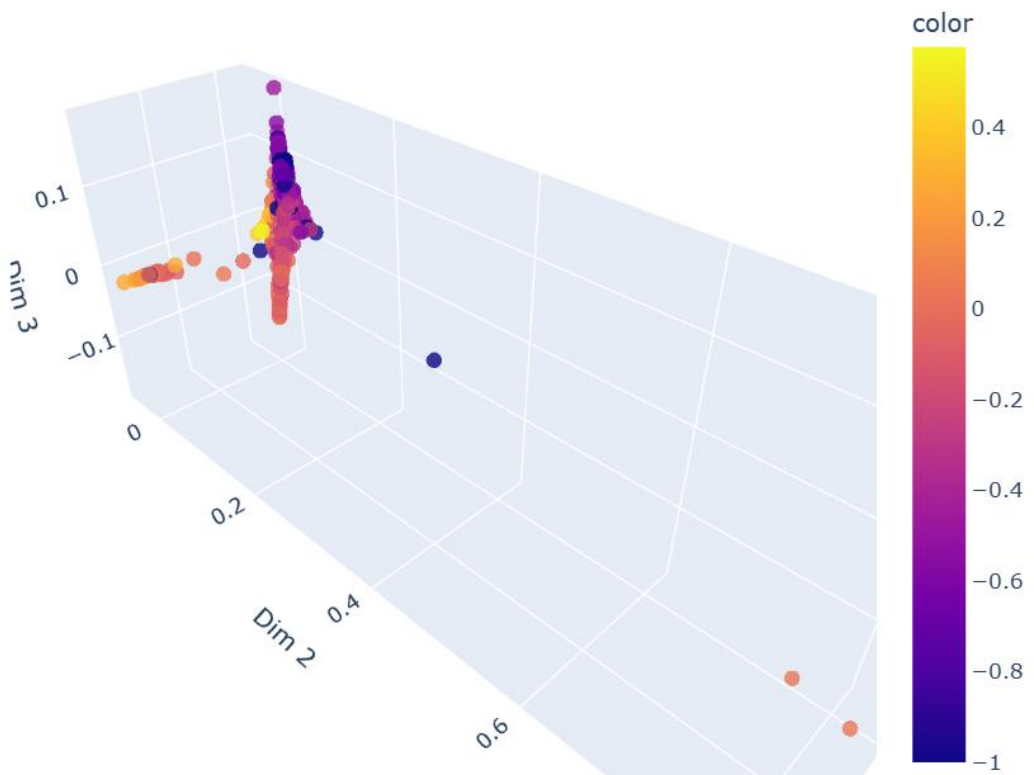
RGC

2145 significant boutons

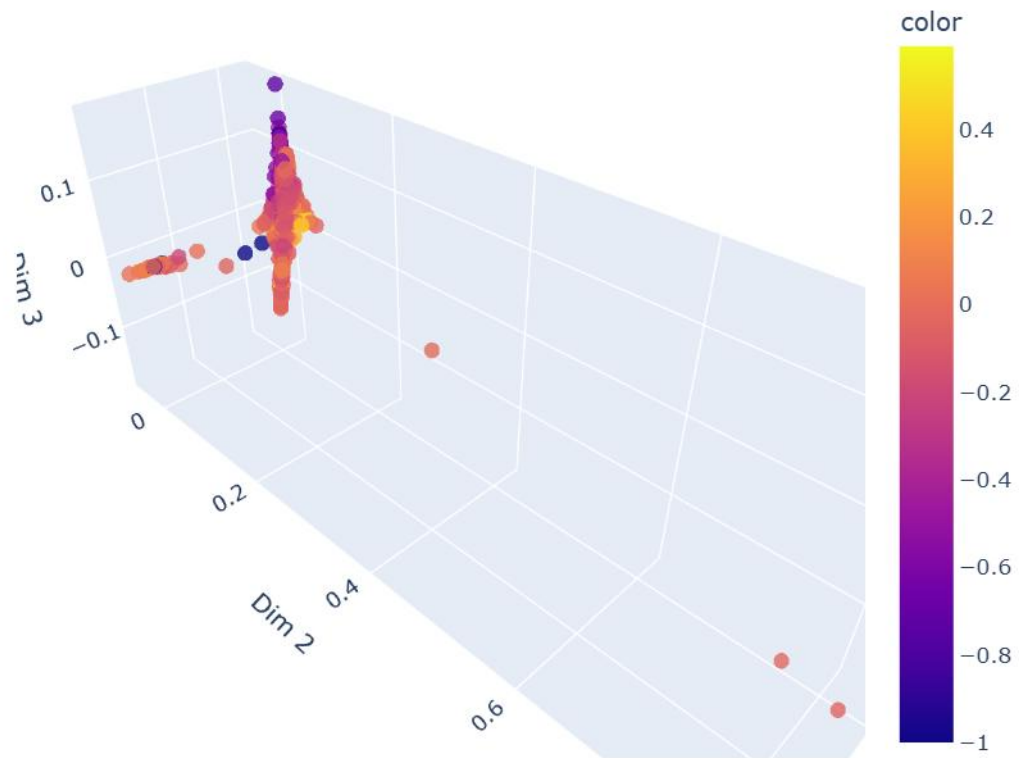
$$\text{Grating Selectivity Index} = \frac{\Delta R_g - \Delta R_f}{|\Delta R_g| + |\Delta R_f|}$$

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

Neuron Diffusion Map (Grating Selectivity Index)



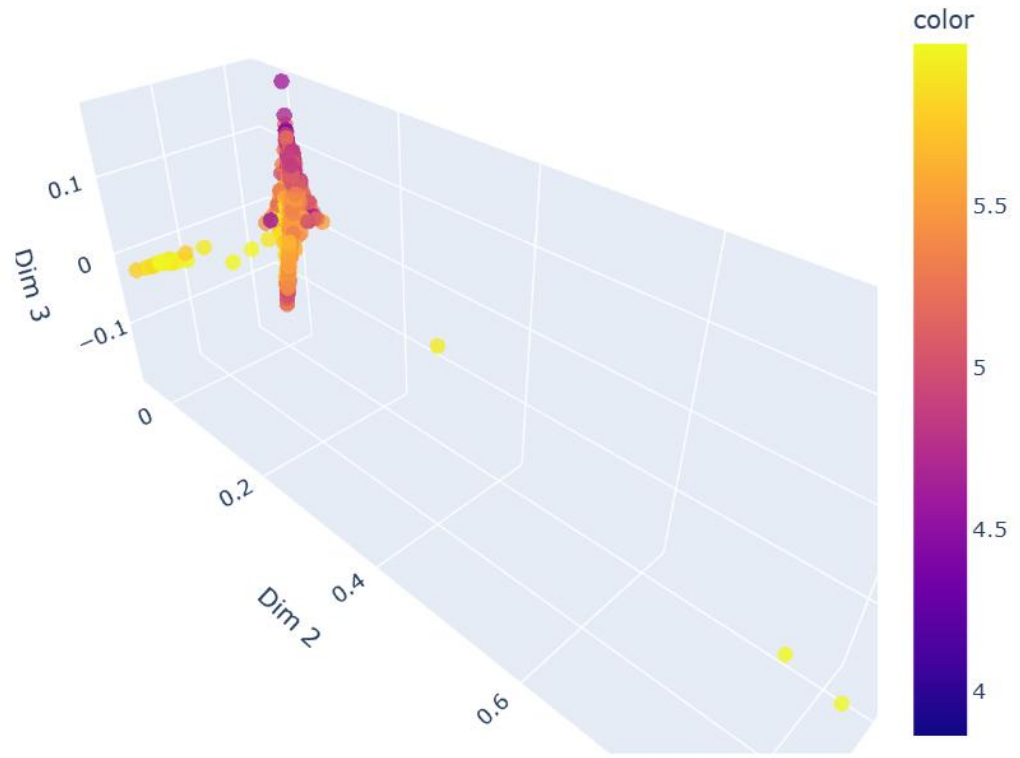
Neuron Diffusion Map (Flow Polarity Index)



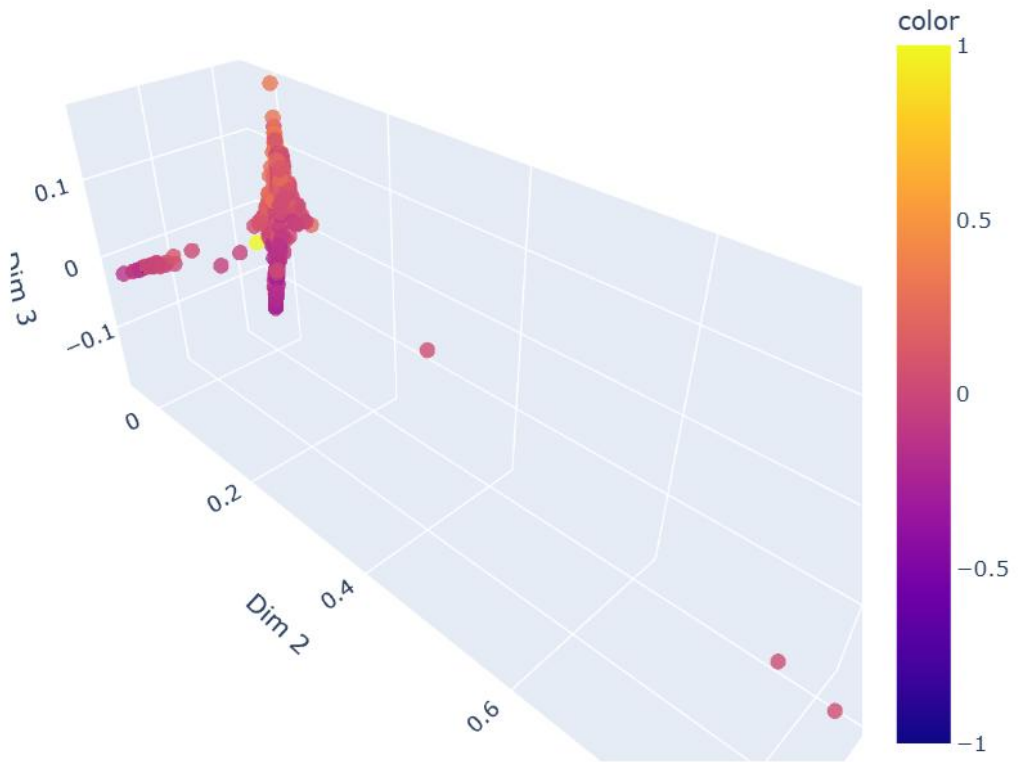
Higher stimulus specificity: An index close to 1 indicates strong selectivity — the neuron responds strongly to a specific stimulus and weakly (or not at all) to others.
Uniform responses: An index close to 6 indicates no selectivity — the neuron has similar amplitudes across all six stimuli.
Note: the index only reflects the response magnitudes only. It does not distinguish the signs of responses.

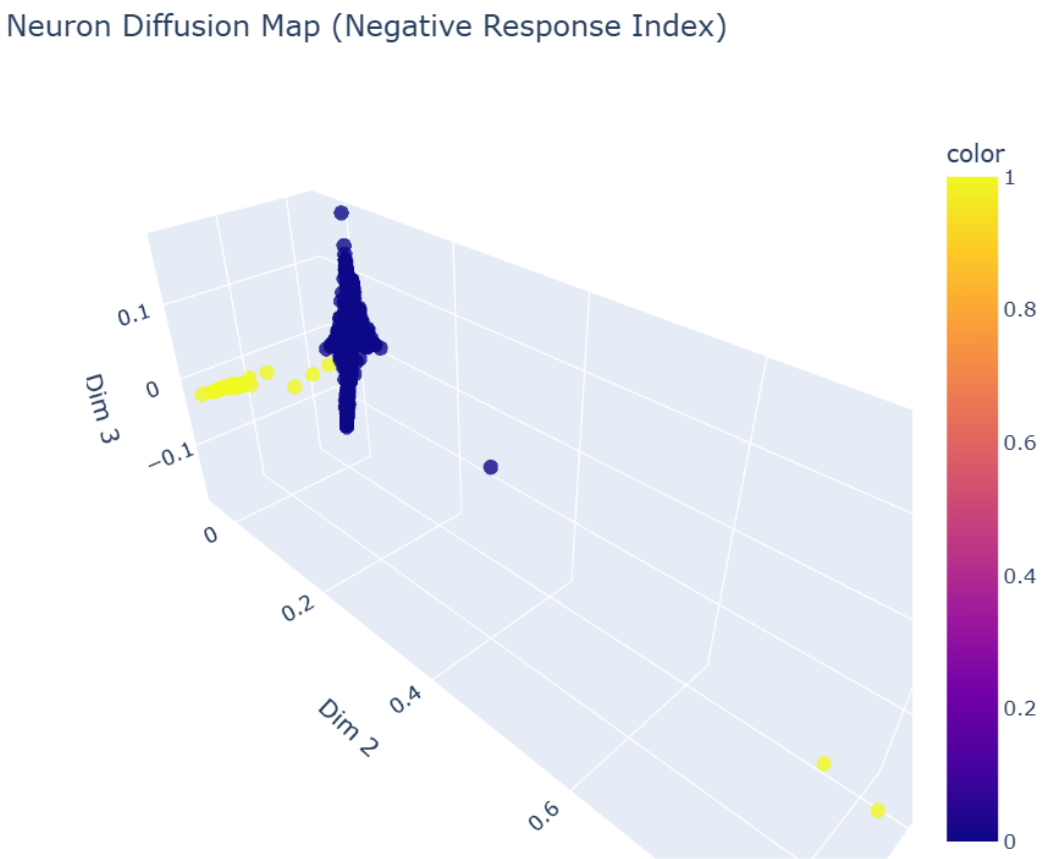
$$\text{Dot Selectivity Index} = \frac{\Delta R_{1\text{dot}} - \Delta R_{3\text{dot}}}{|\Delta R_{1\text{dot}}| + |\Delta R_{3\text{dot}}|}$$

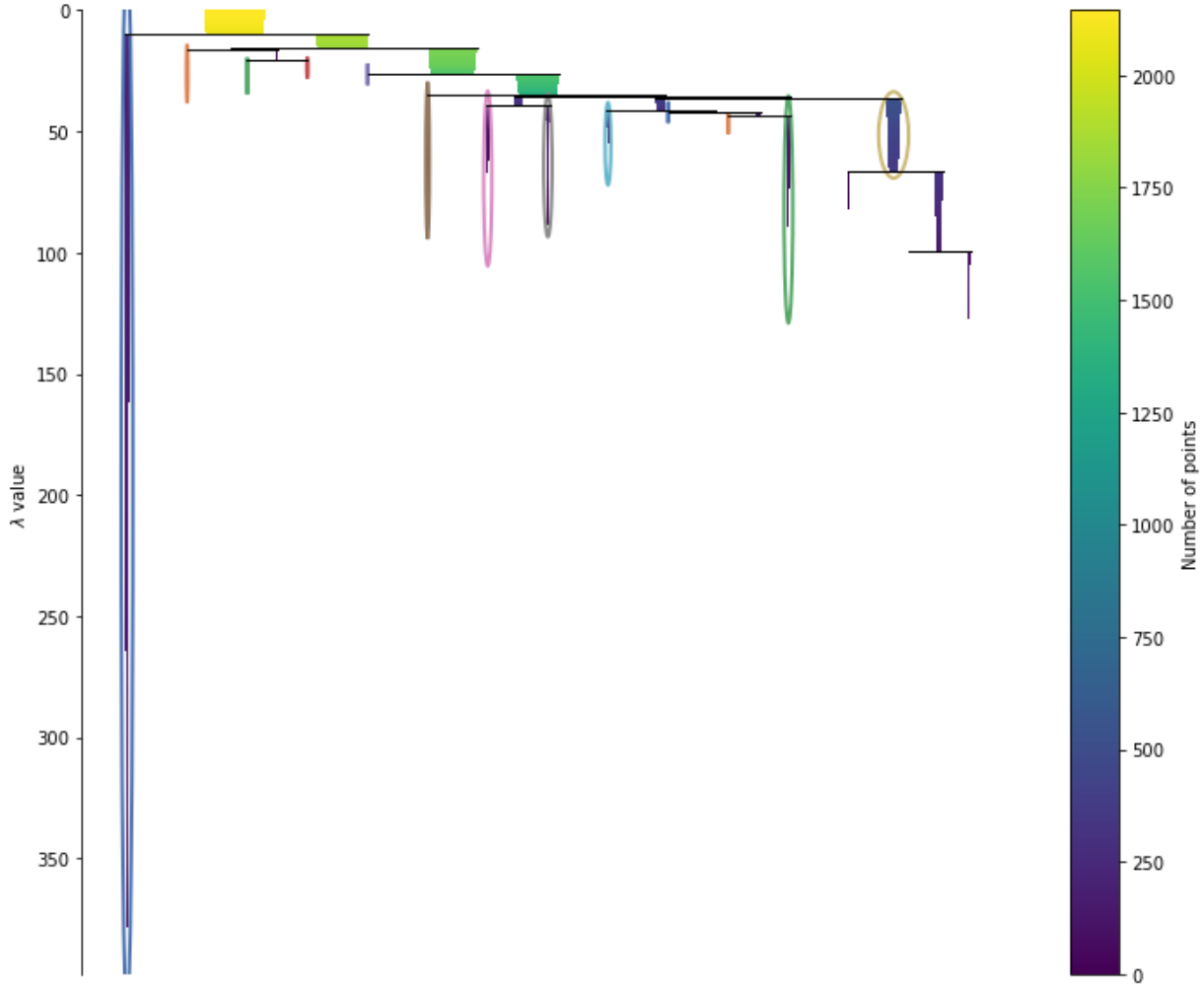
Neuron Diffusion Map (Stimulus Entropy Index)



Neuron Diffusion Map (Dot Selectivity Index)



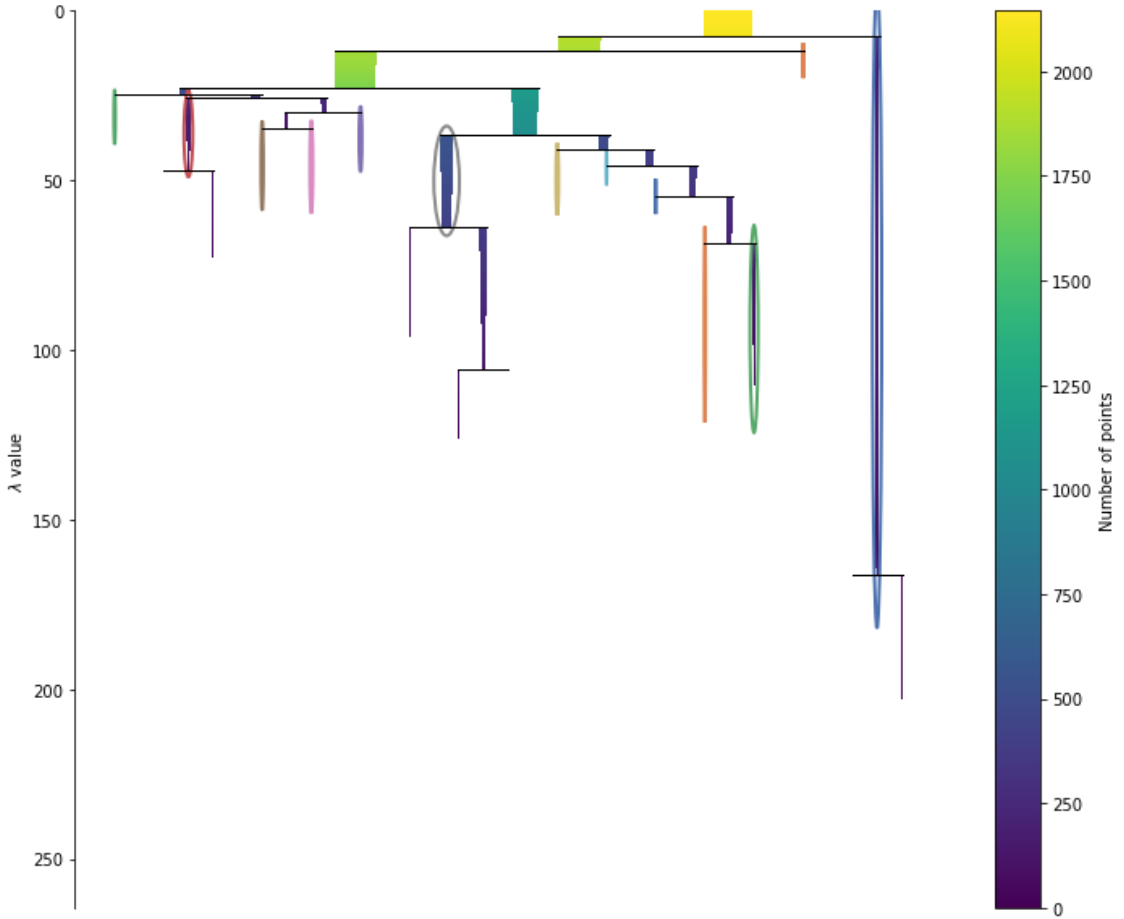




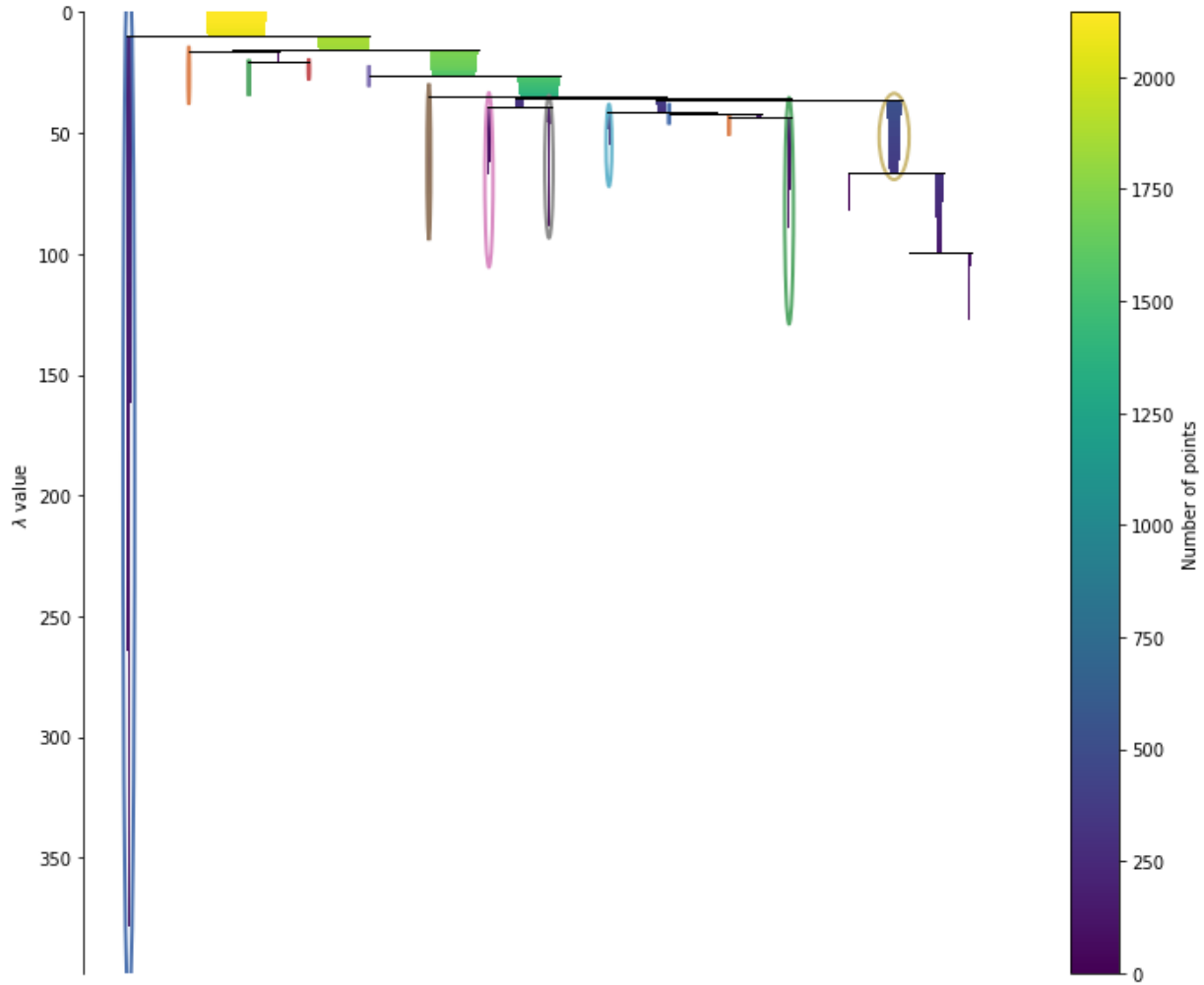
13 classes `min_cluster_size=15`

If min_cluster_size=5, 36 clusters.

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

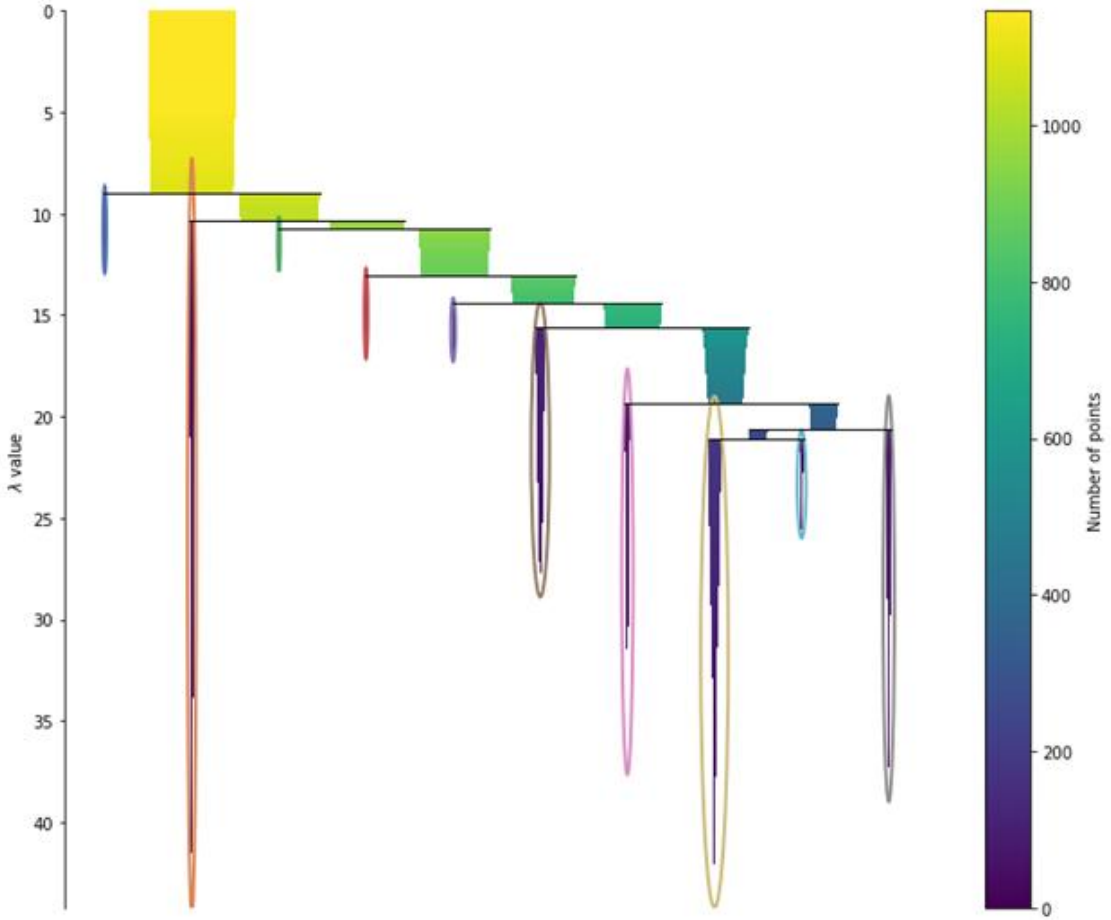


New cut: 0.5s pre+1.5s trial+2s post



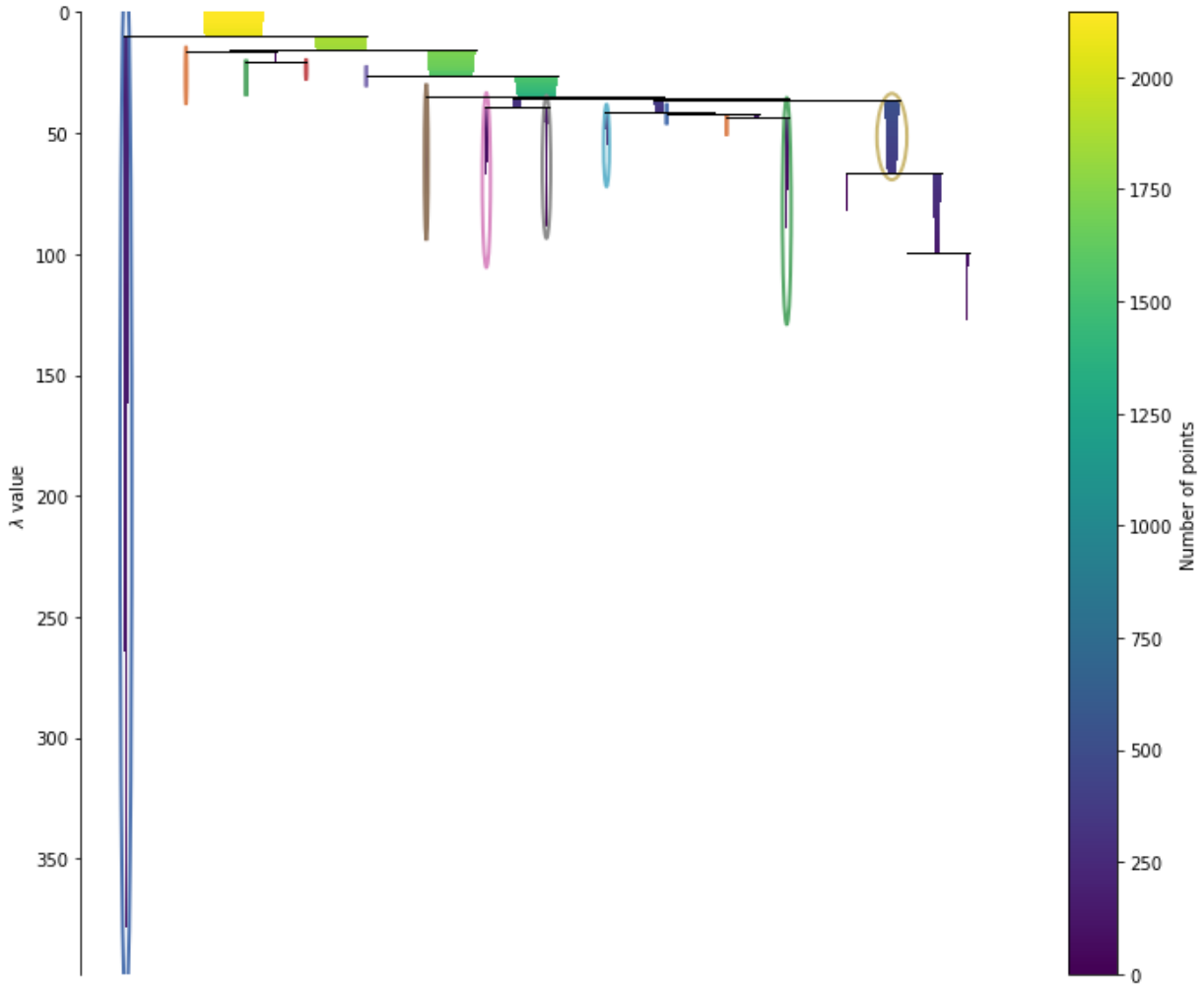
Both are 13 classes

Public retina data



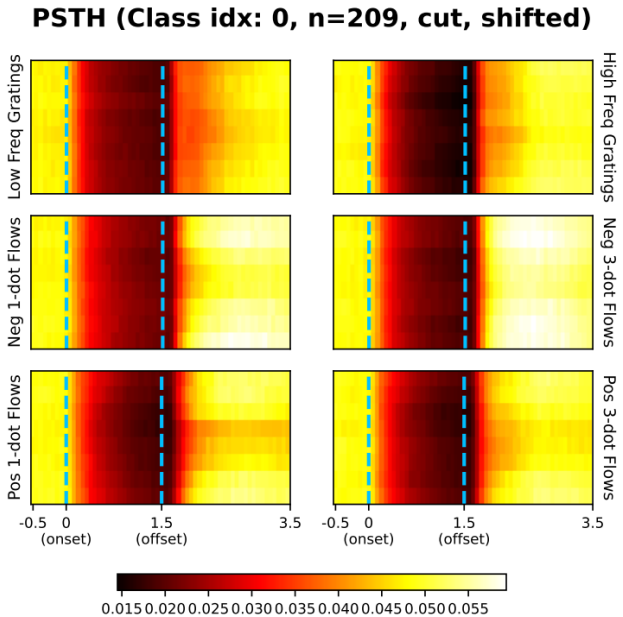
10 classes

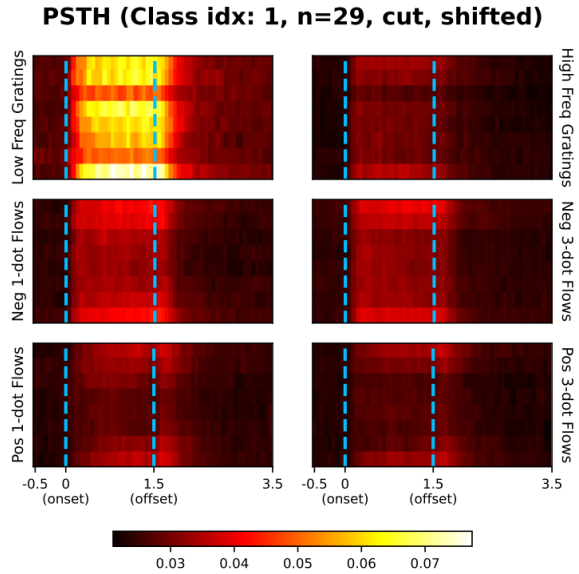
New cut: 0.5s pre+1.5s trial+2s post

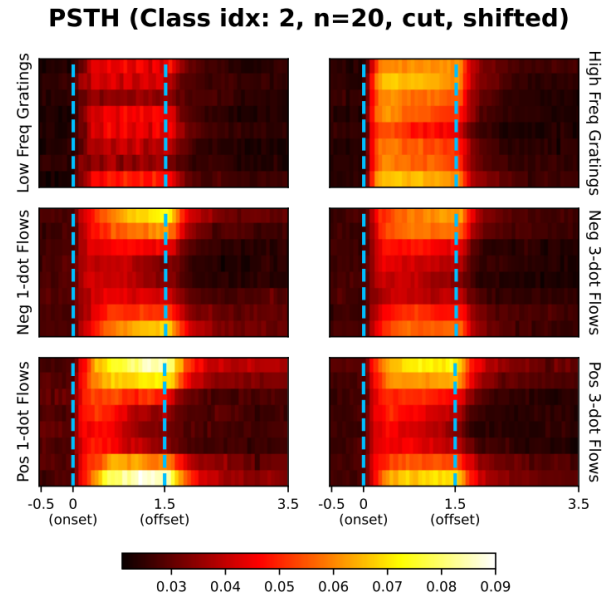


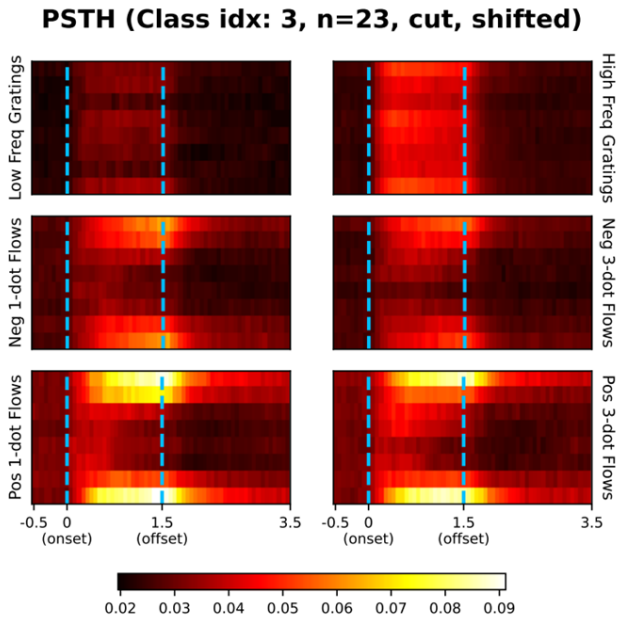
13 classes

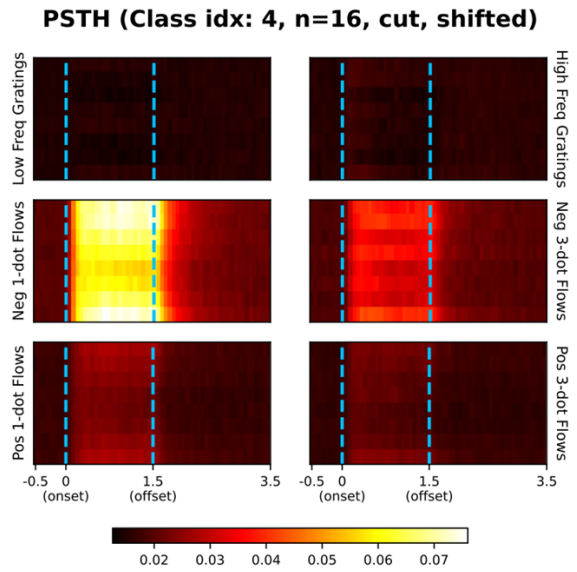
Examples of Cluster Average response

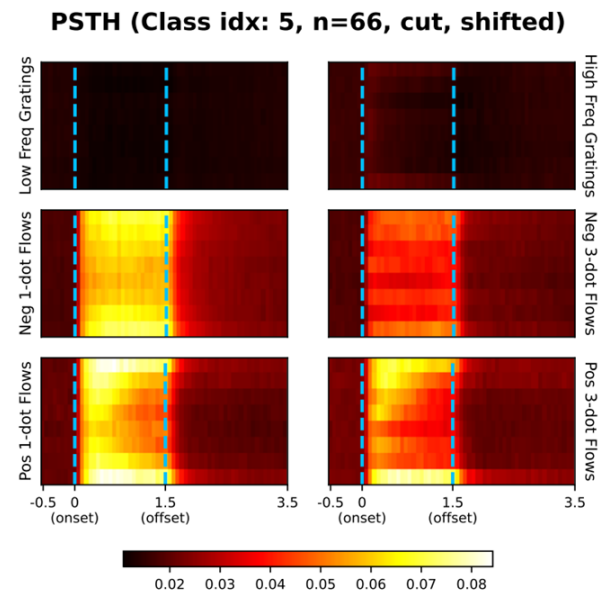


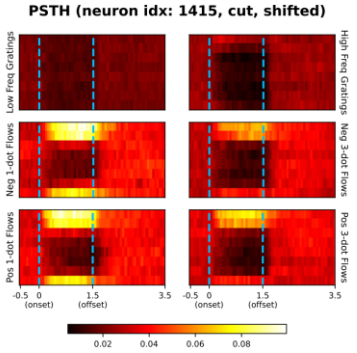












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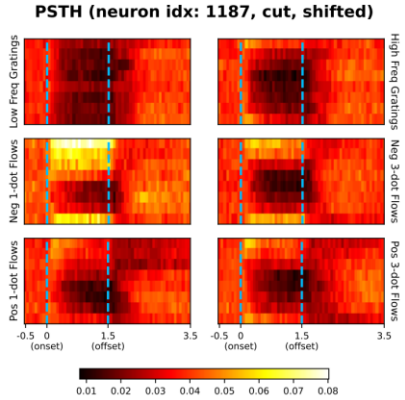

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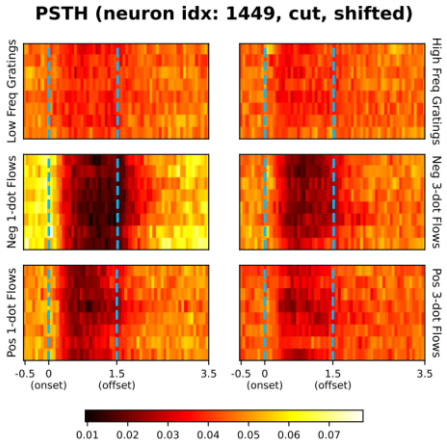

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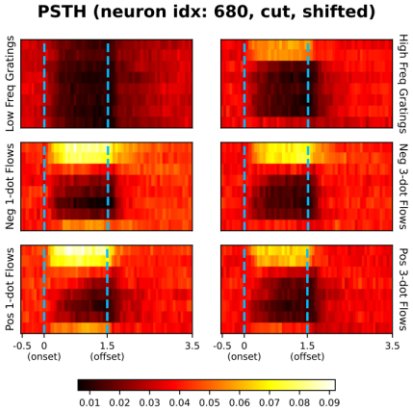

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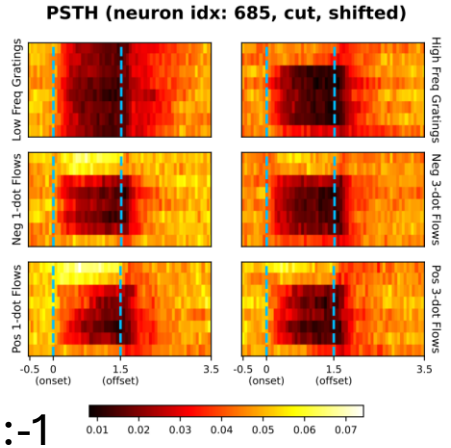

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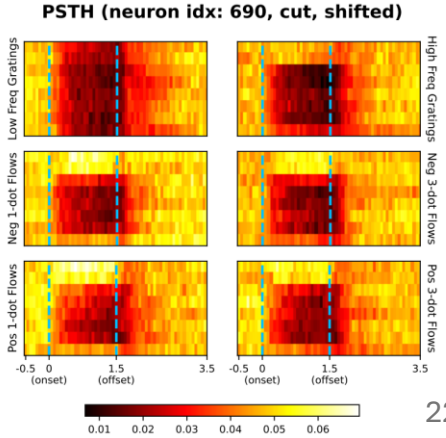

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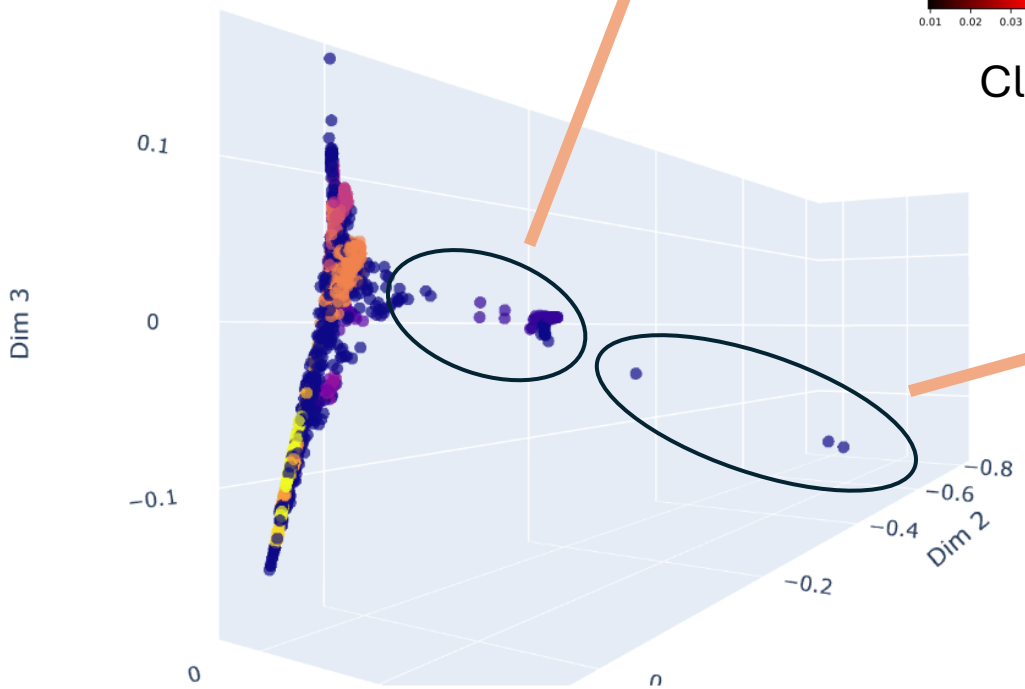

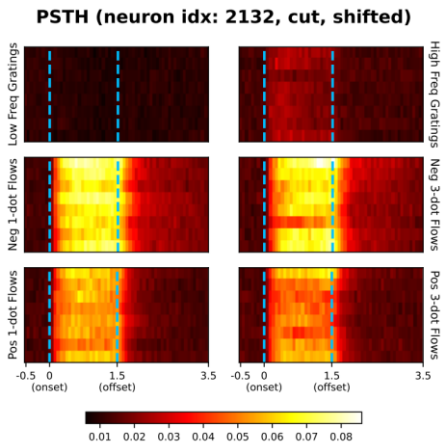

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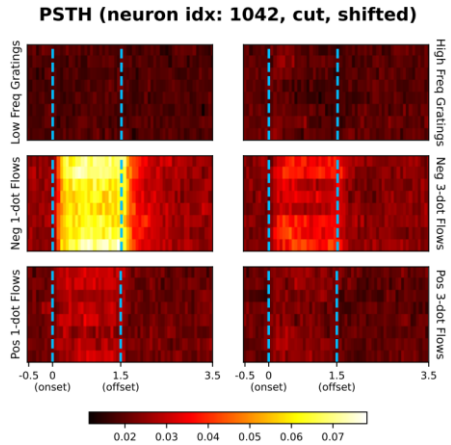

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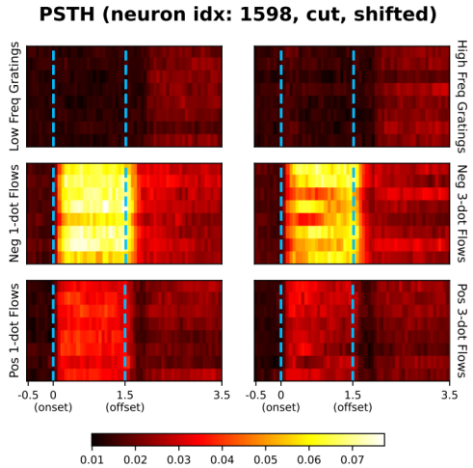

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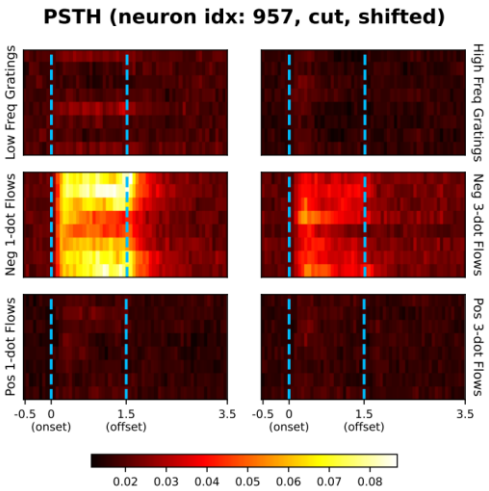

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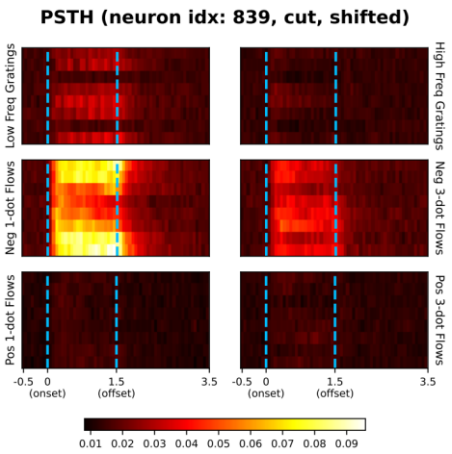

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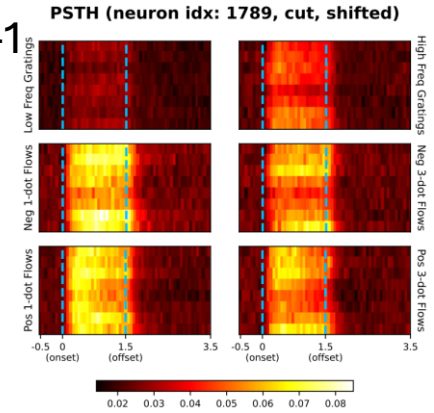

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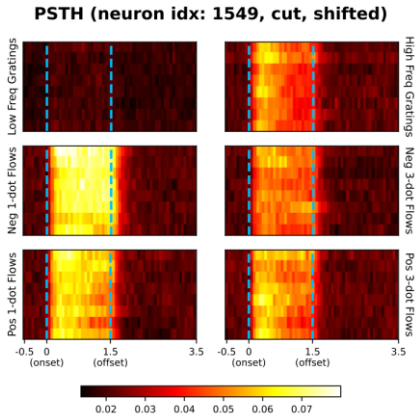
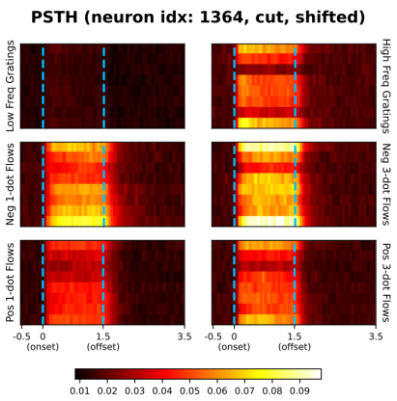
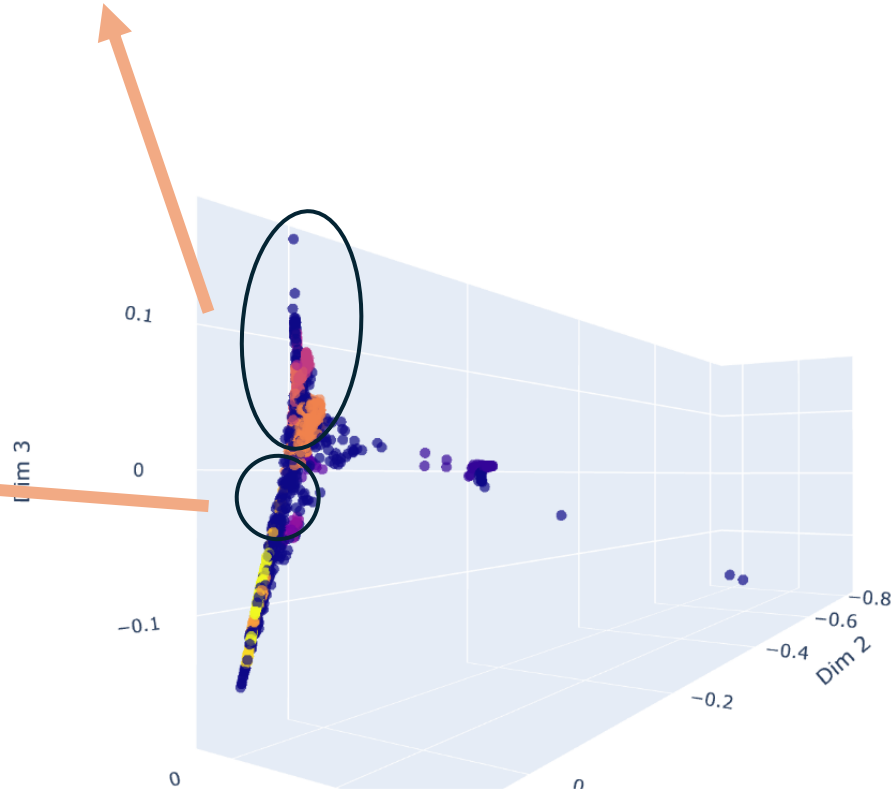
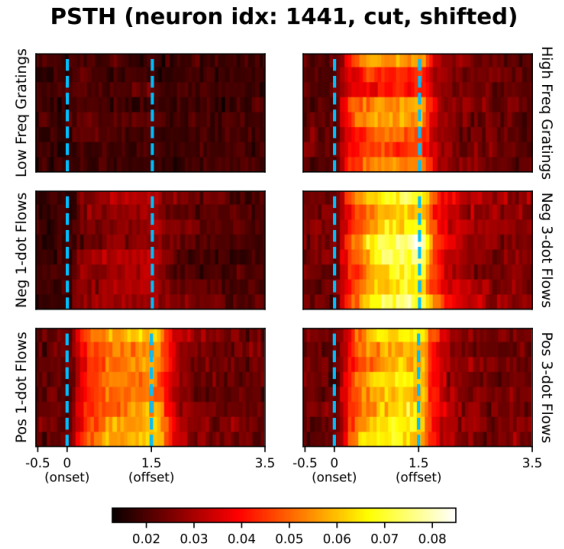


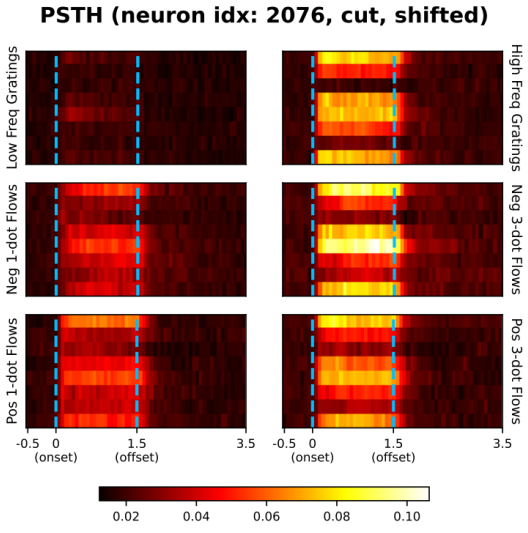
Class:-1



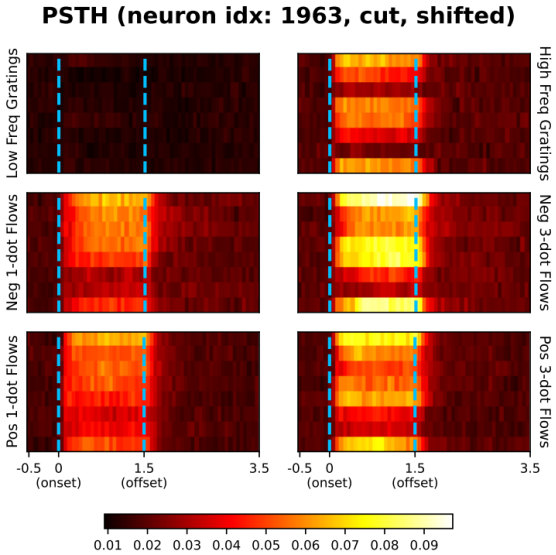




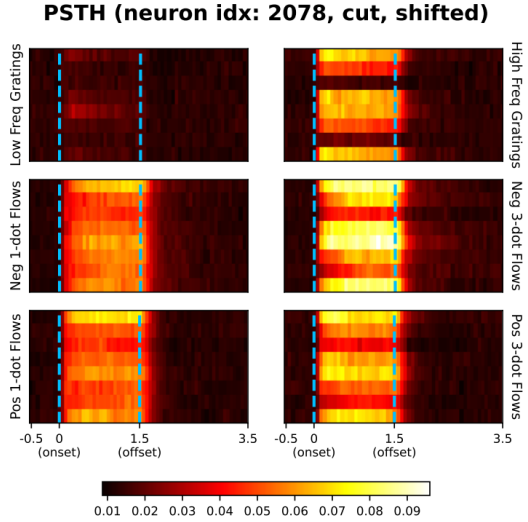
Class:12



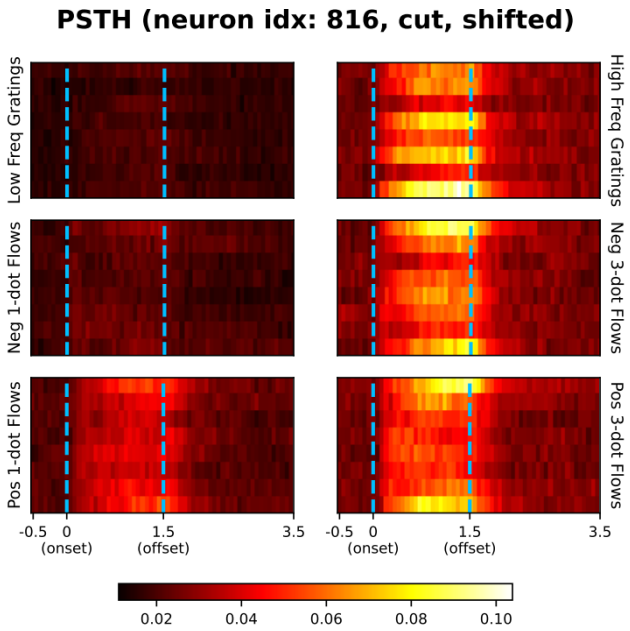
Class:12



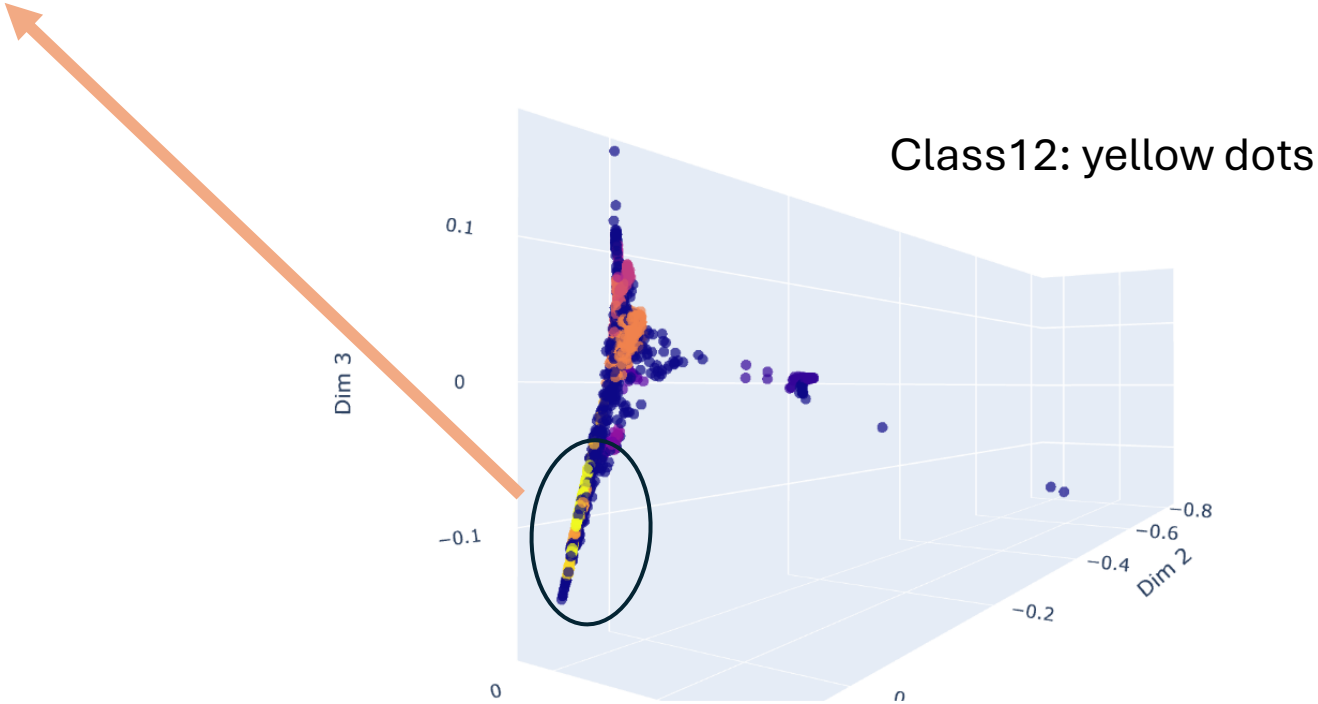
Class:12



Class:12



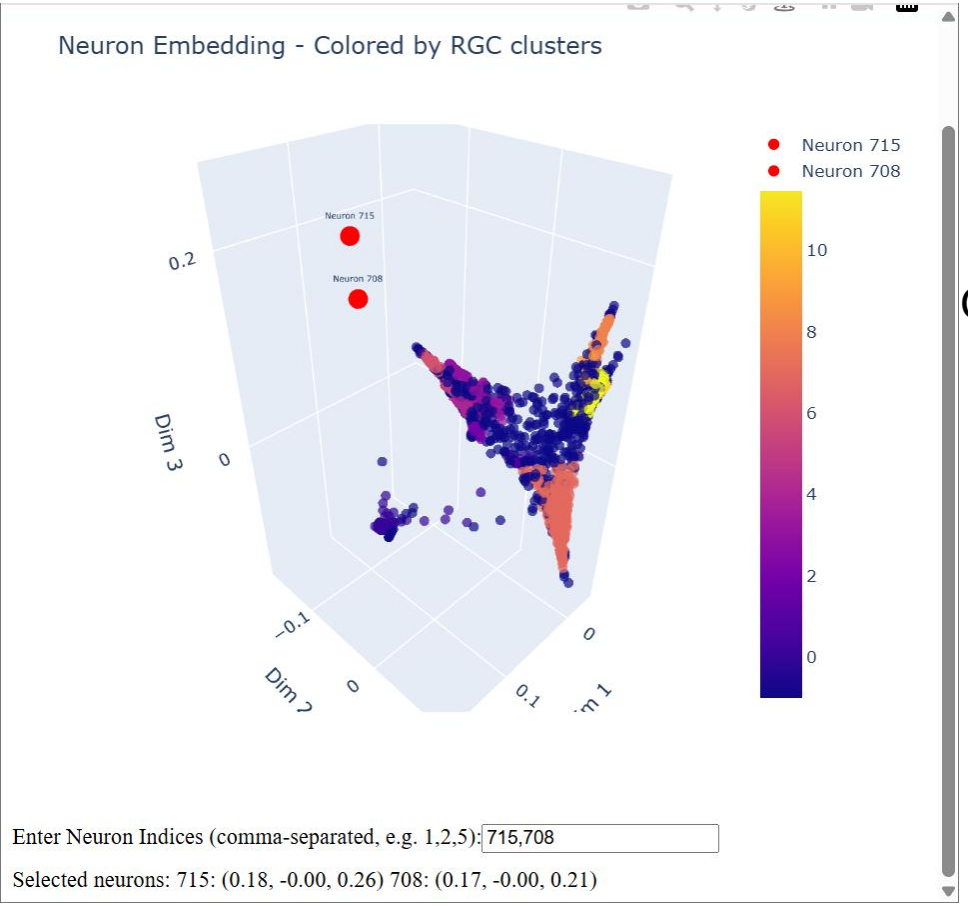
Class:-1

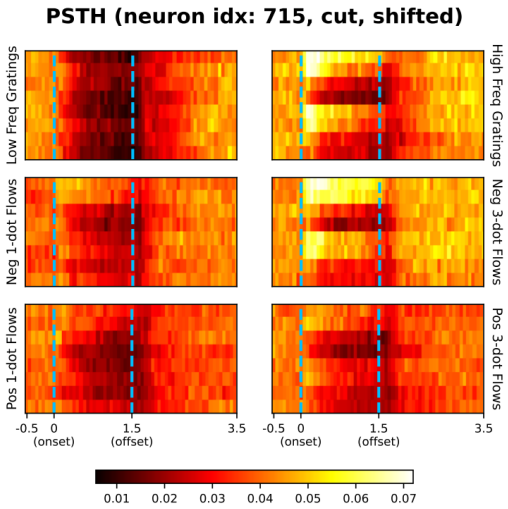


Class12: yellow dots

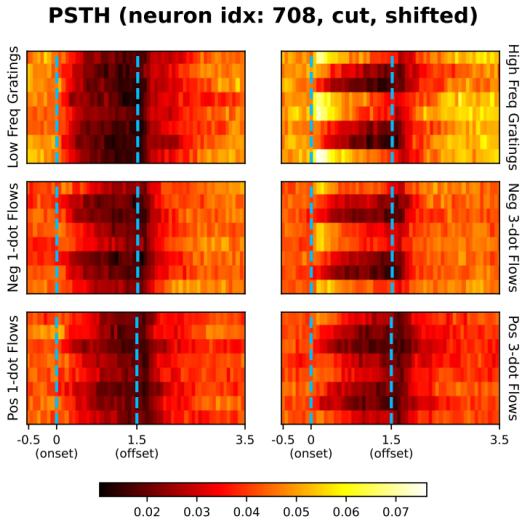
Neuron location comparison between the old clusters and new clusters.

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

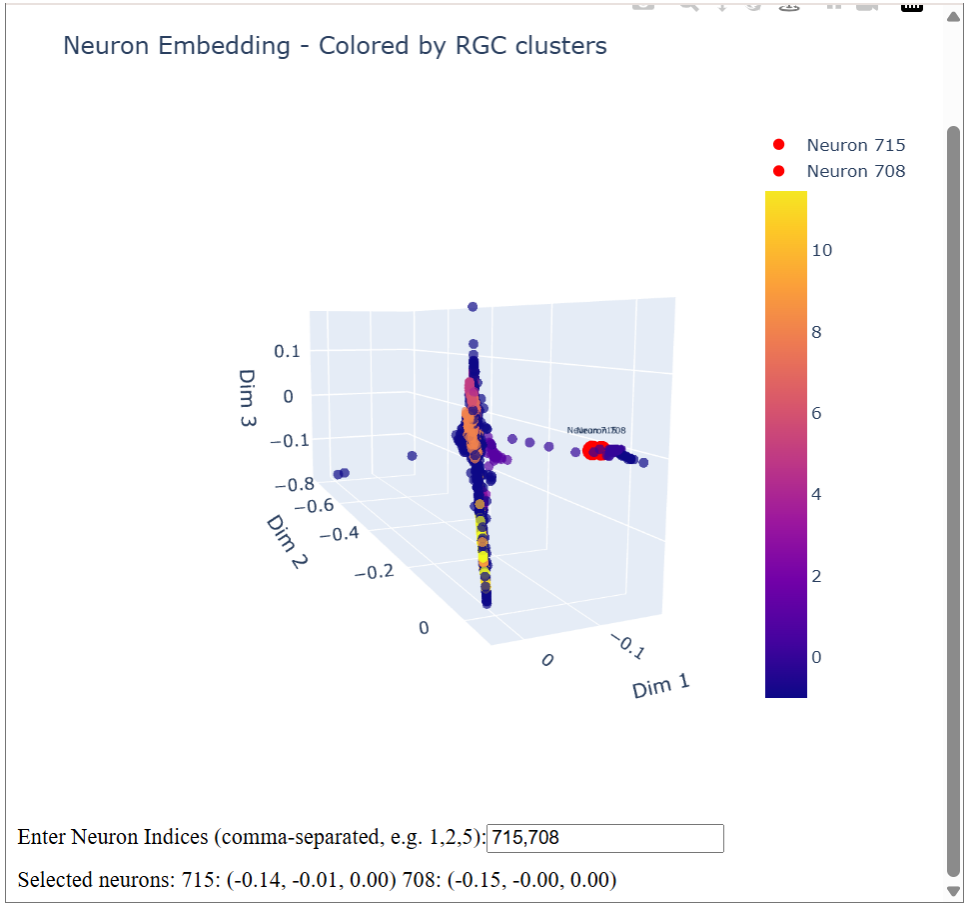




Class:0 (new cut), -1 (old cut)



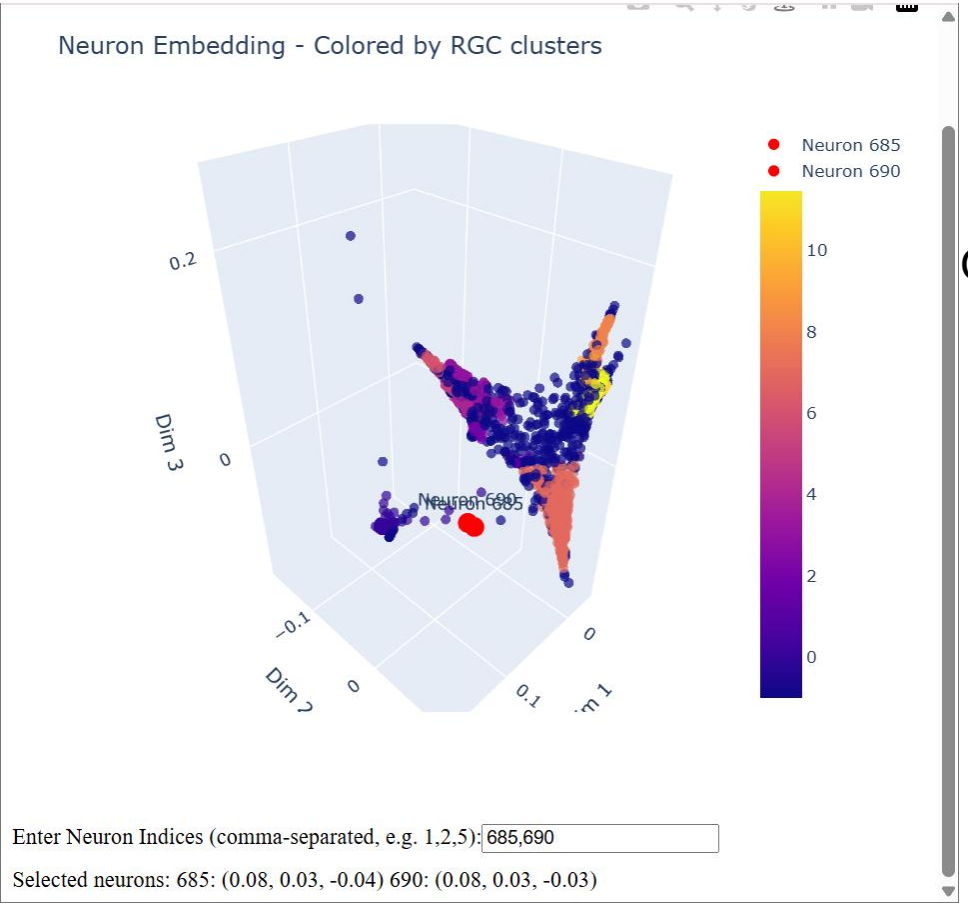
New cut: 0.5s pre+1.5s trial+2s post
dims: 1 2 3

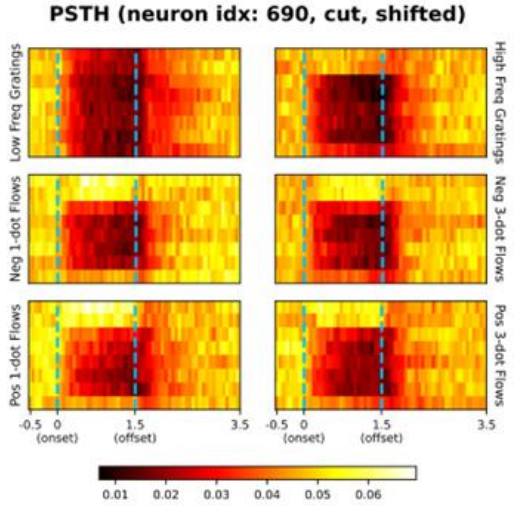


Class:0 (new cut), -1 (old cut)

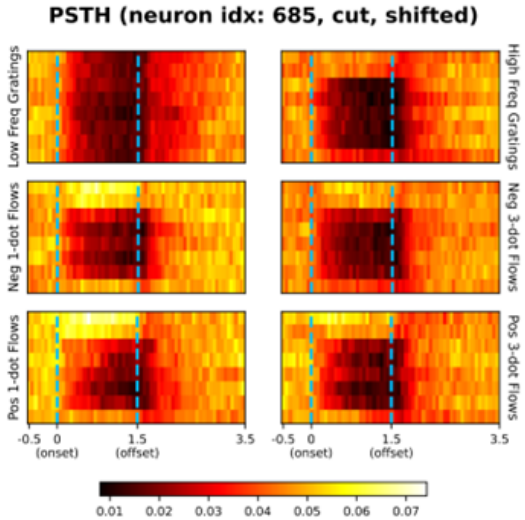
Neuron location comparison between the old clusters and new clusters.

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



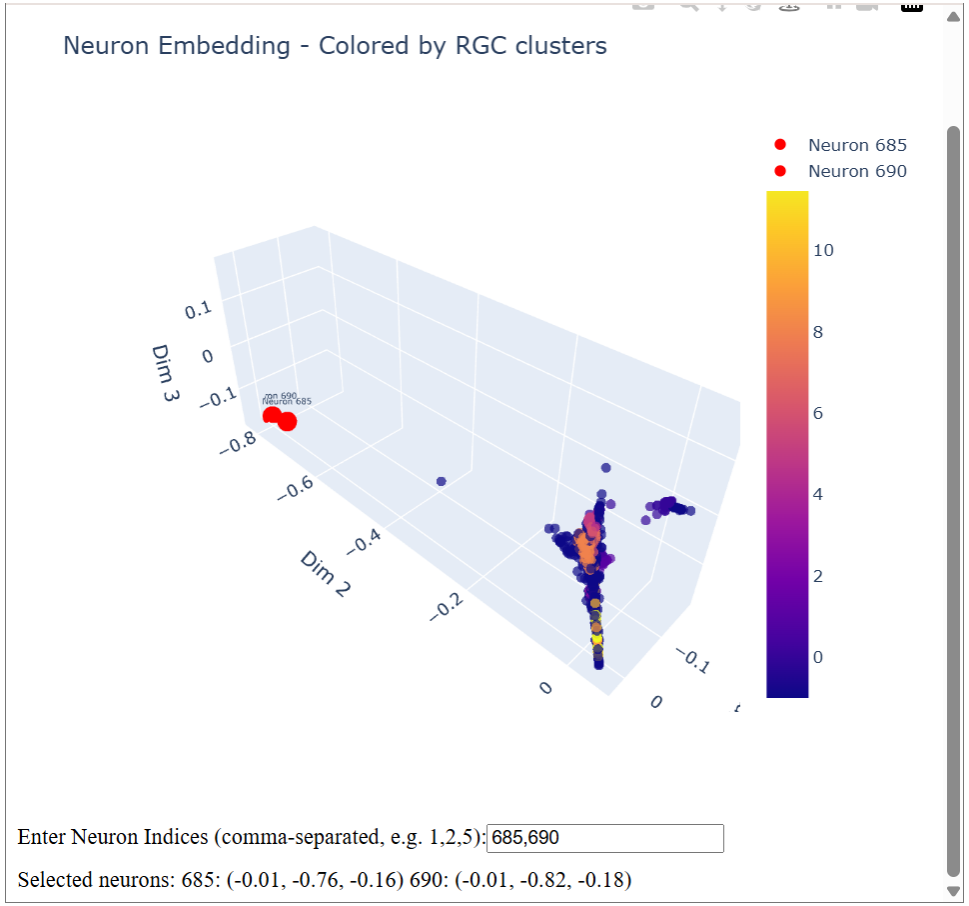


Class:-1 (new cut), 0 (old cut)



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

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



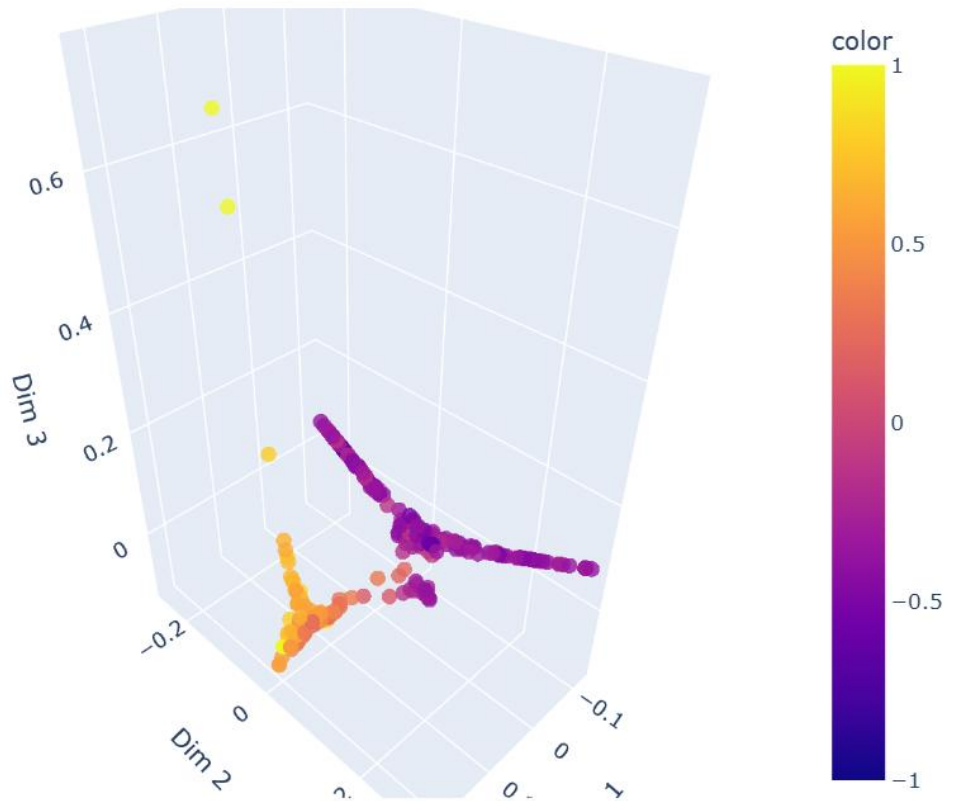
Superior Colliculus (SC)

2145 significant boutons

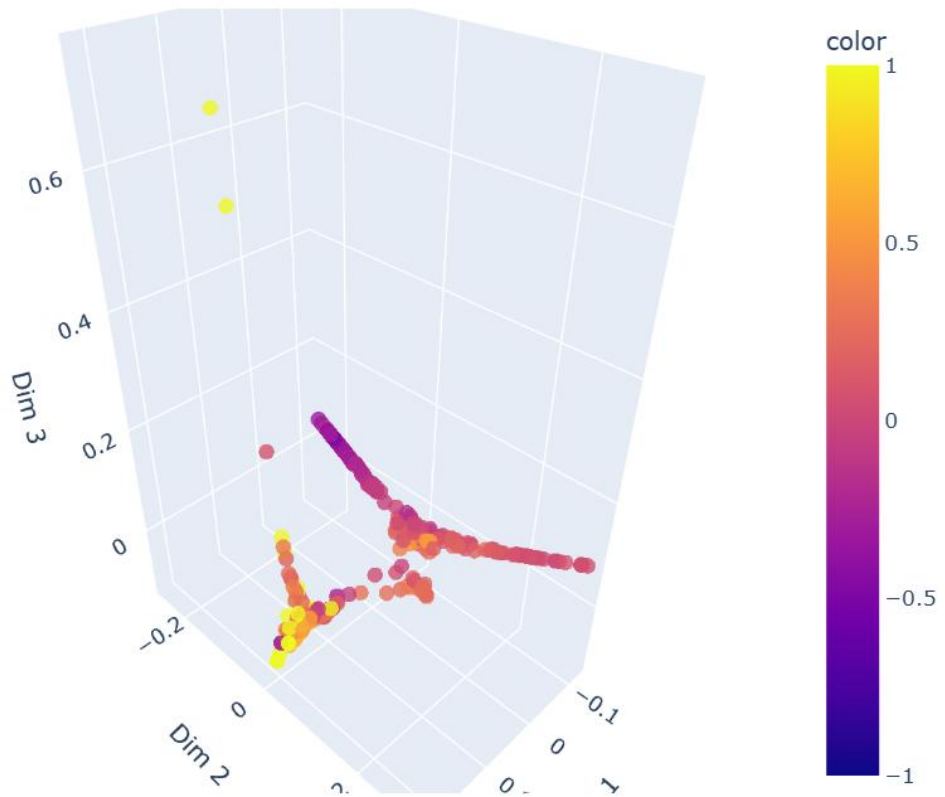
$$\text{Grating Selectivity Index} = \frac{\Delta R_g - \Delta R_f}{|\Delta R_g| + |\Delta R_f|}$$

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

Neuron Diffusion Map (Grating Selectivity Index)



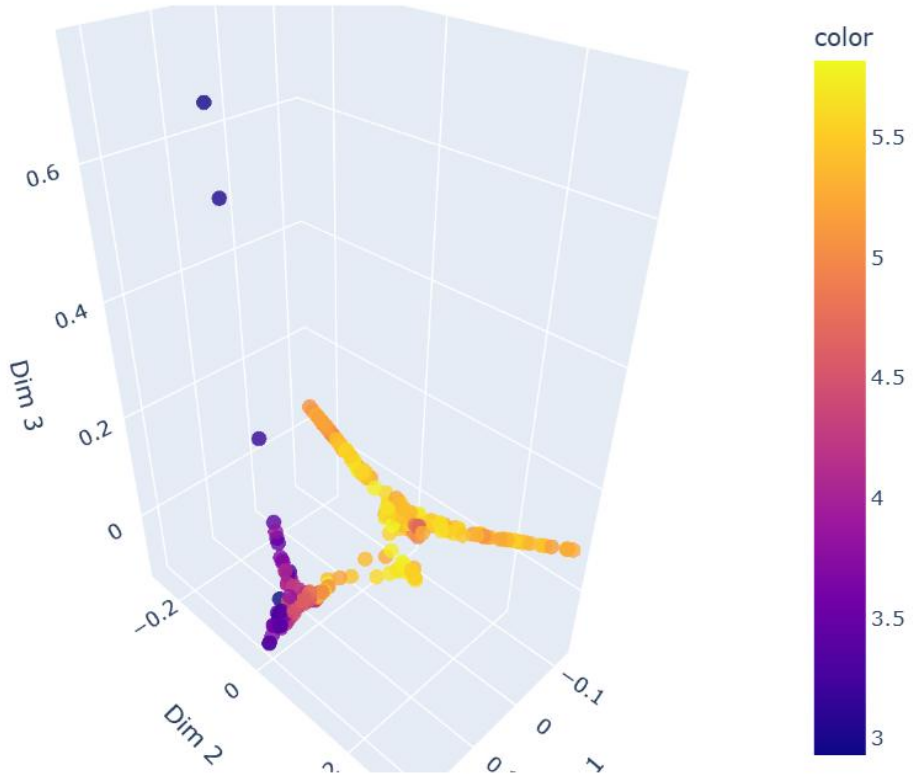
Neuron Diffusion Map (Flow Polarity Index)



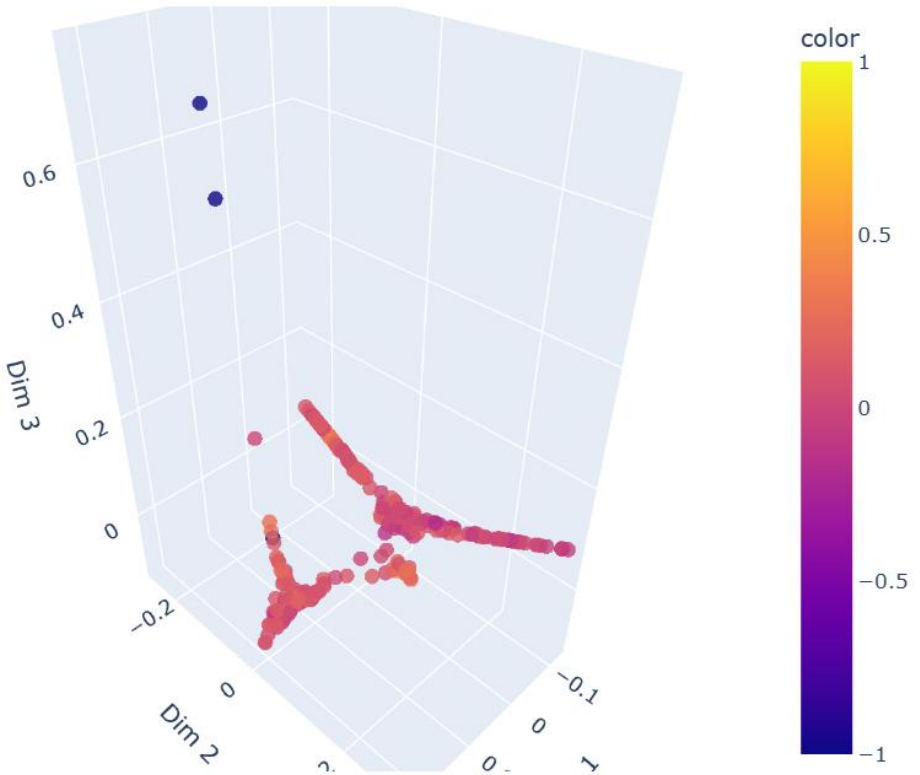
Higher stimulus specificity: An index close to 1 indicates strong selectivity — the neuron responds strongly to a specific stimulus and weakly (or not at all) to others.
Uniform responses: An index close to 6 indicates no selectivity — the neuron has similar amplitudes across all six stimuli.
Note: the index only reflects the response magnitudes only. It does not distinguish the signs of responses.

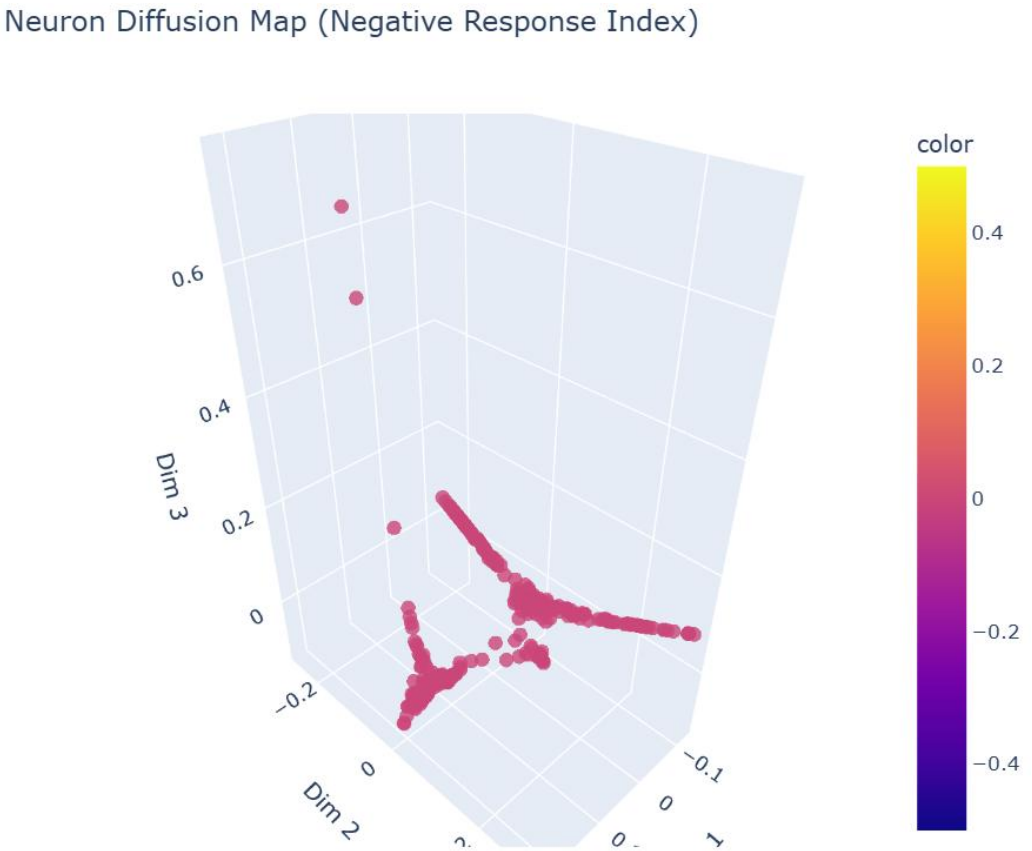
$$\text{Dot Selectivity Index} = \frac{\Delta R_{1\text{dot}} - \Delta R_{3\text{dot}}}{|\Delta R_{1\text{dot}}| + |\Delta R_{3\text{dot}}|}$$

Neuron Diffusion Map (Stimulus Entropy Index)

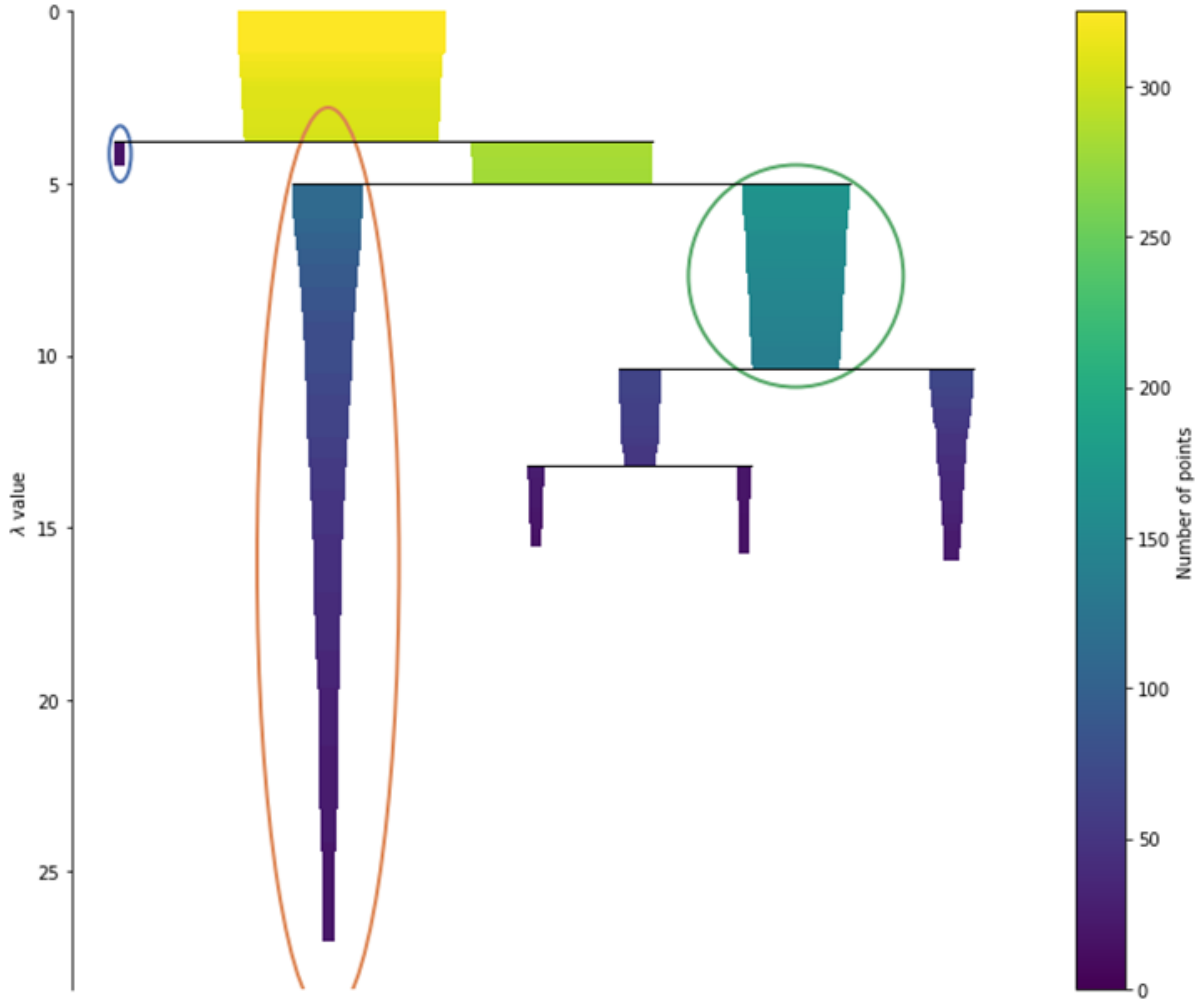


Neuron Diffusion Map (Dot Selectivity Index)





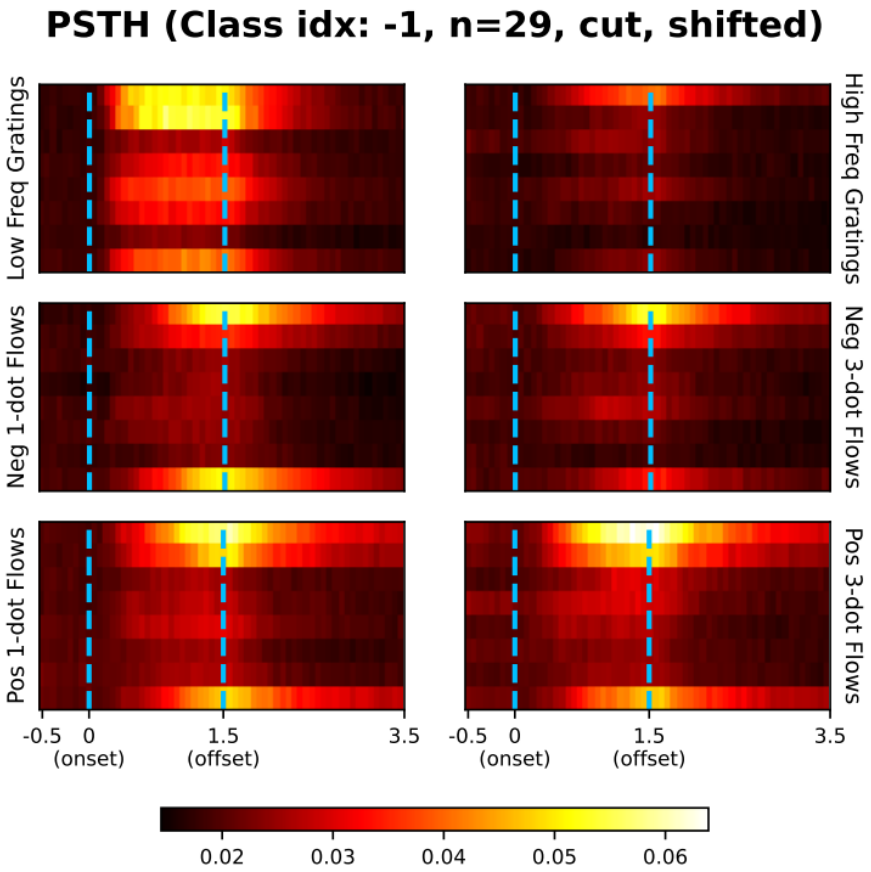
Few suppressed cells in SC.



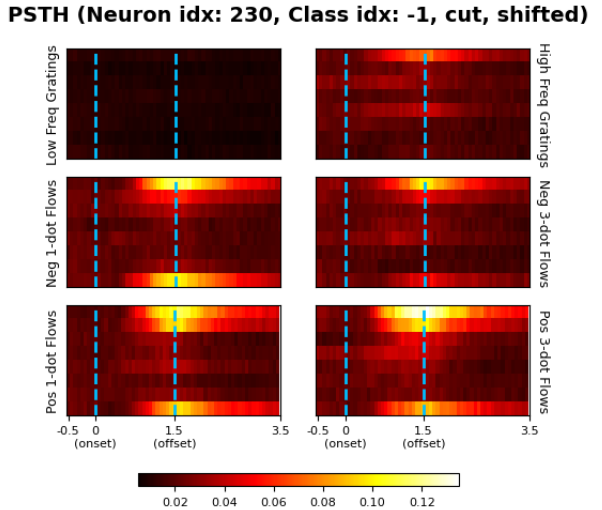
3 classes `min_cluster_size=15`

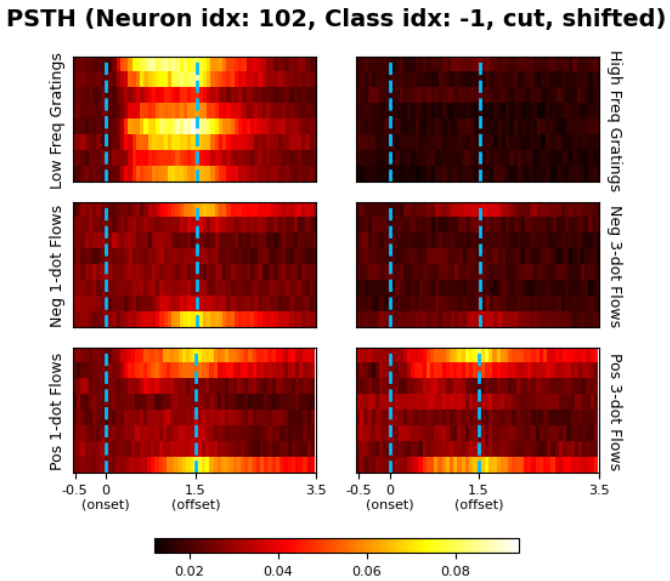
If min_cluster_size=5, 8 clusters.

Class Avg PSTH

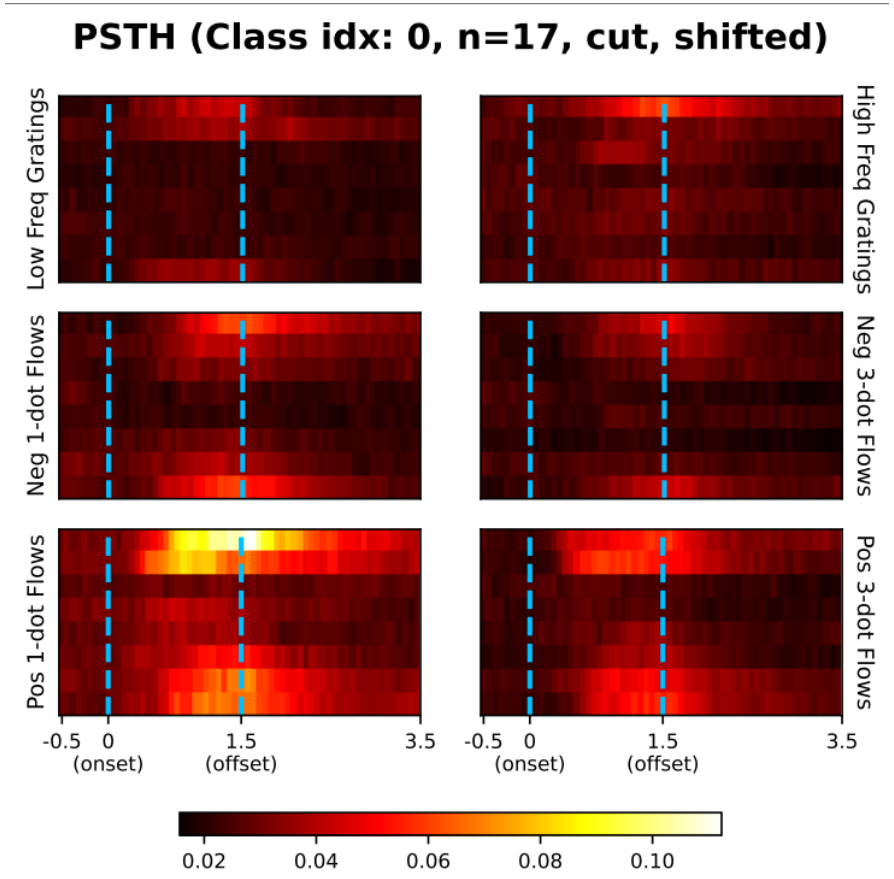


Examples

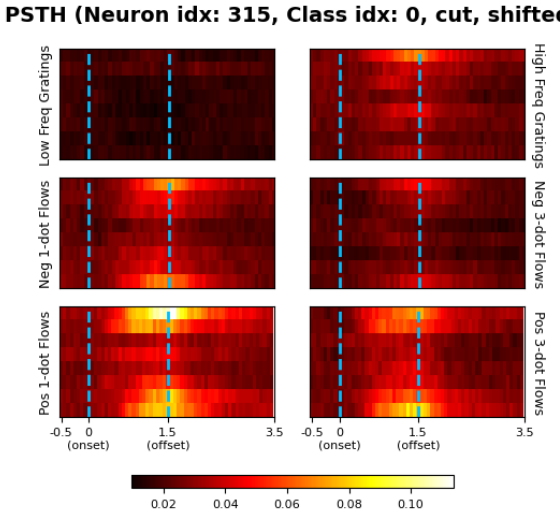


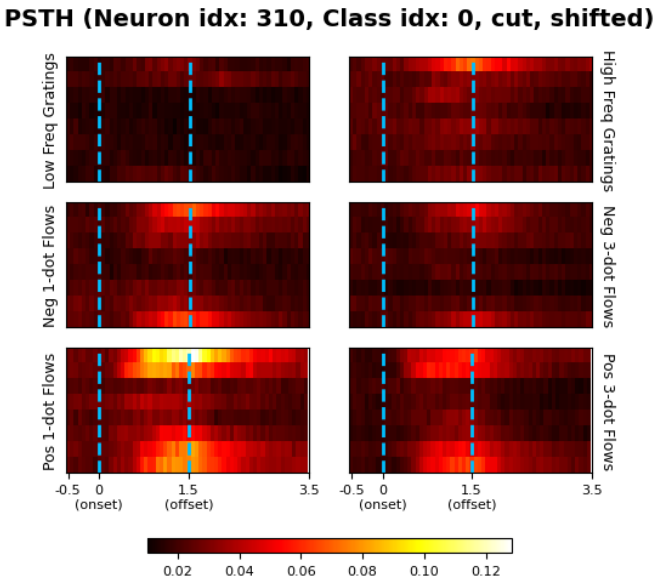


Class Avg PSTH

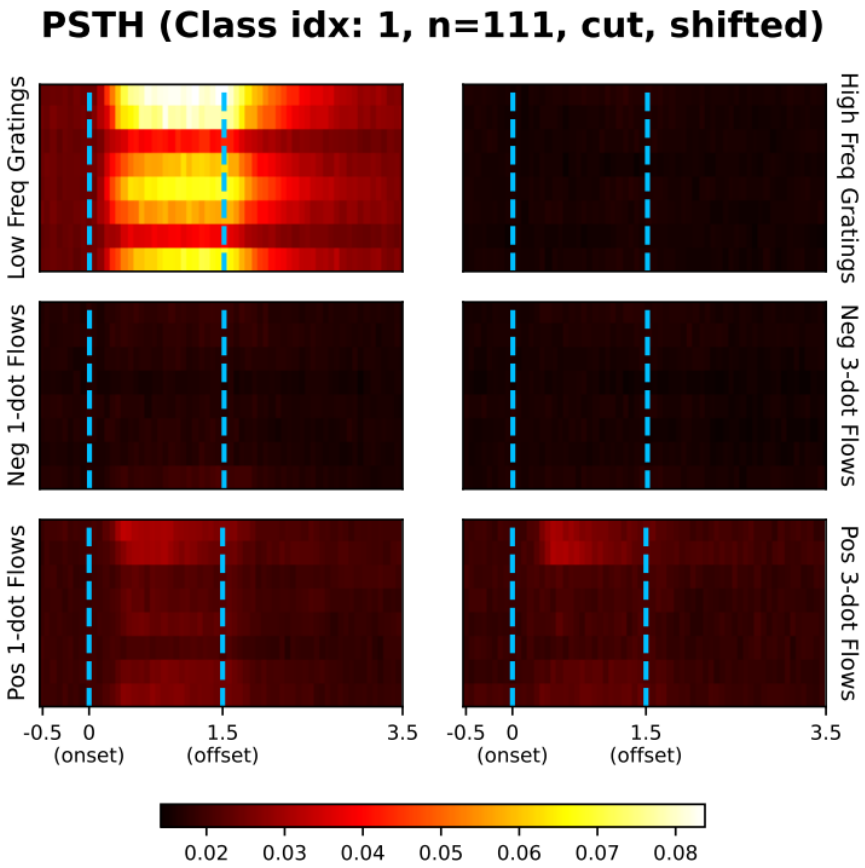


Examples

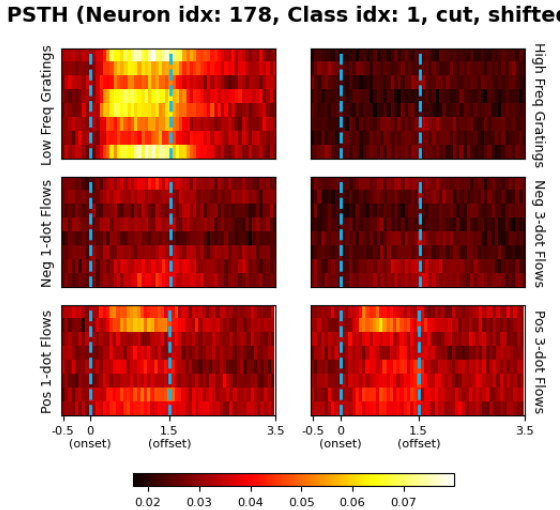


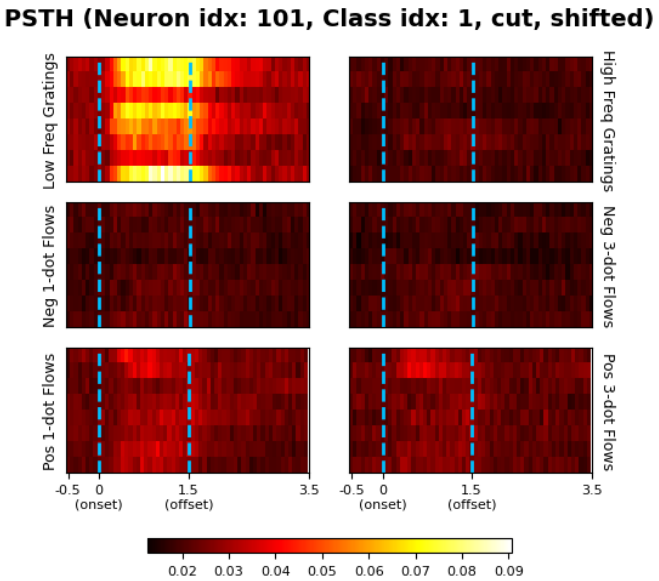


Class Avg PSTH

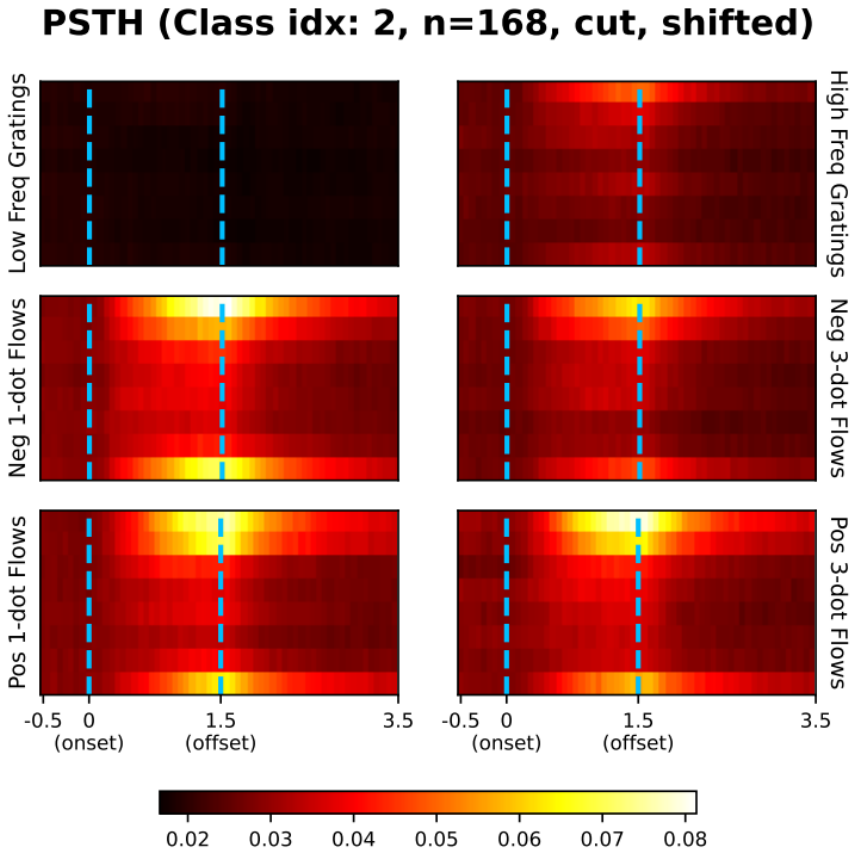


Examples

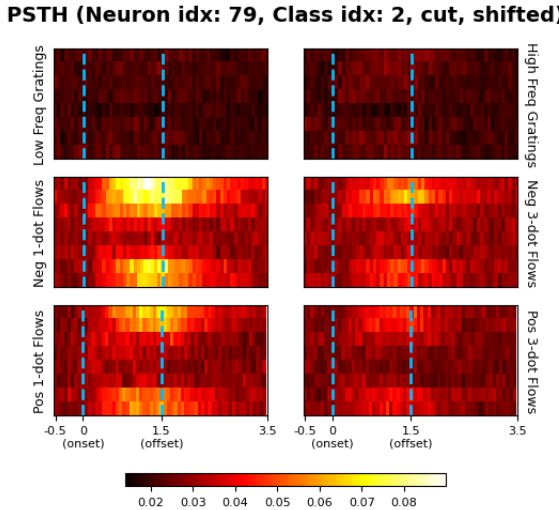


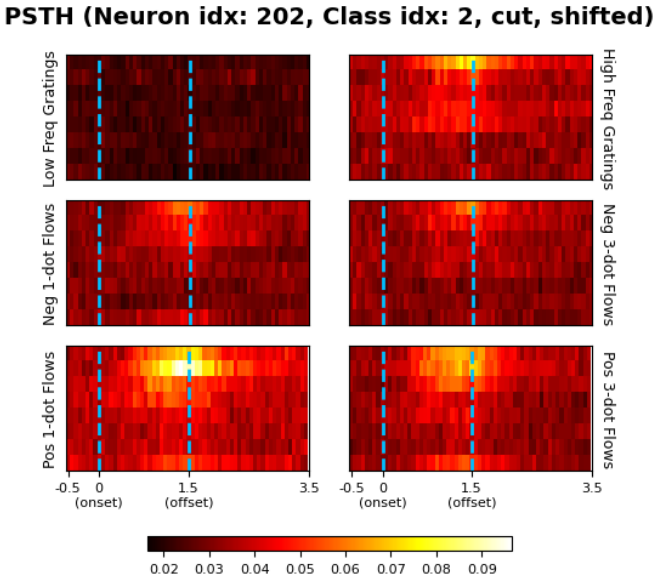


Class Avg PSTH

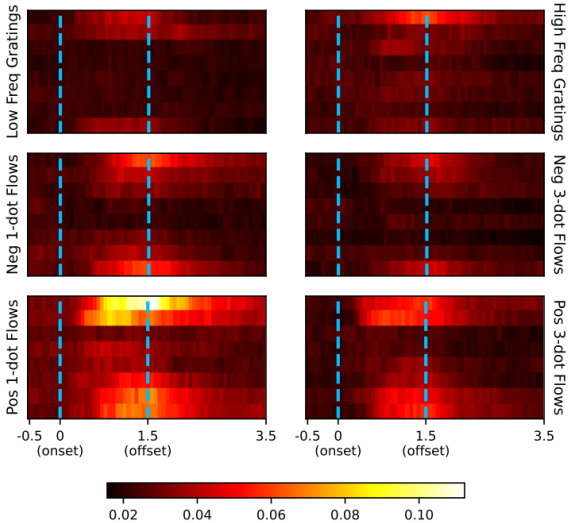


Examples

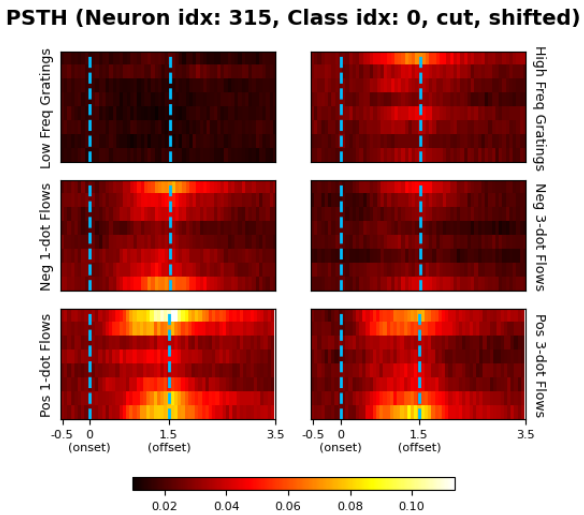


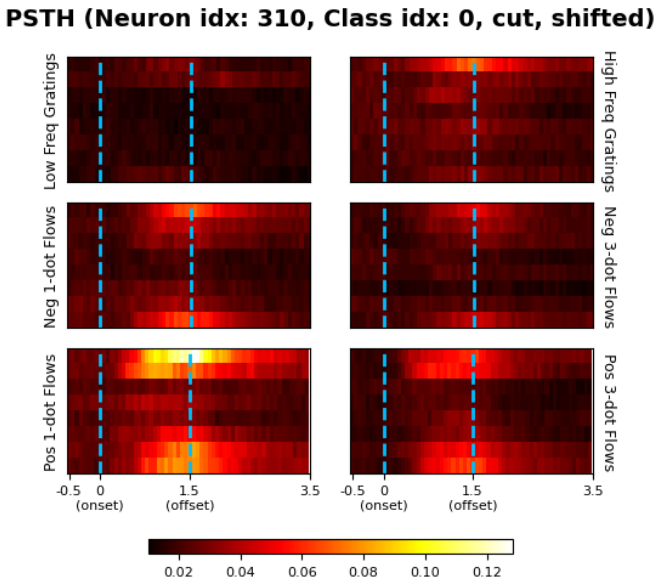


Class Avg PSTH (SC)



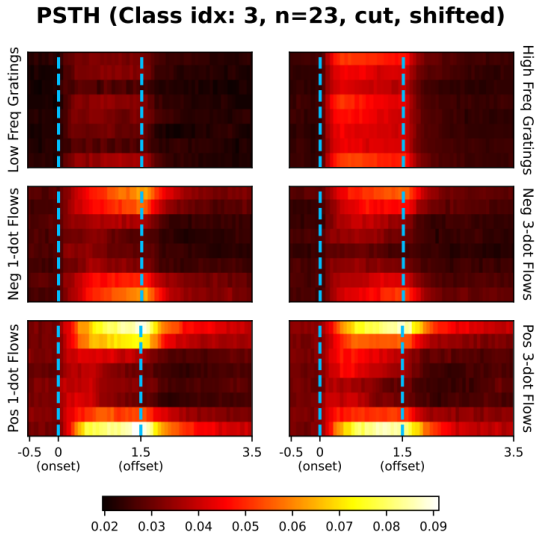
Examples



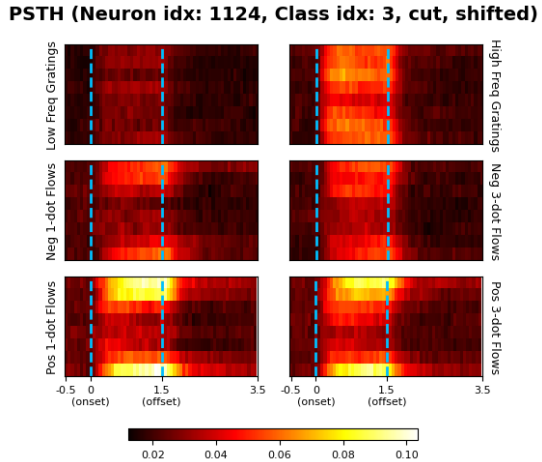


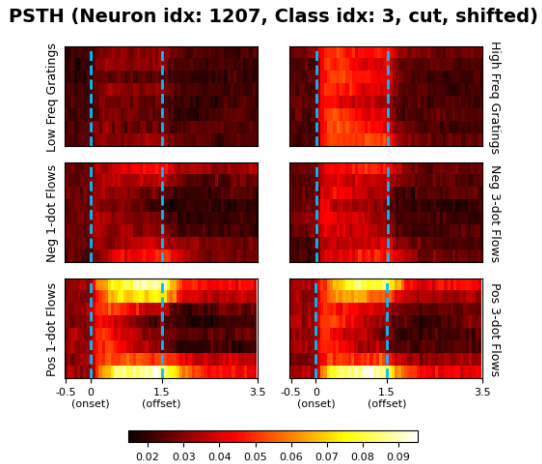
Most similar RGC class

Class Avg PSTH (RGC)



Examples



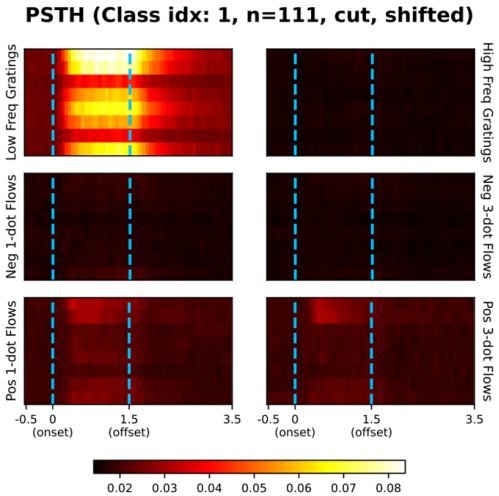


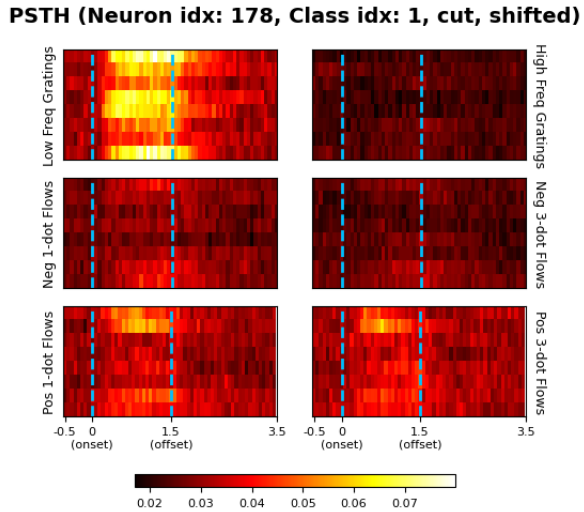
Examples

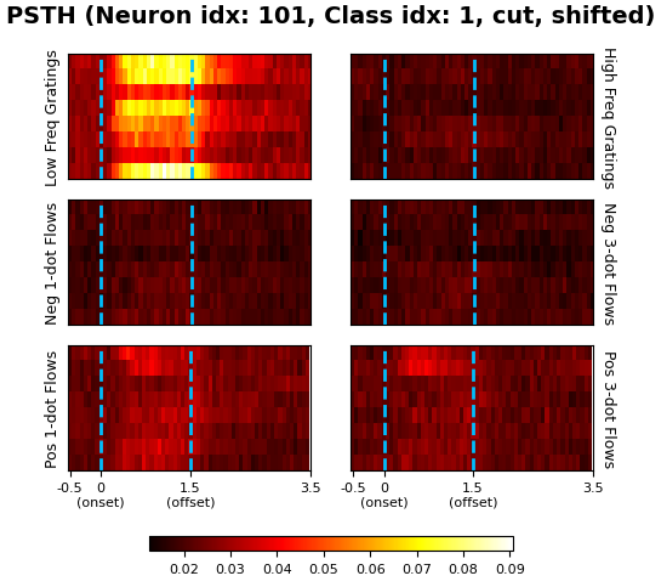
Most similar RGC class

Examples

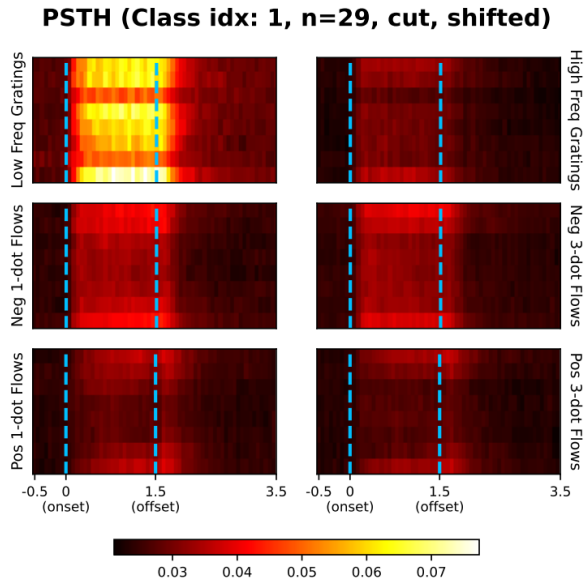
Class Avg PSTH (SC)

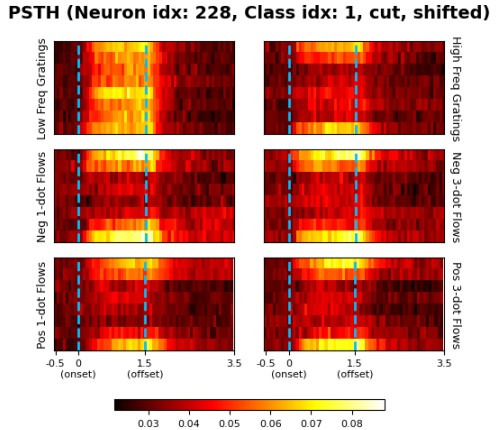


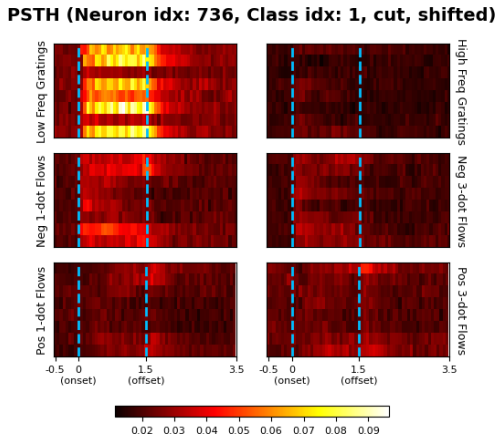




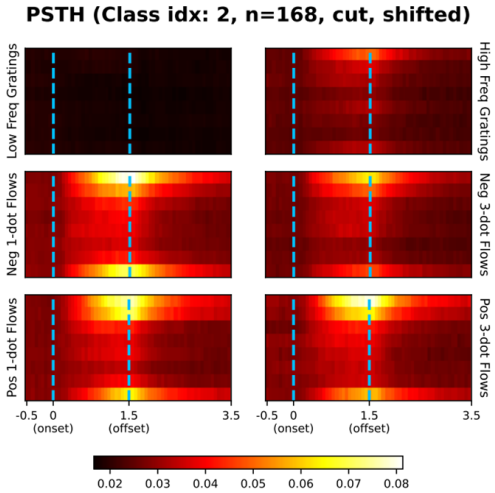
Class Avg PSTH (RGC)



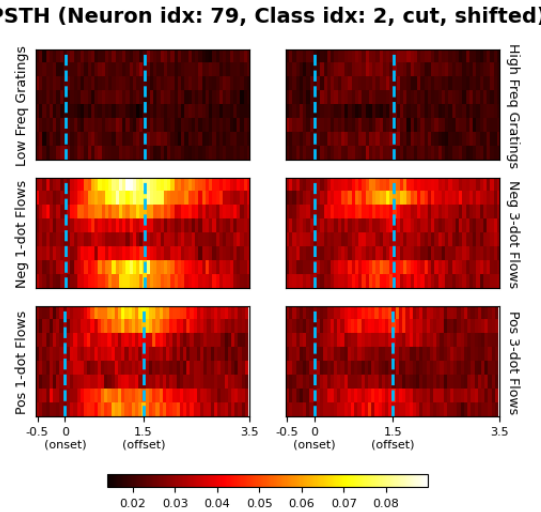


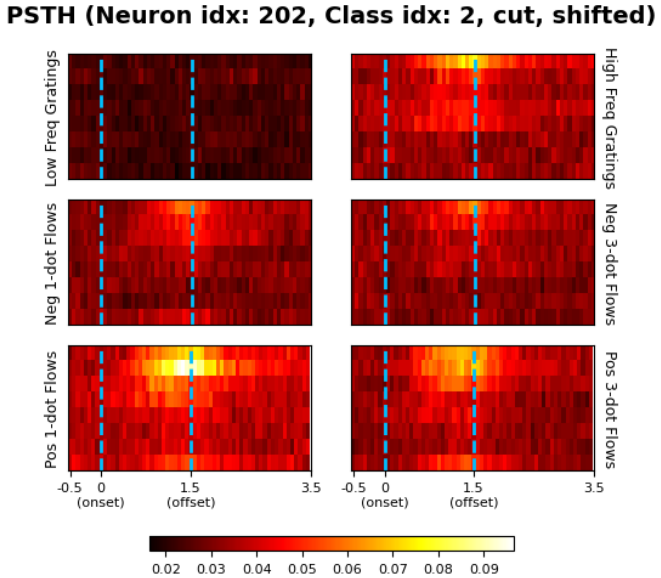


Class Avg PSTH (SC)



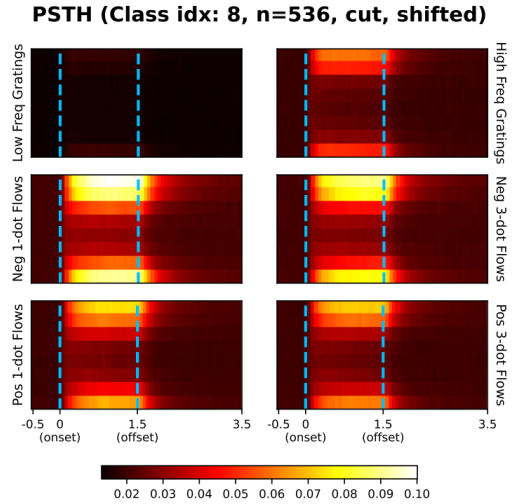
Examples



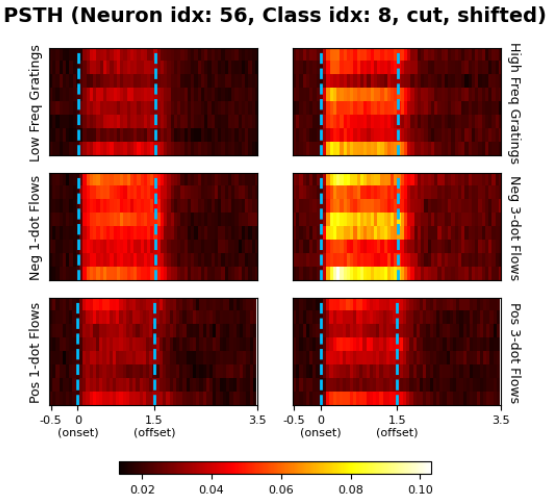


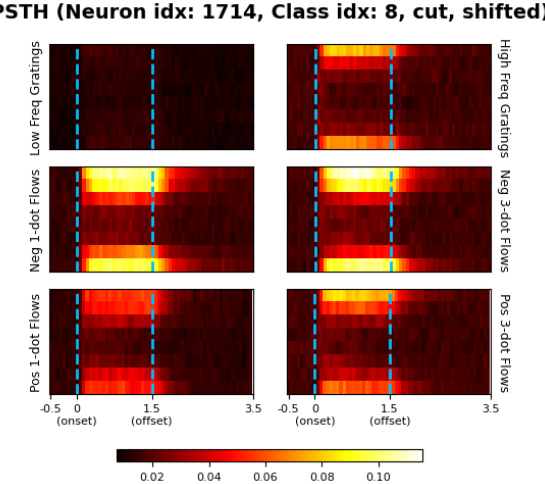
Most similar RGC class

Class Avg PSTH (RGC)



Examples





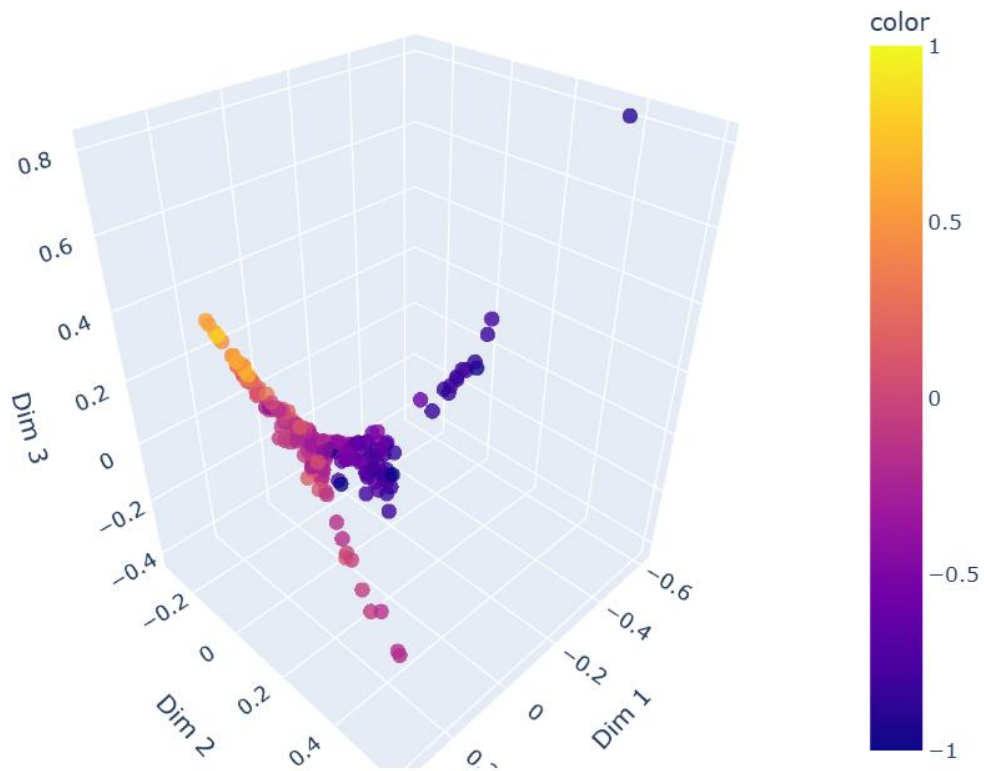
dLGN

229 significant neurons

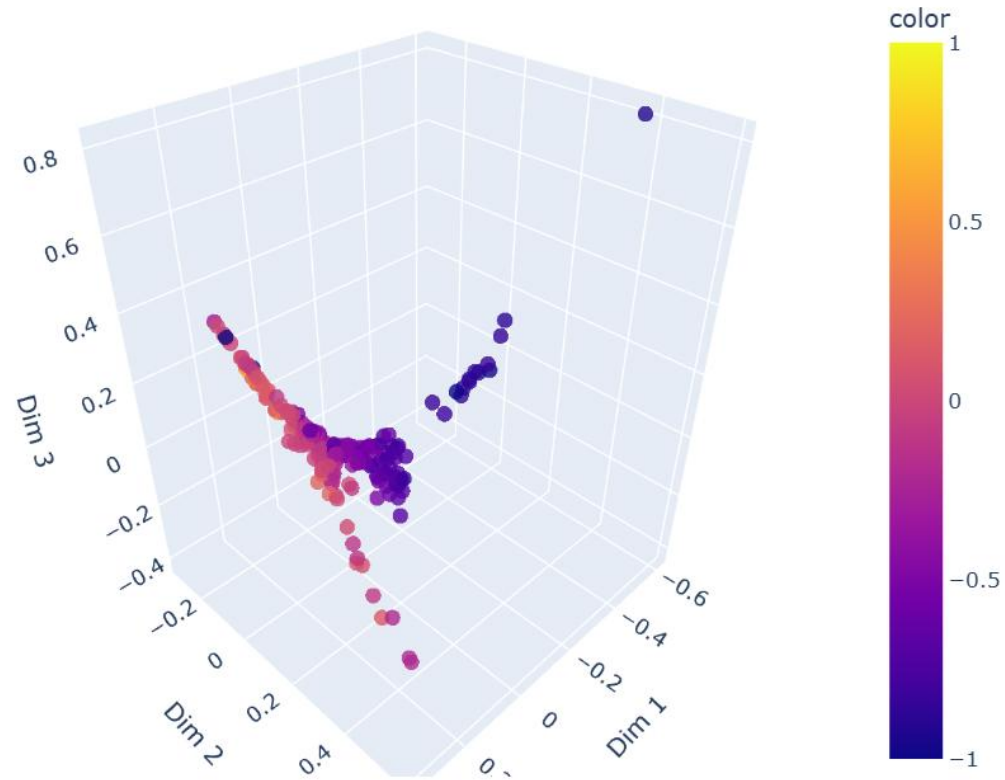
$$\text{Grating Selectivity Index} = \frac{\Delta R_g - \Delta R_f}{|\Delta R_g| + |\Delta R_f|}$$

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

Neuron Diffusion Map (Grating Selectivity Index)



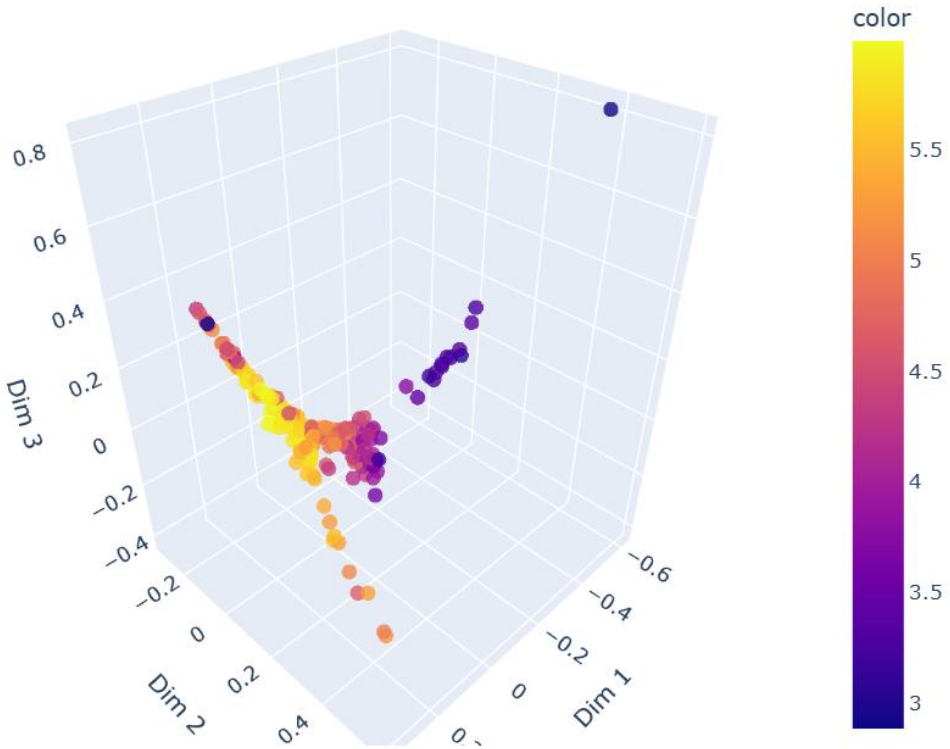
Neuron Diffusion Map (Flow Polarity Index)



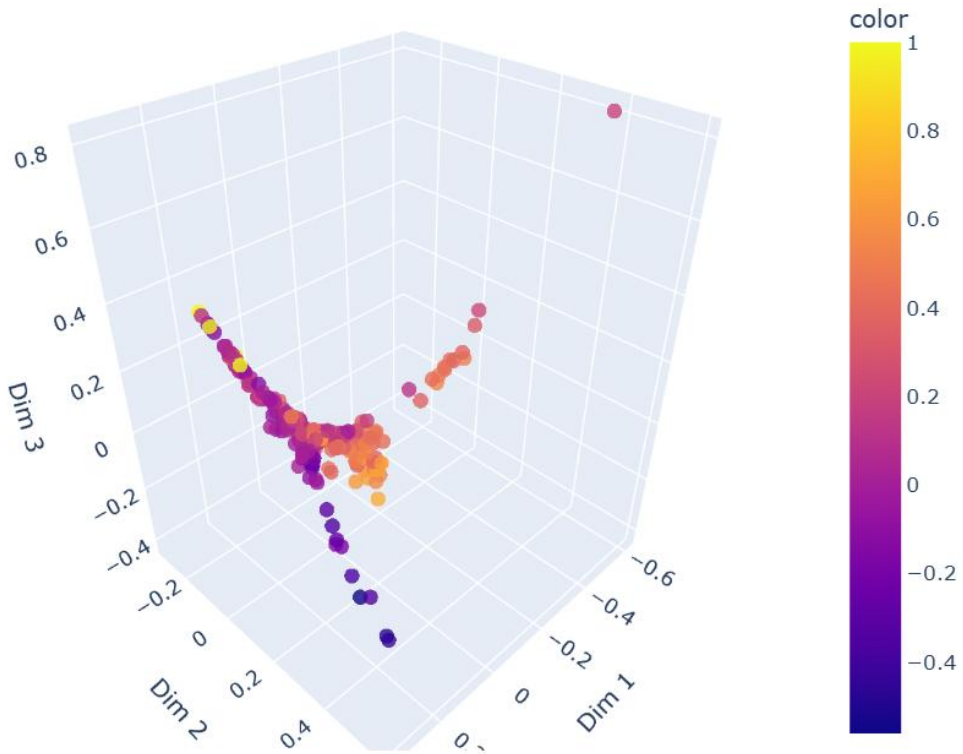
Higher stimulus specificity: An index close to 1 indicates strong selectivity — the neuron responds strongly to a specific stimulus and weakly (or not at all) to others.
Uniform responses: An index close to 6 indicates no selectivity — the neuron has similar amplitudes across all six stimuli.
Note: the index only reflects the response magnitudes only. It does not distinguish the signs of responses.

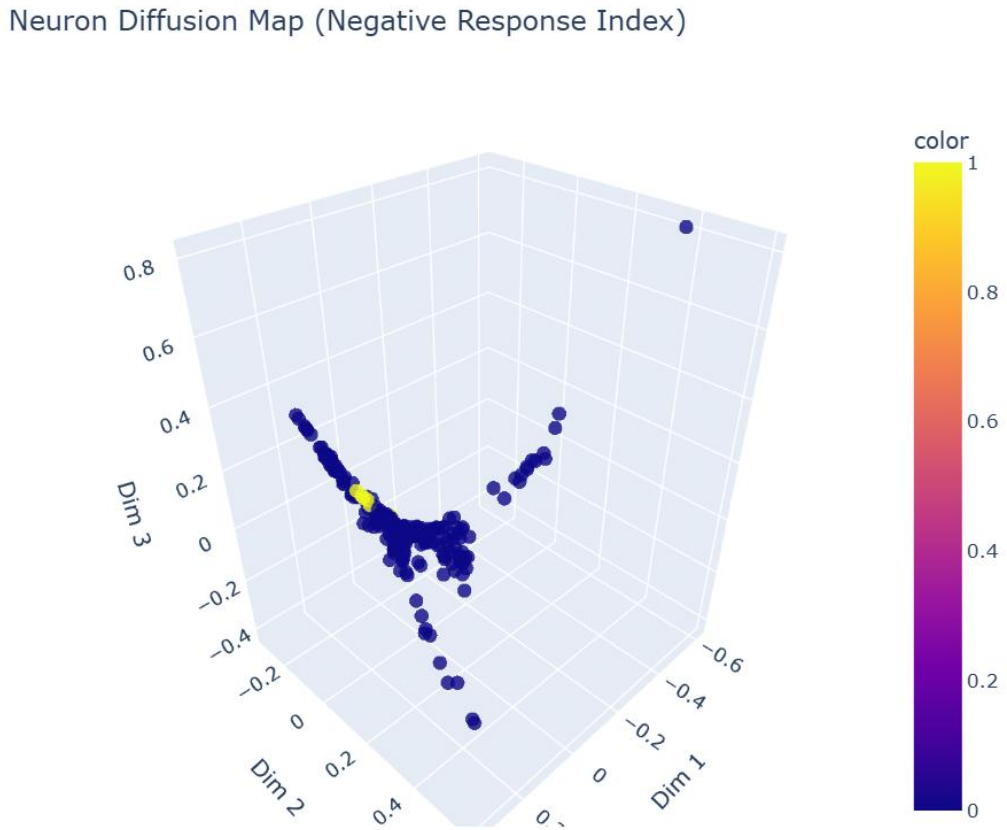
$$\text{Dot Selectivity Index} = \frac{\Delta R_{1\text{dot}} - \Delta R_{3\text{dot}}}{|\Delta R_{1\text{dot}}| + |\Delta R_{3\text{dot}}|}$$

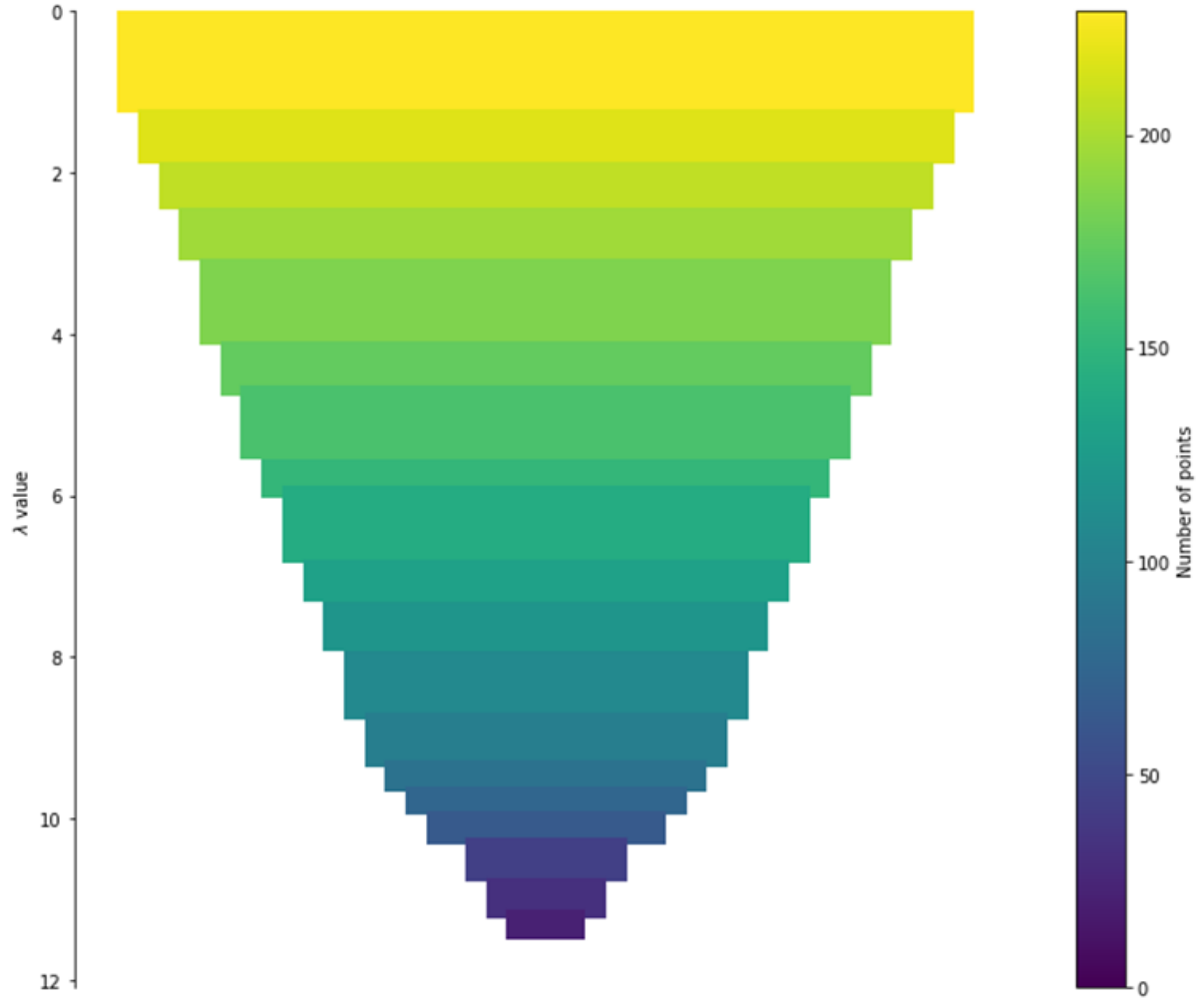
Neuron Diffusion Map (Stimulus Entropy Index)



Neuron Diffusion Map (Dot Selectivity Index)



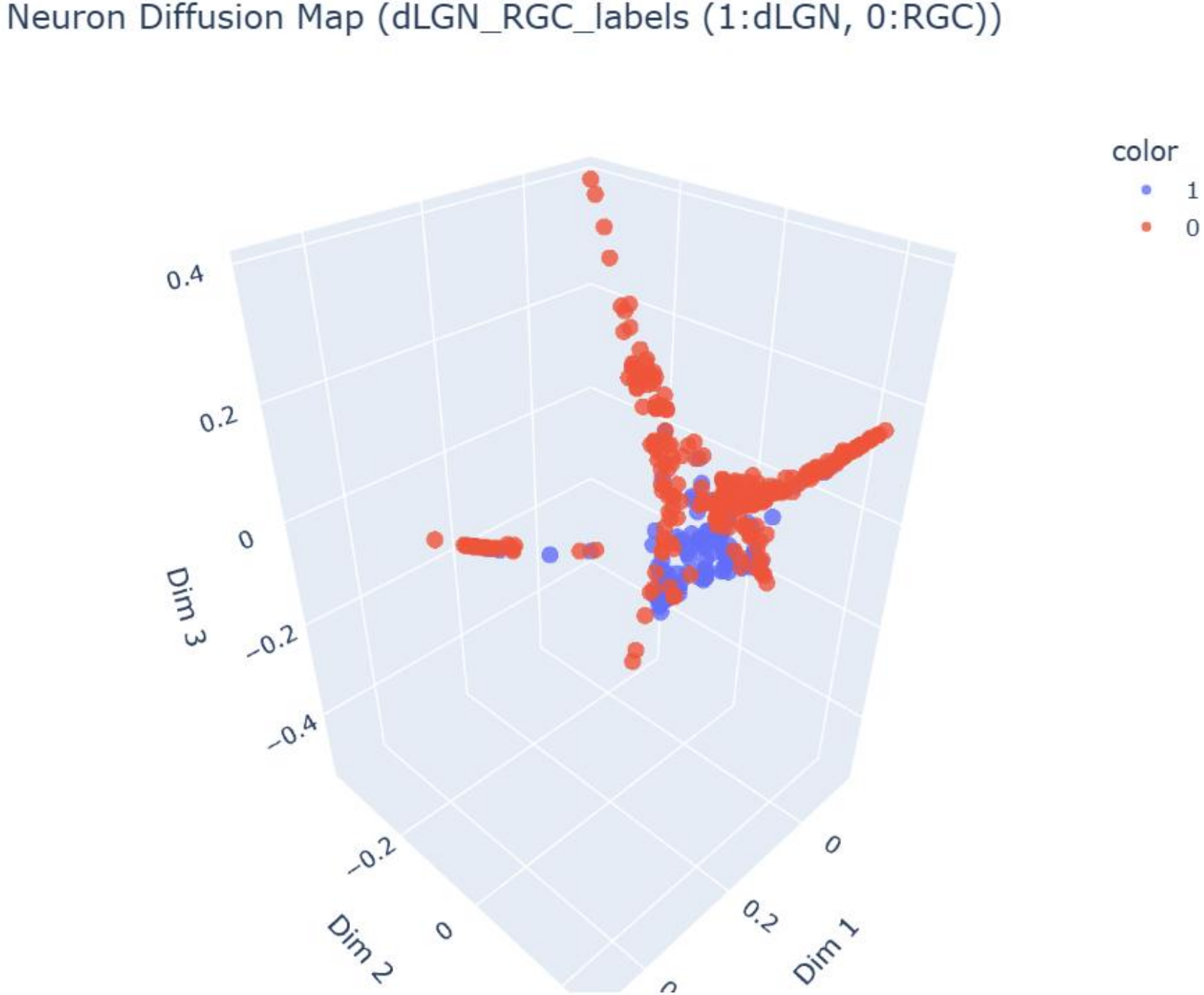




continuous `min_cluster_size=15`

If min_cluster_size=5, 2 clusters.

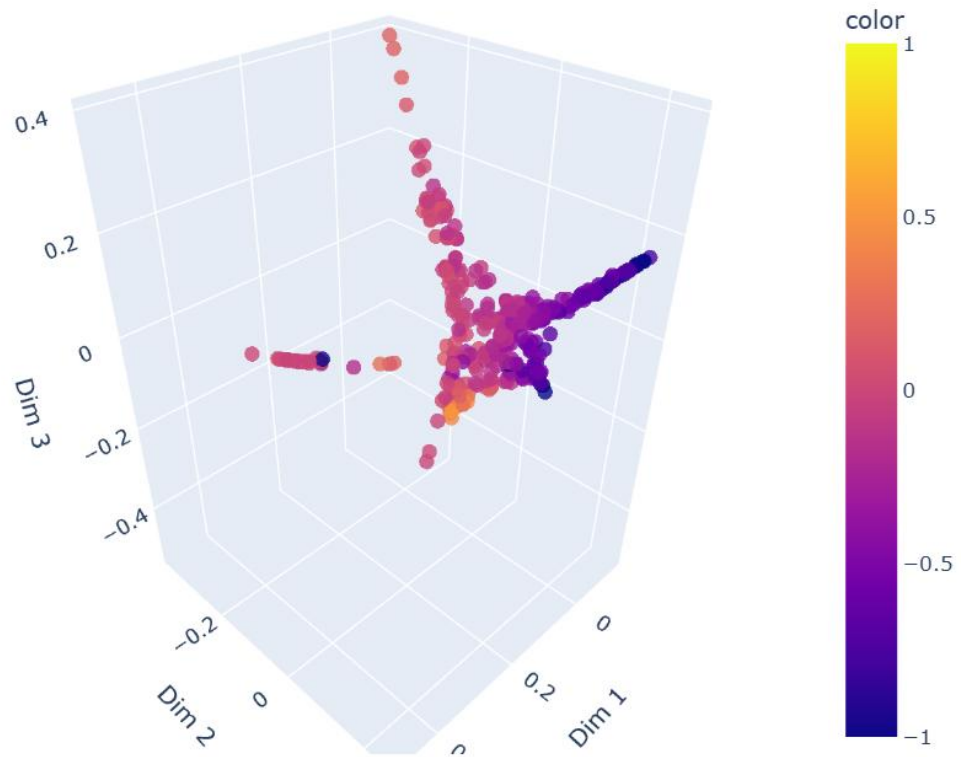
dLGN+RGC
(117 neurons + 300 boutons, both significant)


Neuron Diffusion Map (dLGN_RGC_labels (1:dLGN, 0:RGC))
color
1
0
0.4
0.2
0
−0.2
−0.4
Dim 3
−0.2
0
Dim 2
0
0.2
Dim 1

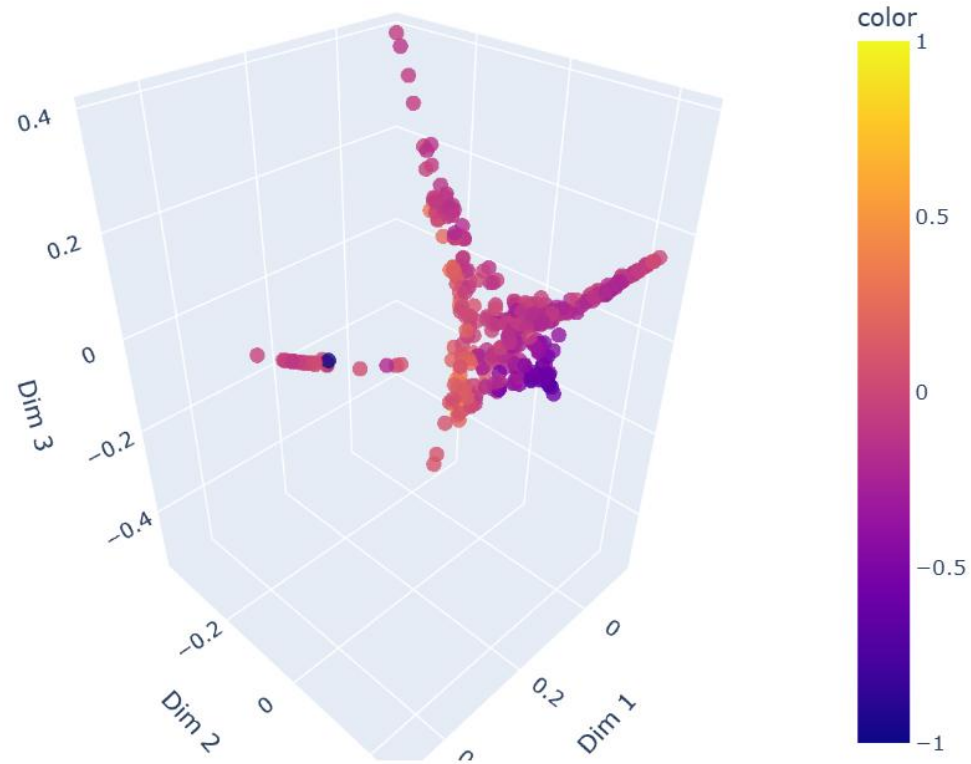
$$\text{Grating Selectivity Index} = \frac{\Delta R_g - \Delta R_f}{|\Delta R_g| + |\Delta R_f|}$$

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

Neuron Diffusion Map (Grating Selectivity Index)



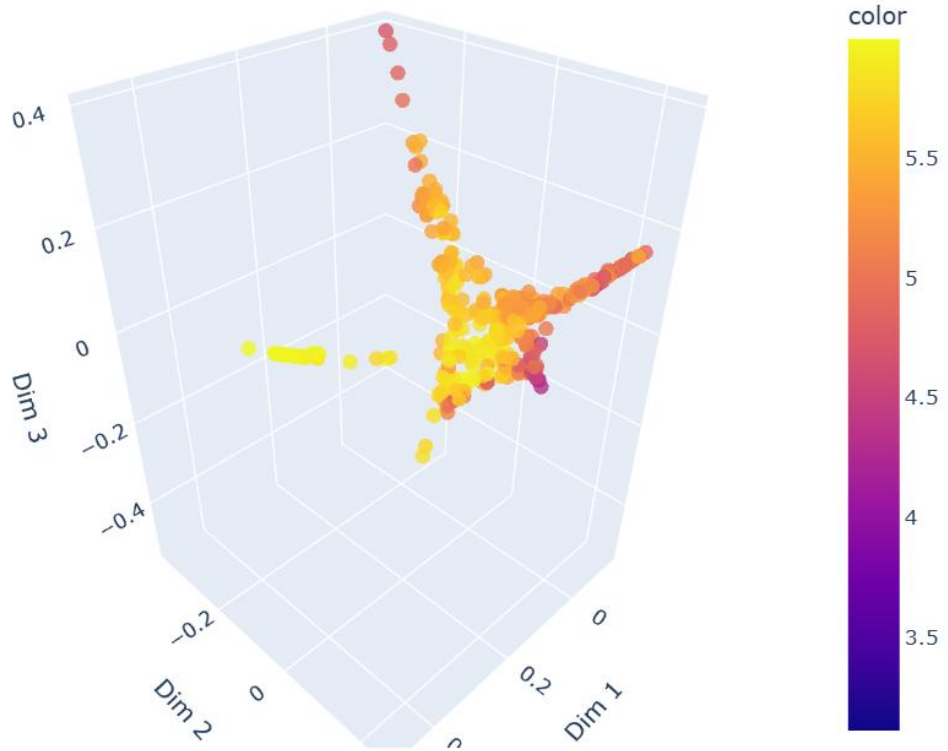
Neuron Diffusion Map (Flow Polarity Index)



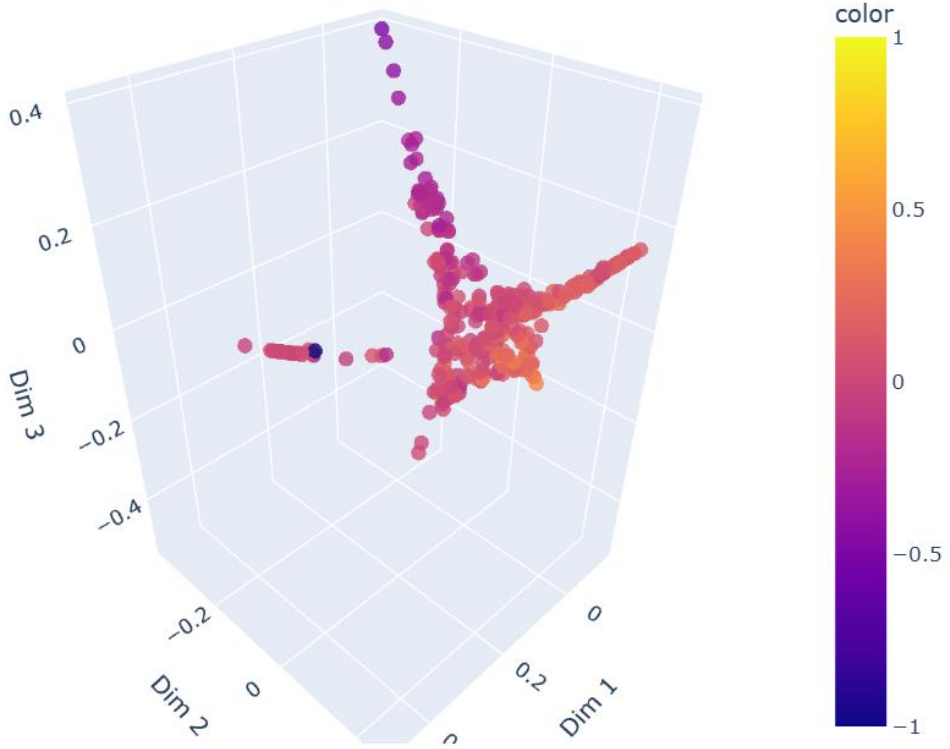
Higher stimulus specificity: An index close to 1 indicates strong selectivity — the neuron responds strongly to a specific stimulus and weakly (or not at all) to others.
Uniform responses: An index close to 6 indicates no selectivity — the neuron has similar amplitudes across all six stimuli.
Note: the index only reflects the response magnitudes only. It does not distinguish the signs of responses.

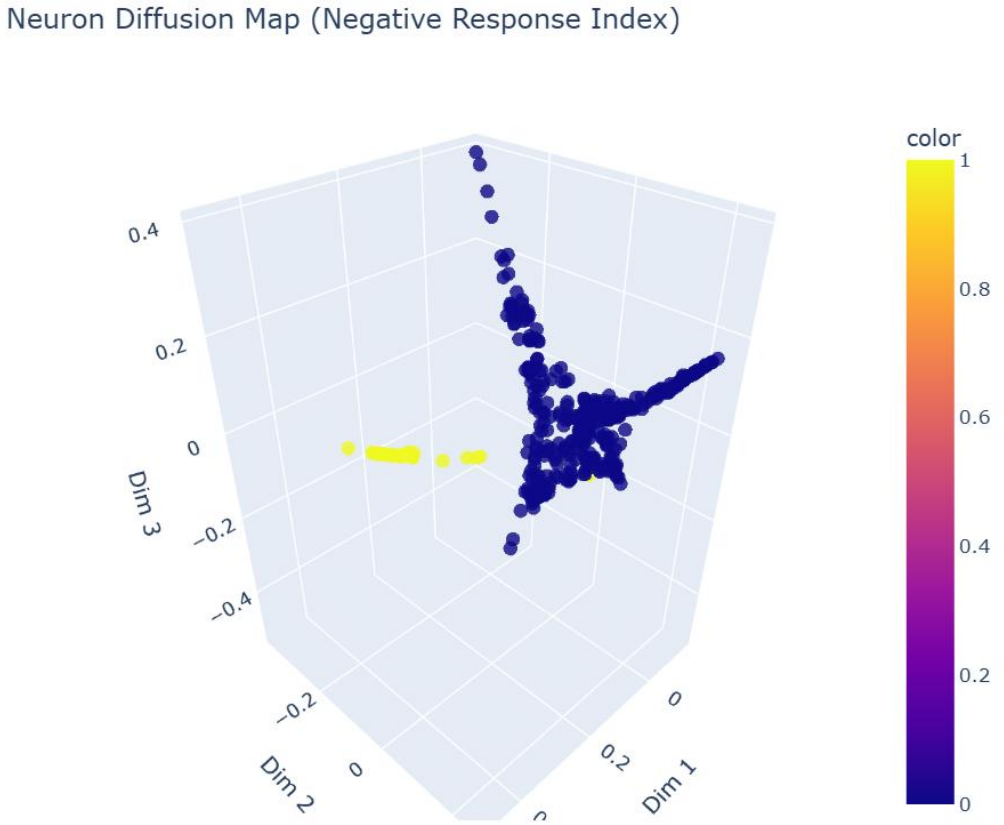
$$\text{Dot Selectivity Index} = \frac{\Delta R_{1\text{dot}} - \Delta R_{3\text{dot}}}{|\Delta R_{1\text{dot}}| + |\Delta R_{3\text{dot}}|}$$

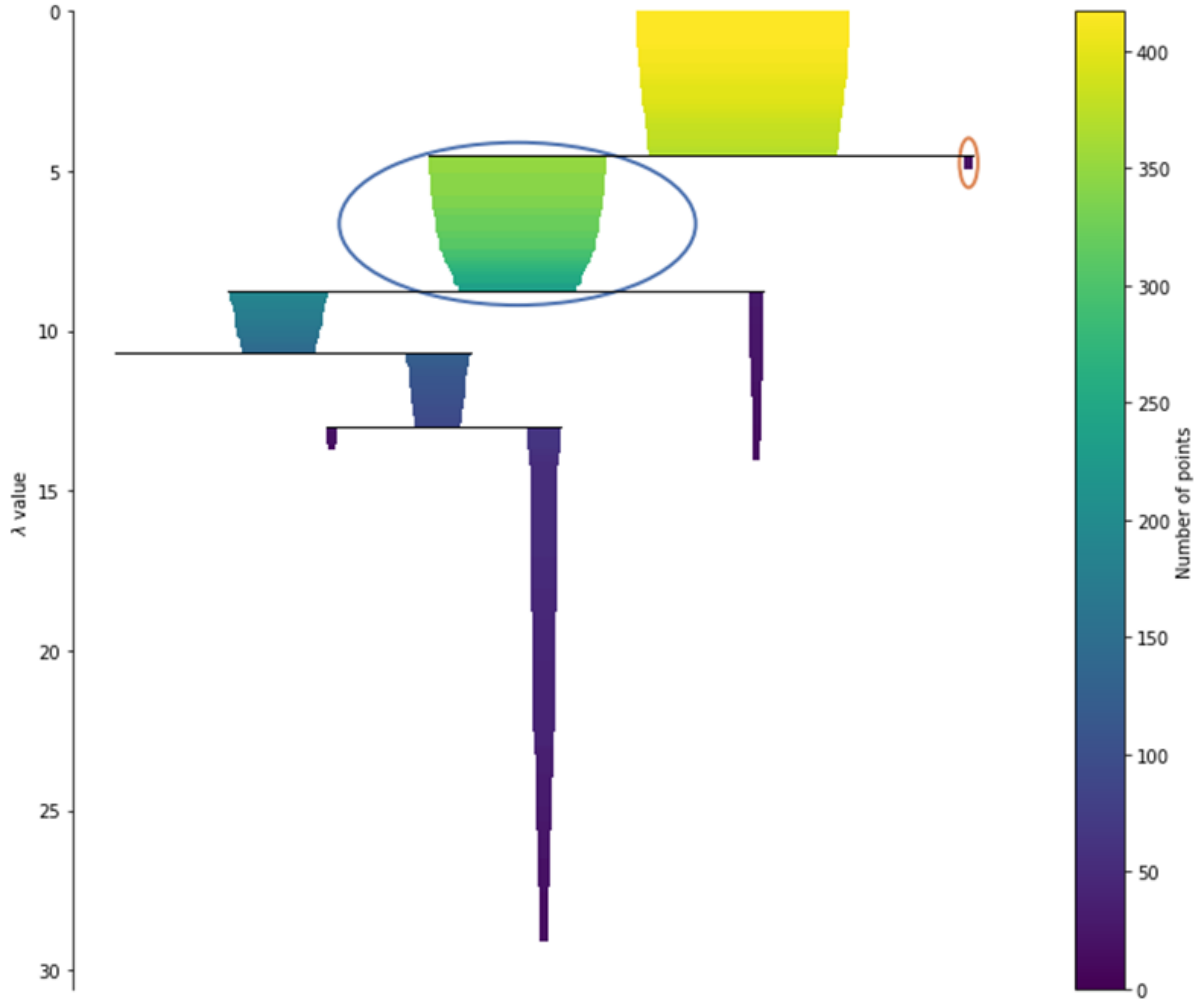
Neuron Diffusion Map (Stimulus Entropy Index)



Neuron Diffusion Map (Dot Selectivity Index)





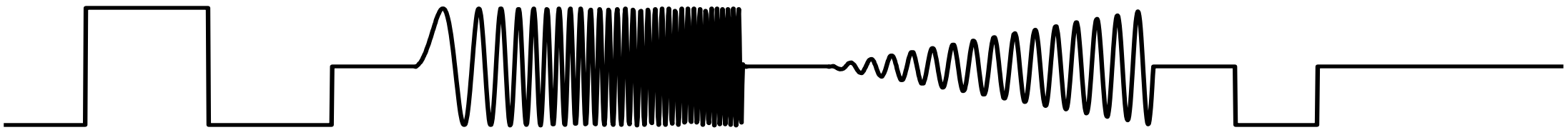


2 clusters `min_cluster_size=15`

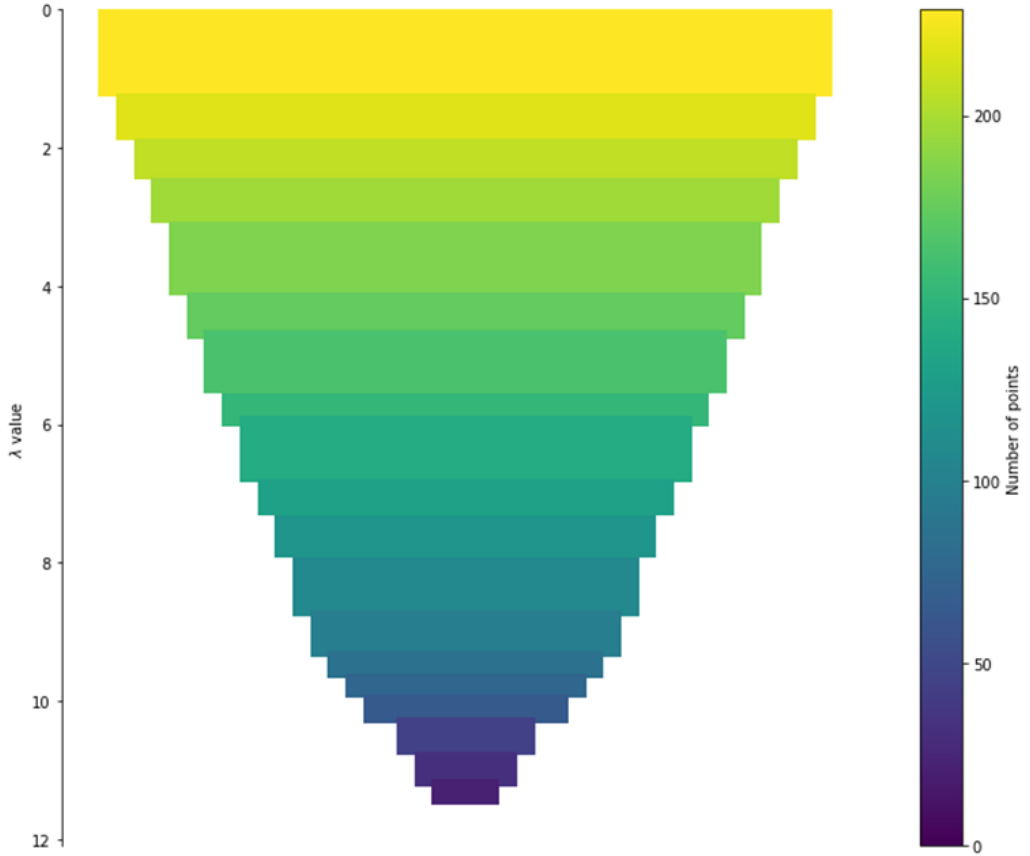
If min_cluster_size=5, 16 clusters.

Chirp based analysis
(dLGN and RGC)

Our chirp

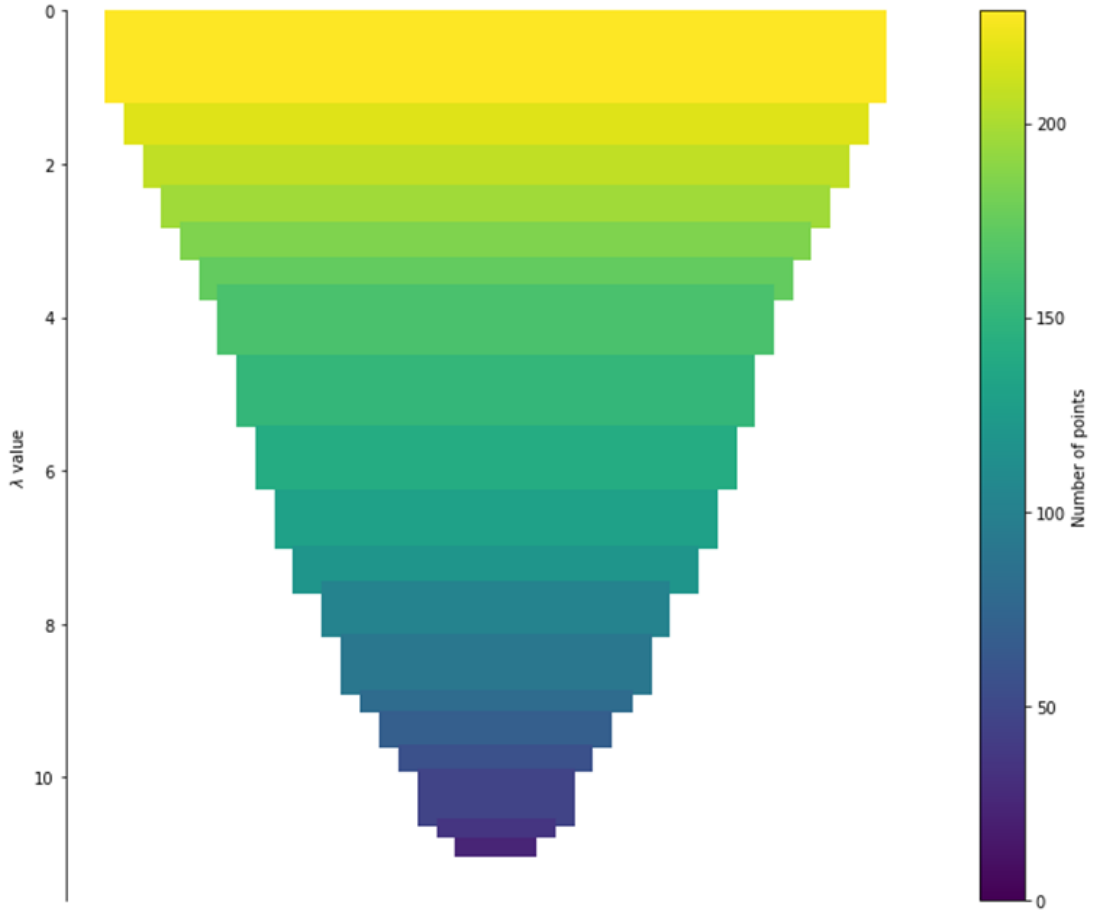


48-stim based dLGN results



If min_cluster_size=5, 2 clusters.

Chirp based dLGN results
(min-max normalization)

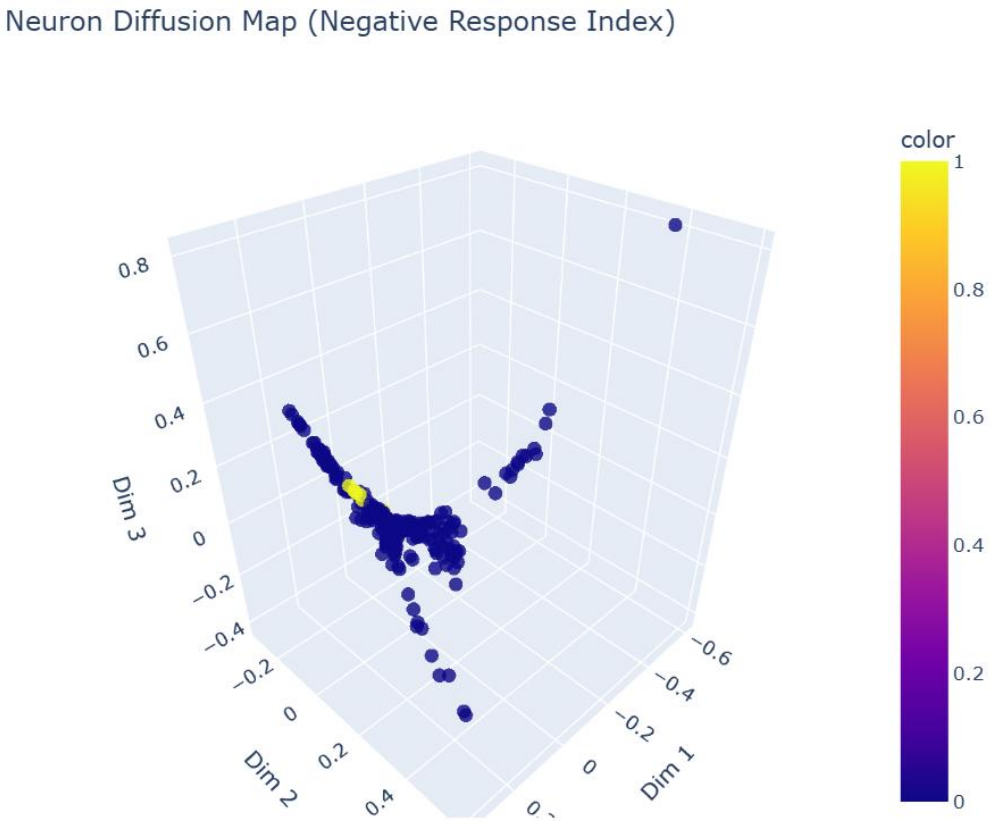


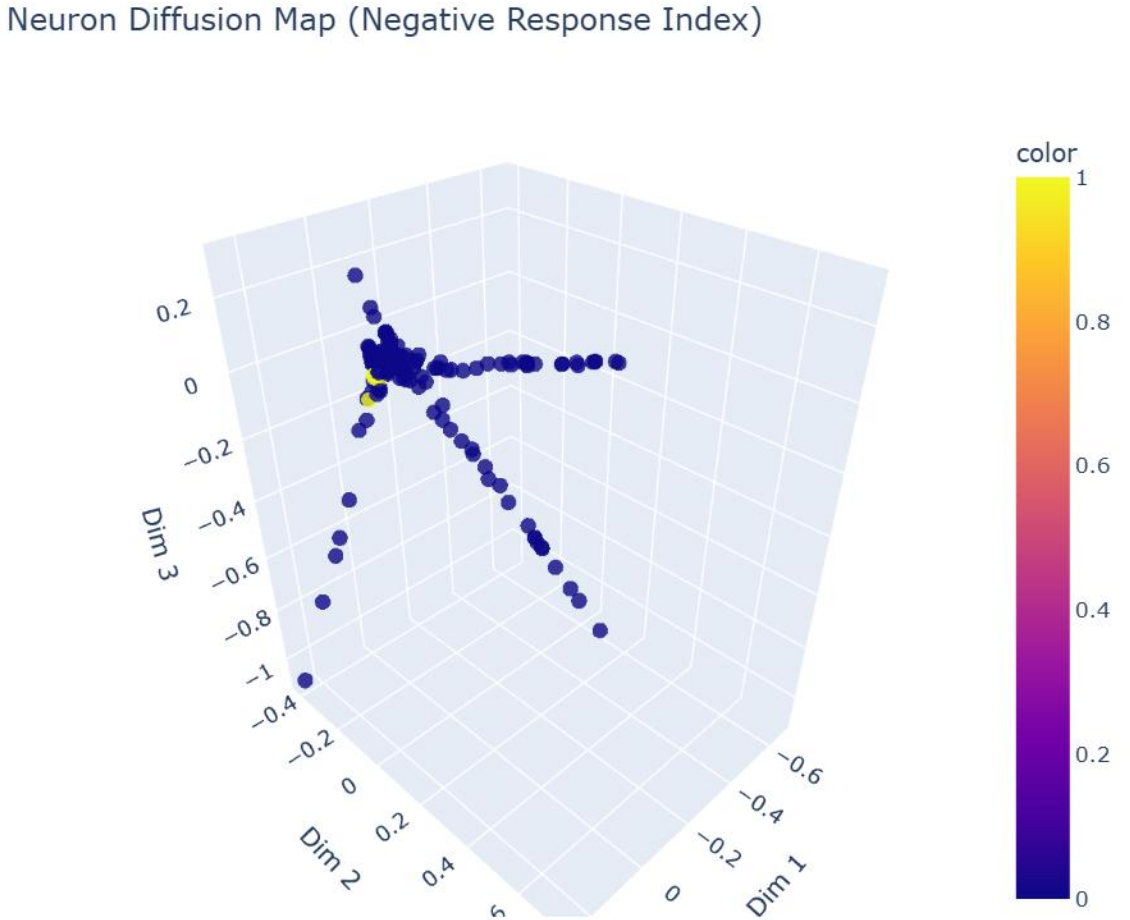
min_cluster_size=15

If min_cluster_size=5, 2 clusters.

48-stim based dLGN results

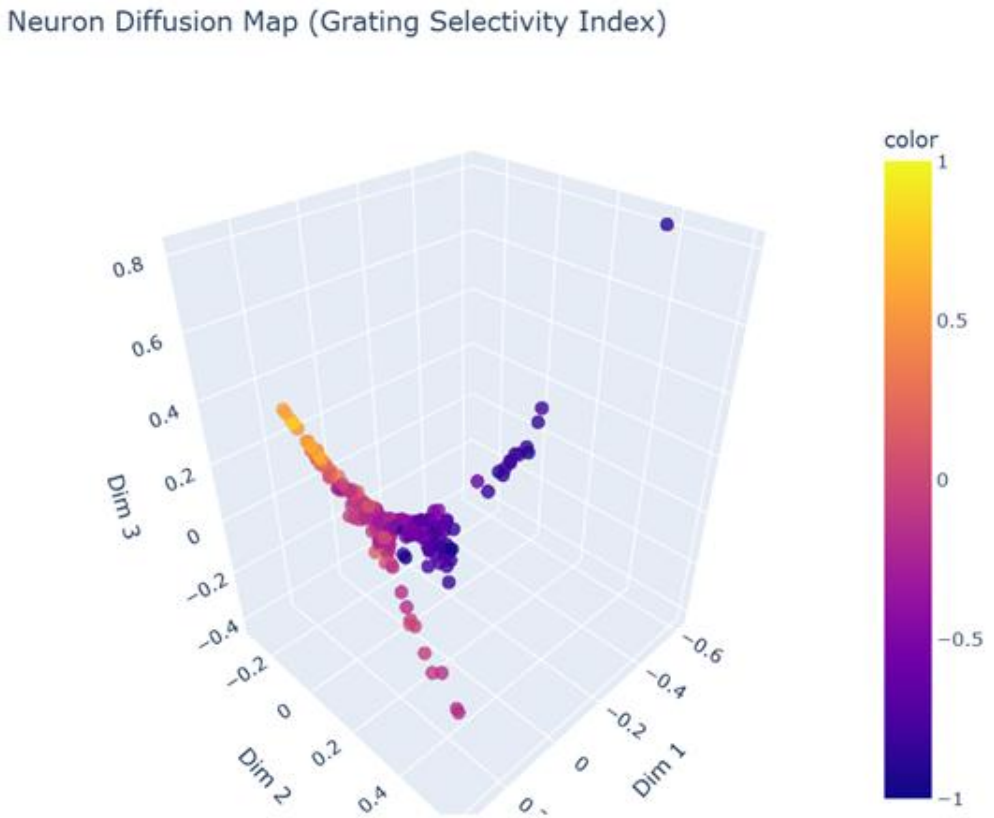
Chirp based dLGN results
(min-max normalization)

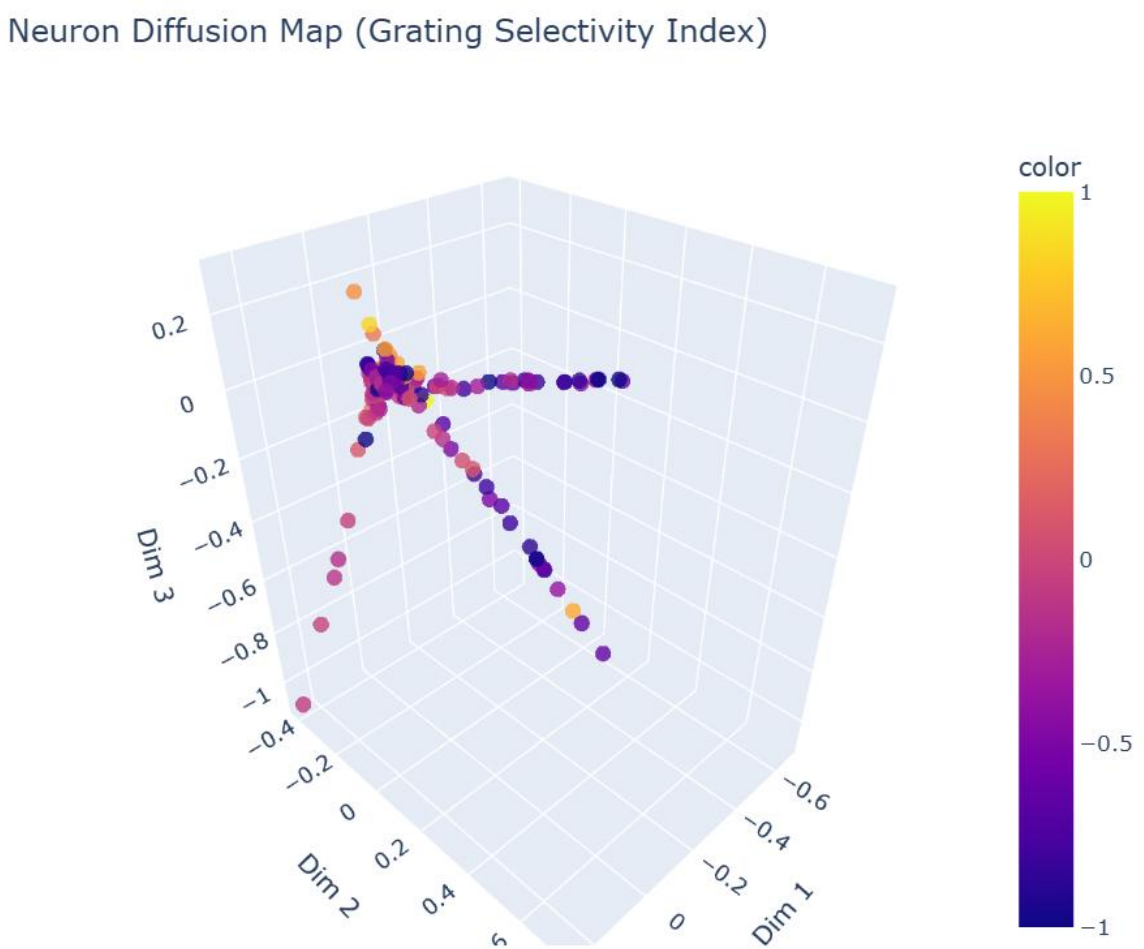




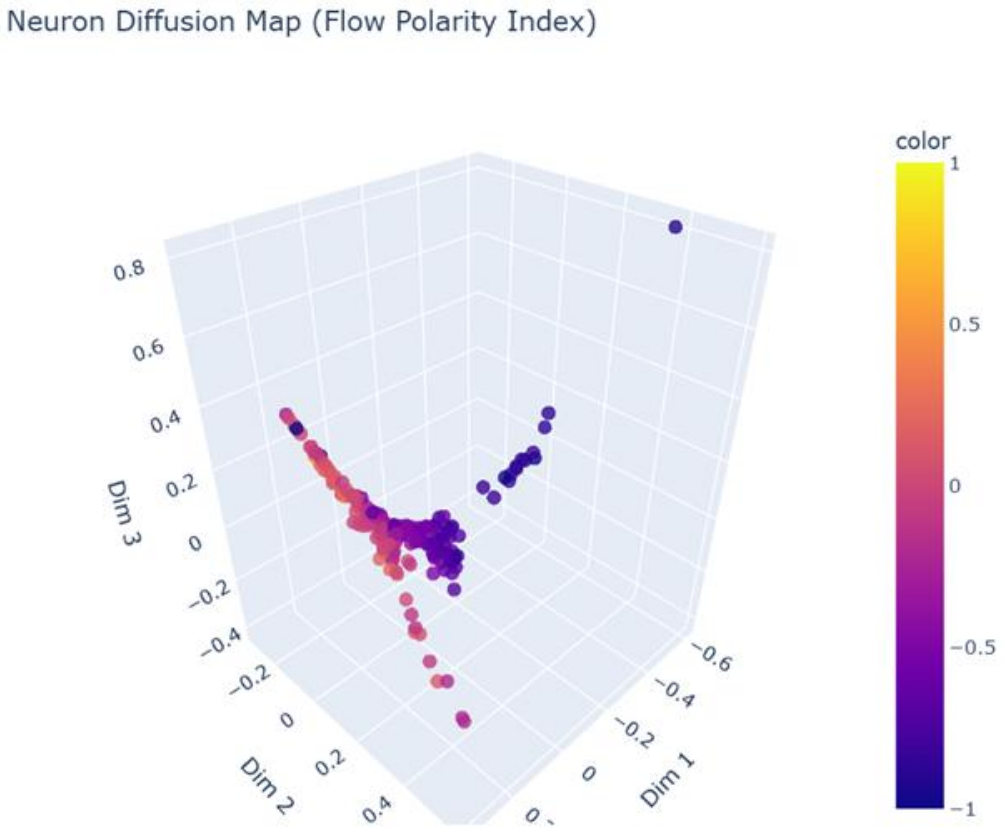
48-stim based dLGN results

Chirp based dLGN results
(min-max normalization)

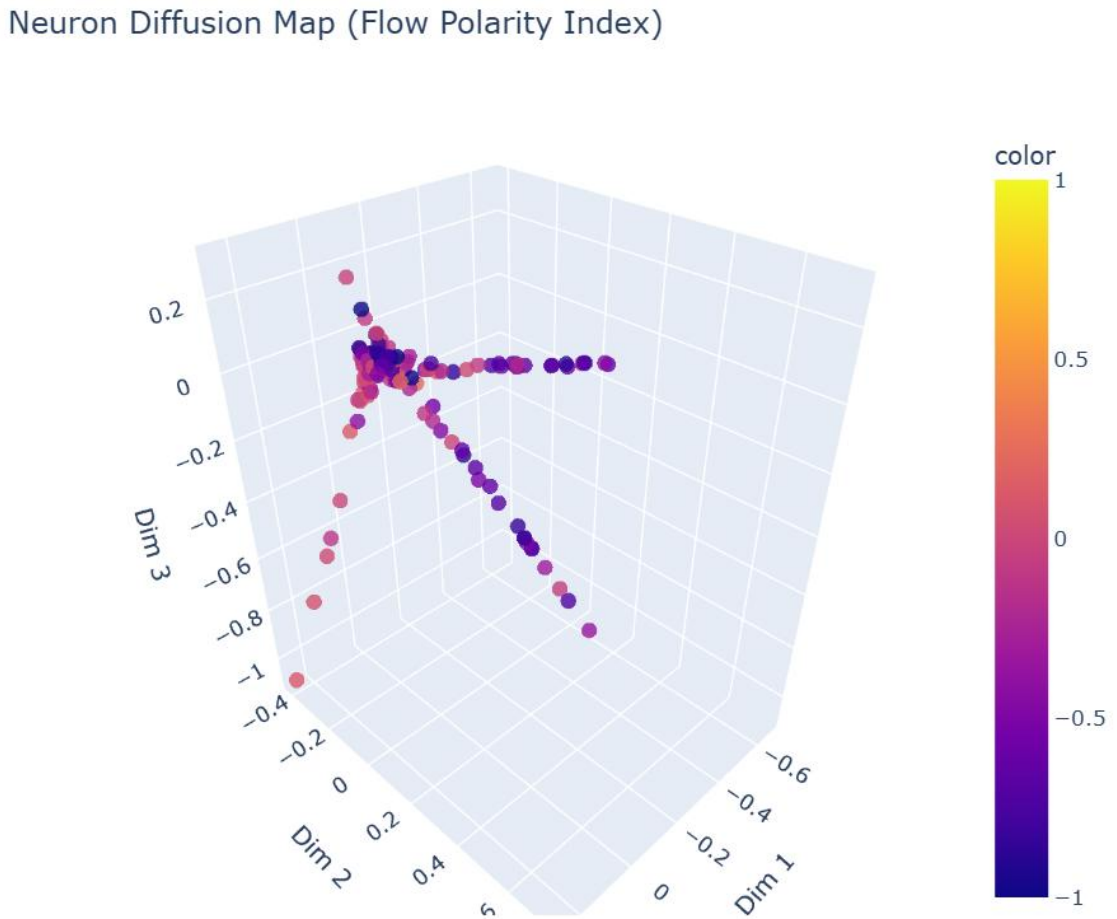




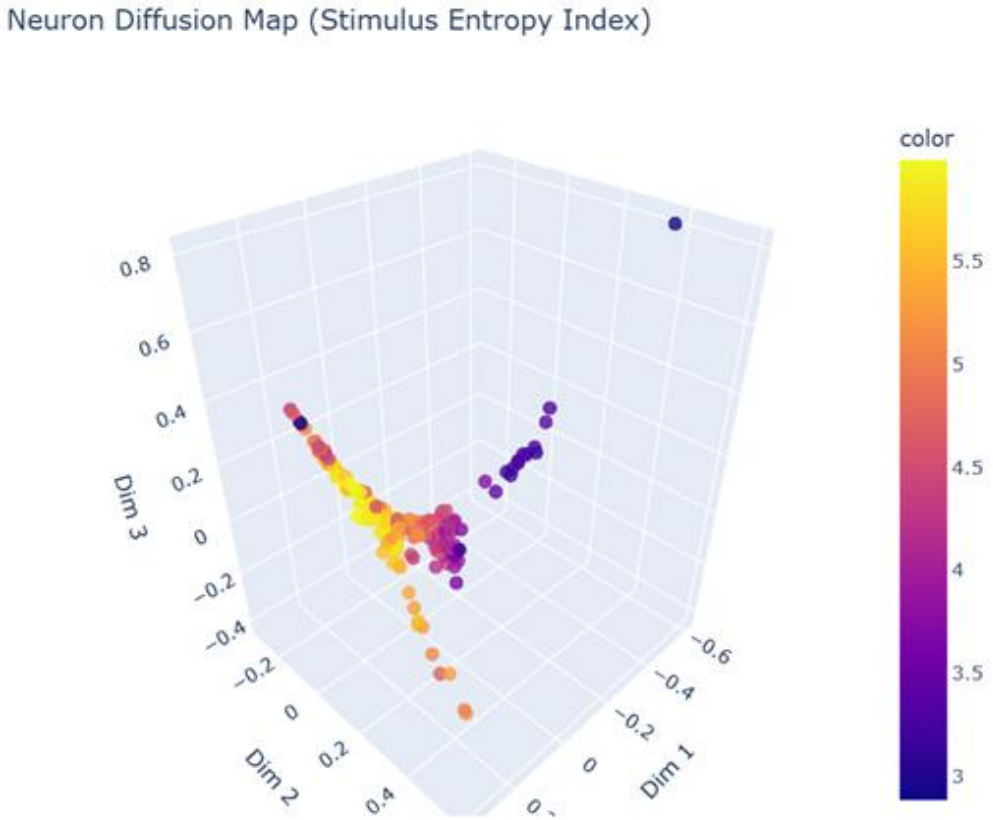
48-stim based dLGN results



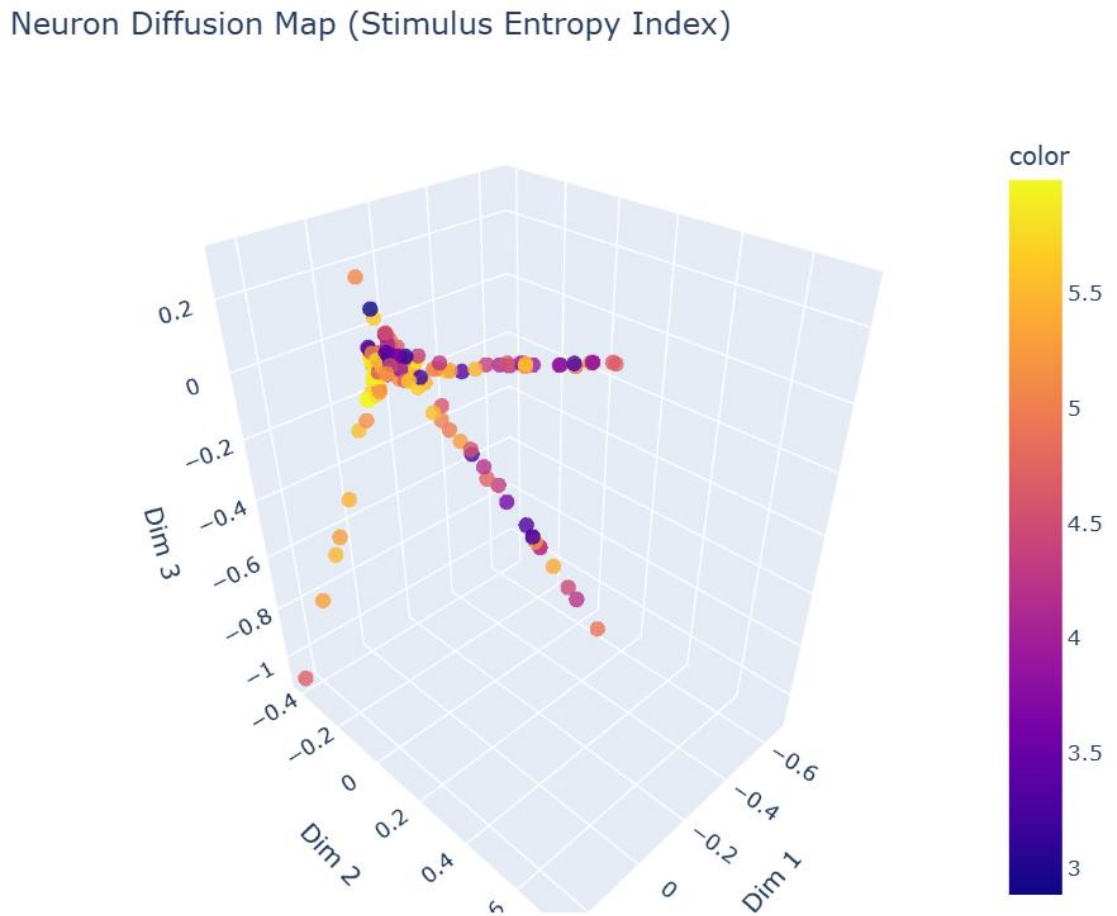
Chirp based dLGN results
(min-max normalization)



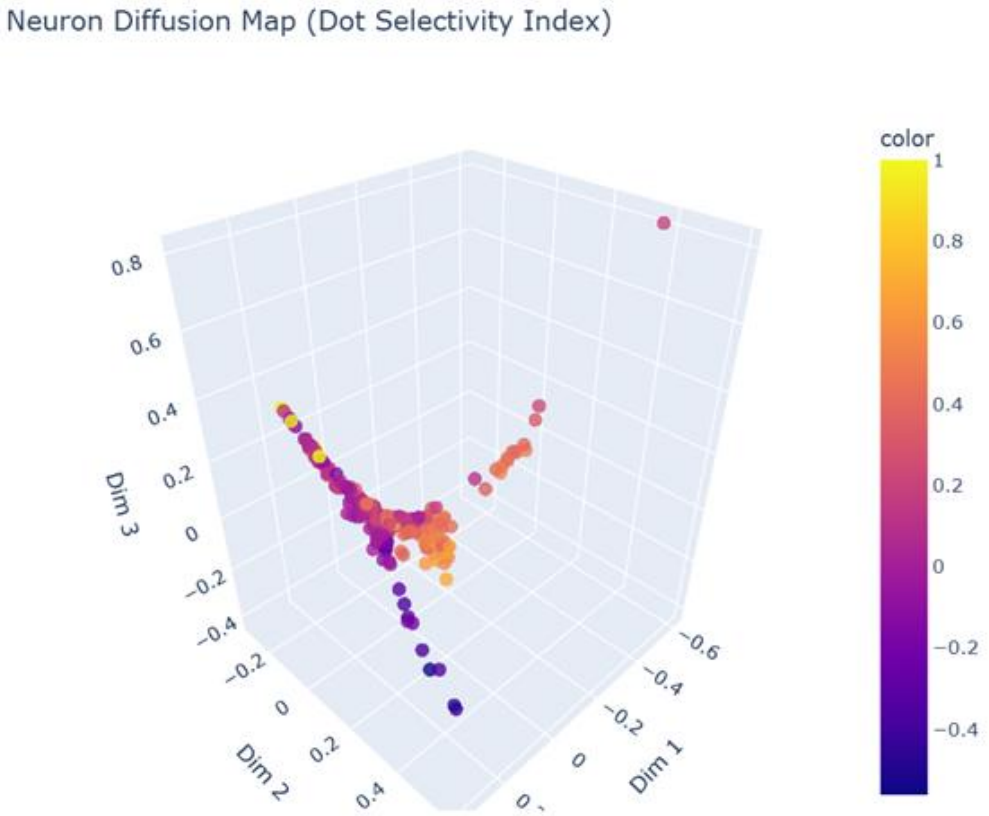
48-stim based dLGN results



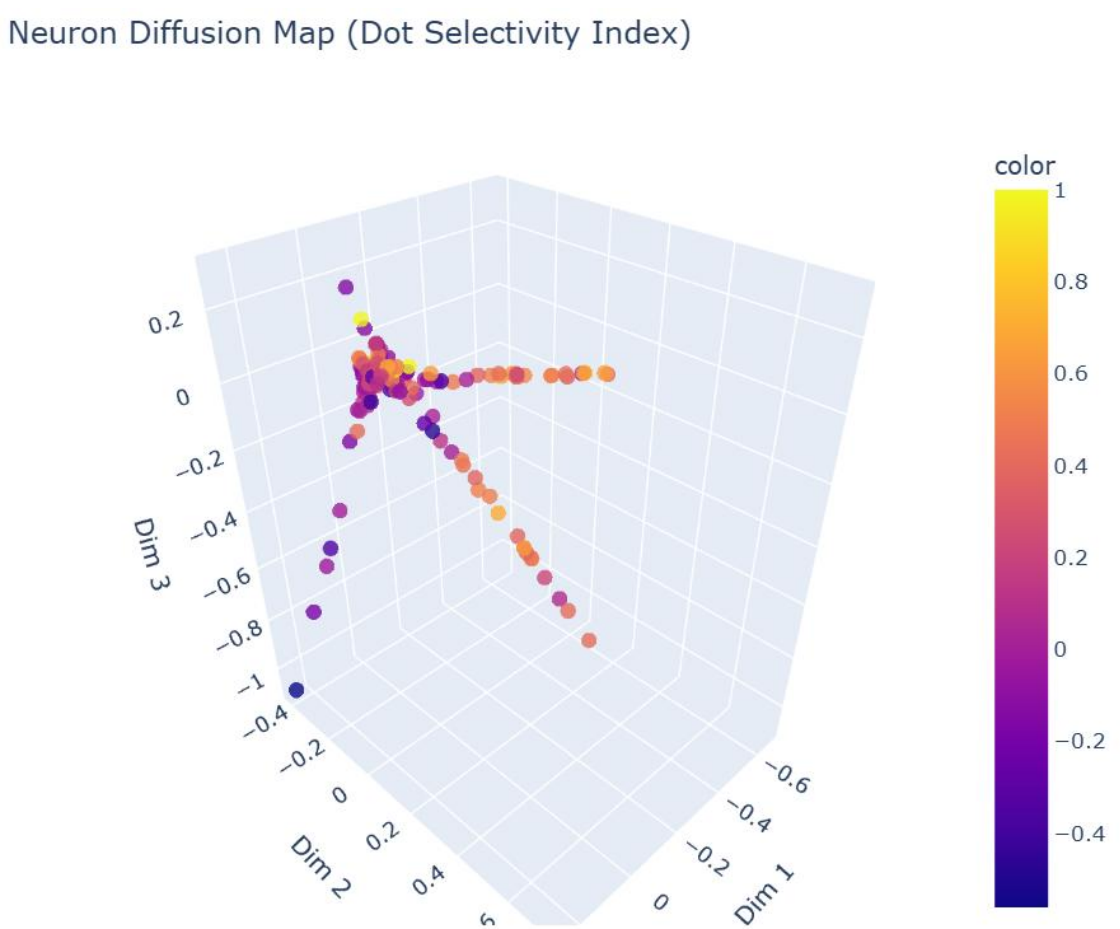
Chirp based dLGN results
(min-max normalization)



48-stim based dLGN results

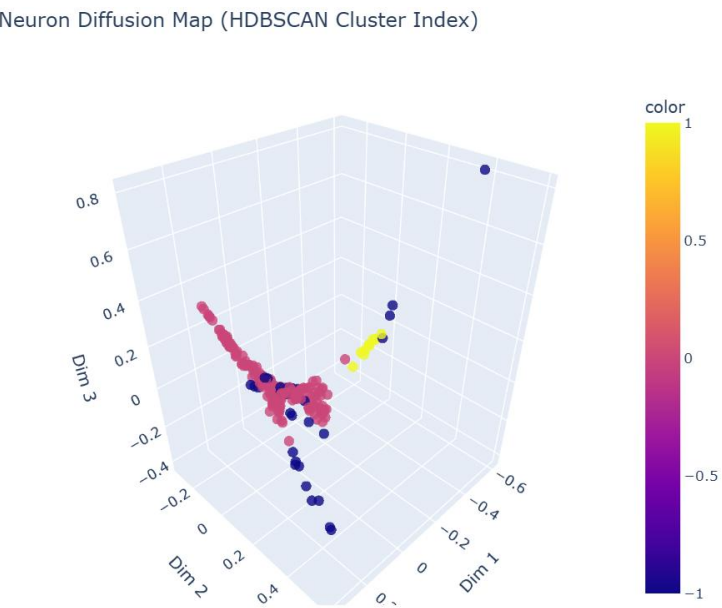


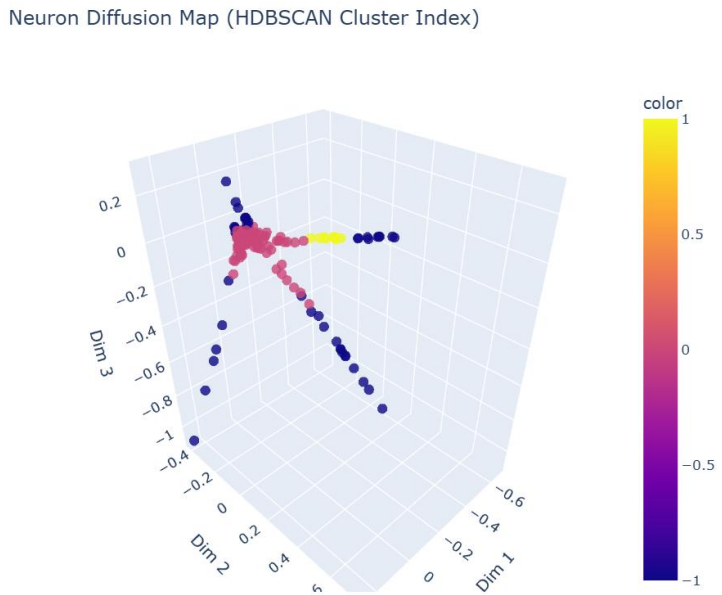
Chirp based dLGN results
(min-max normalization)

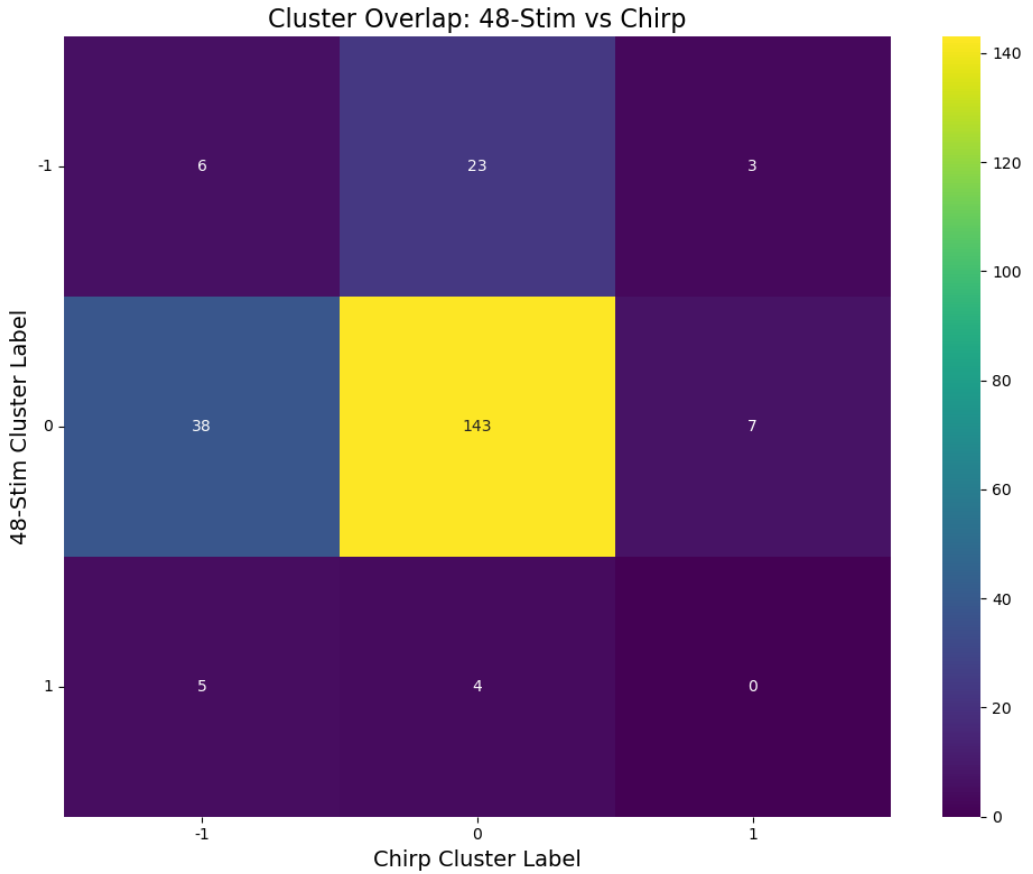


48-stim based dLGN results

Chirp based dLGN results (min-max normalization)

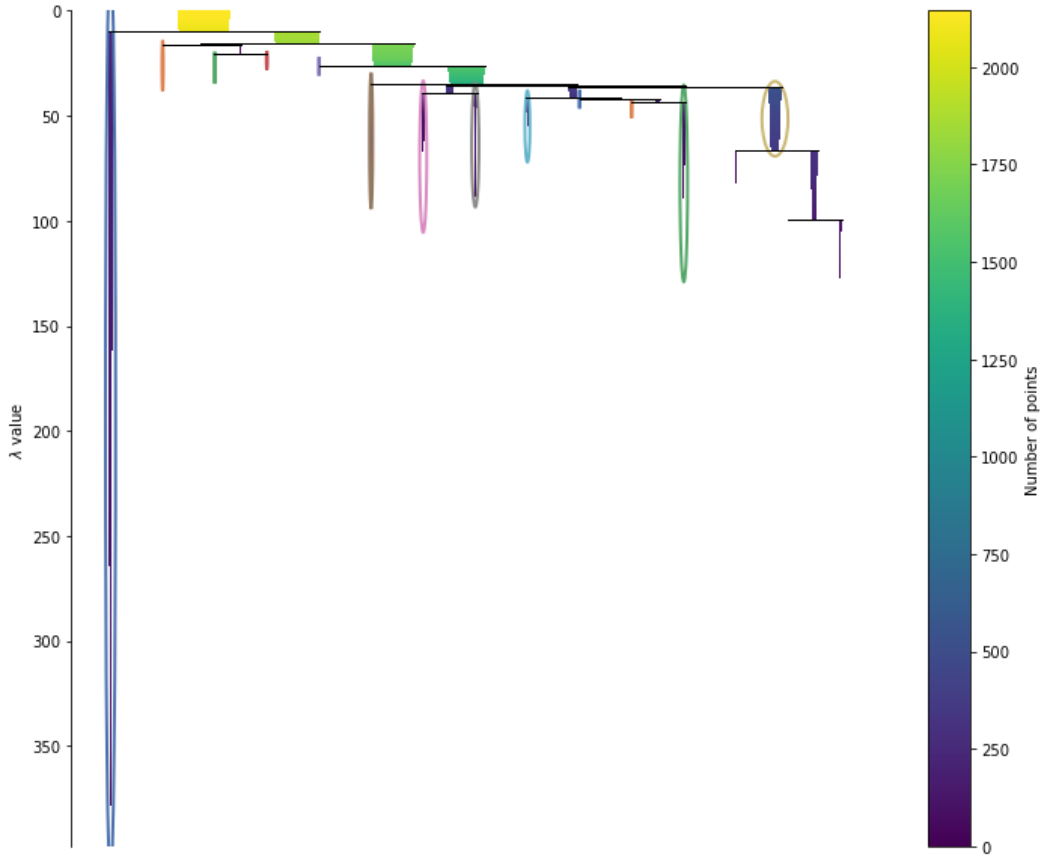







```
min_cluster_size=5
```

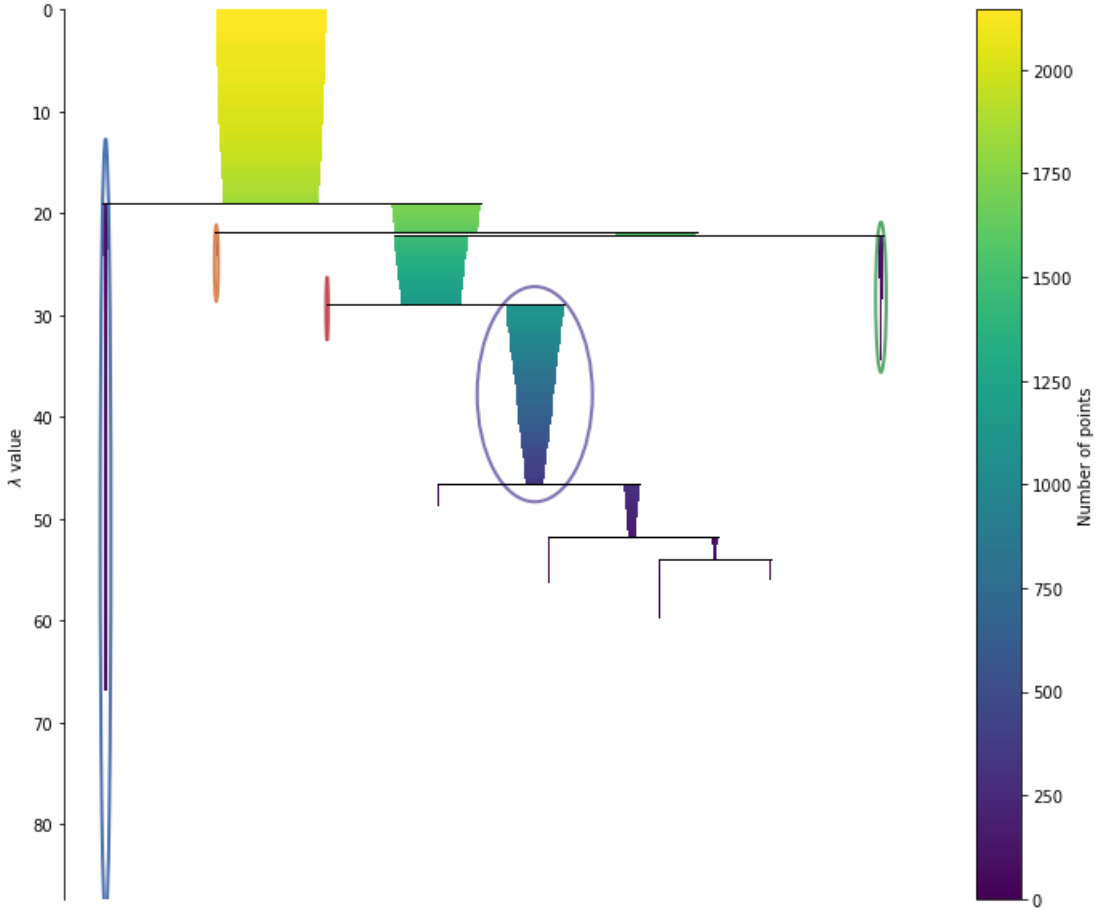
48-stim based RGC results



13 clusters

If min_cluster_size=5, 36 clusters.

Chirp based RGC results
(min-max normalization)

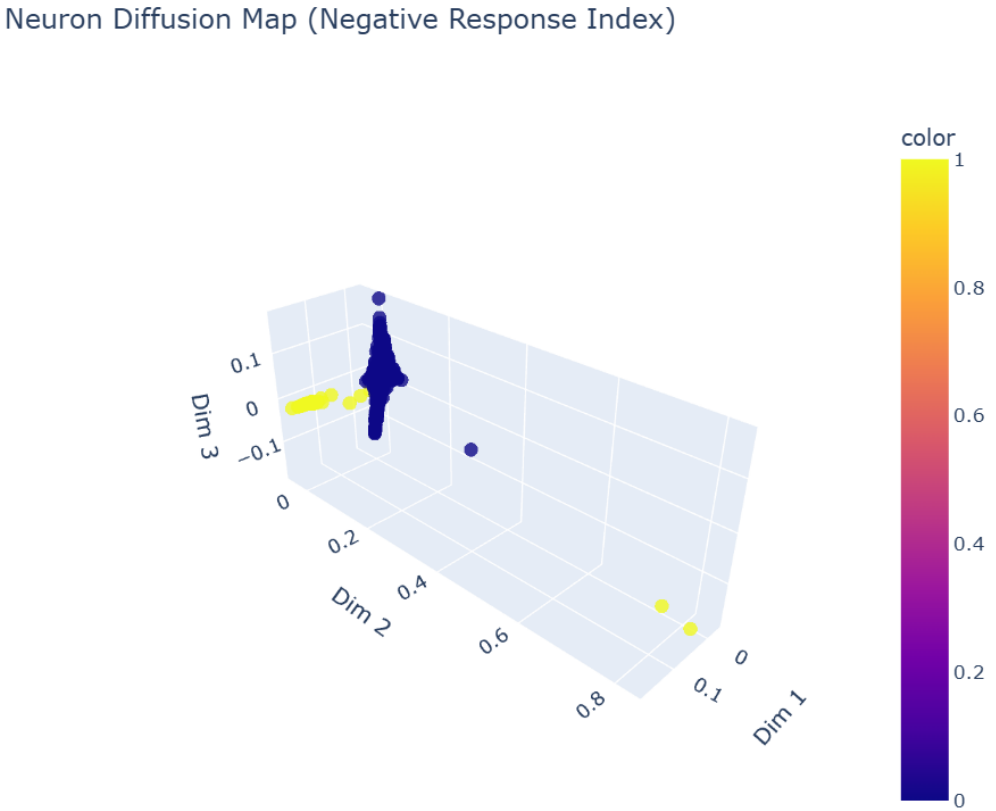


5 clusters

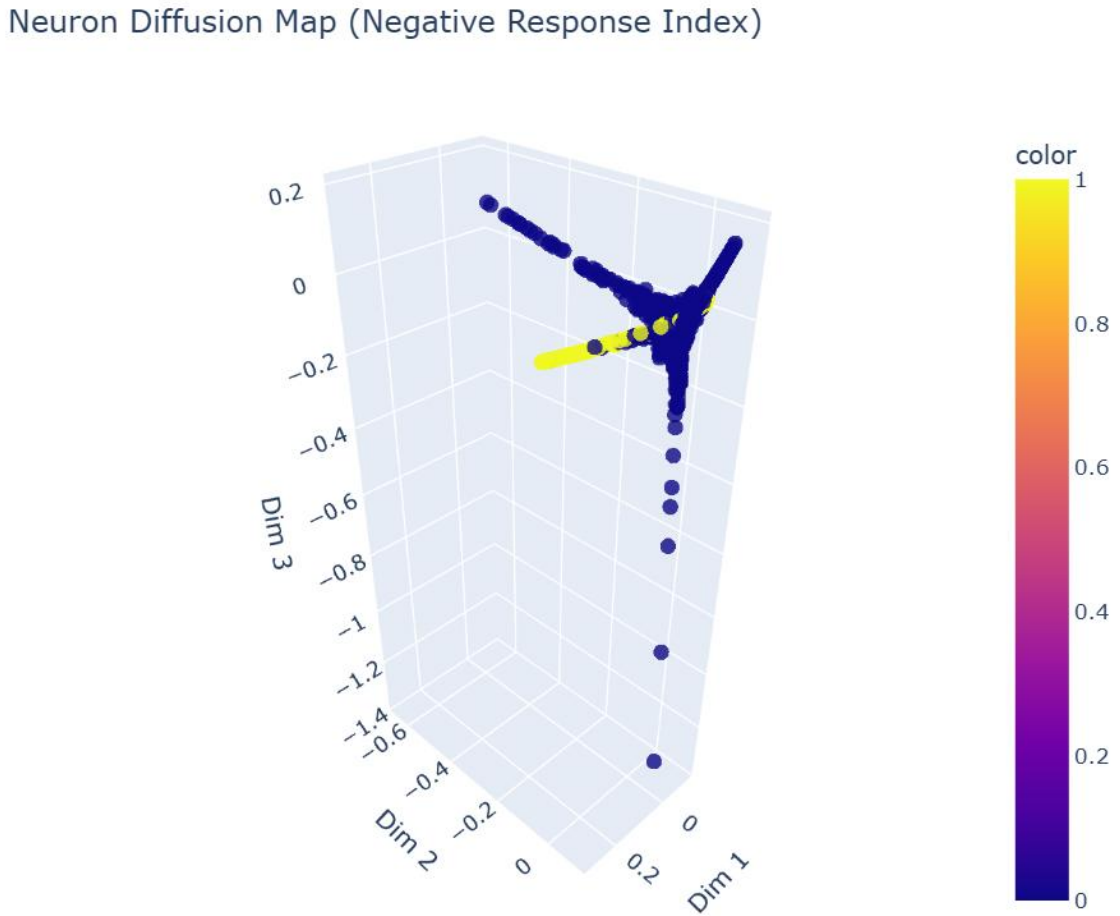
`min_cluster_size=15`

If min_cluster_size=5, 4 clusters. ???

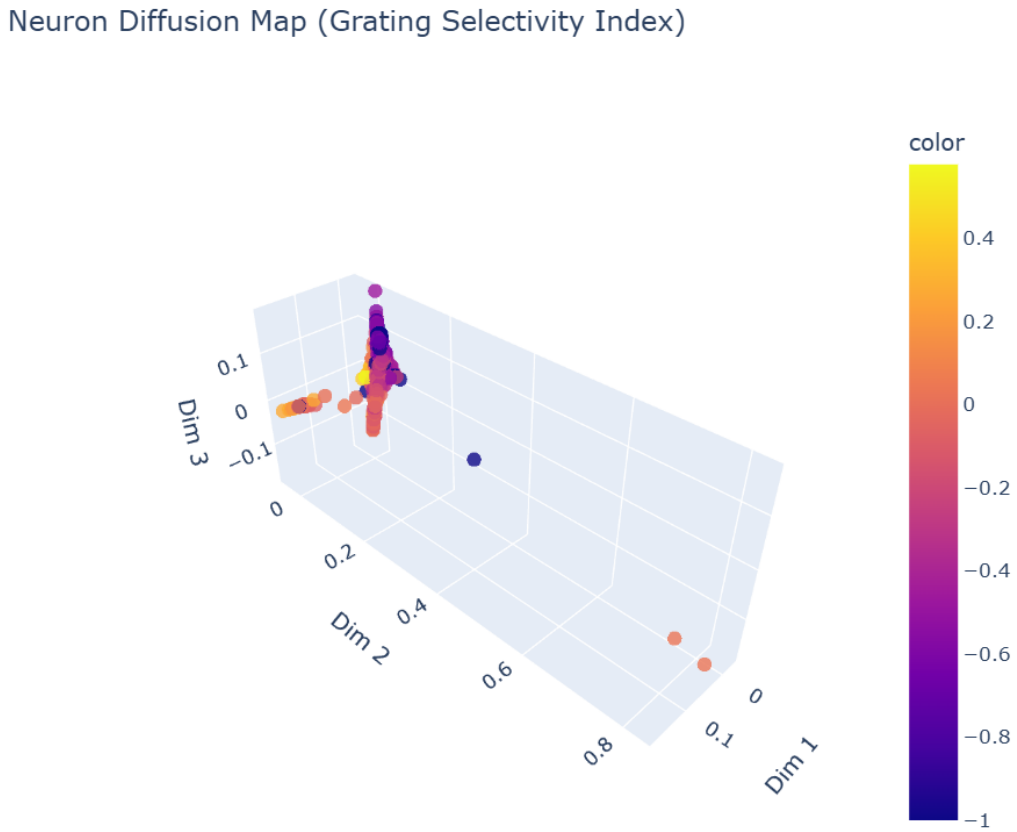
48-stim based RGC results



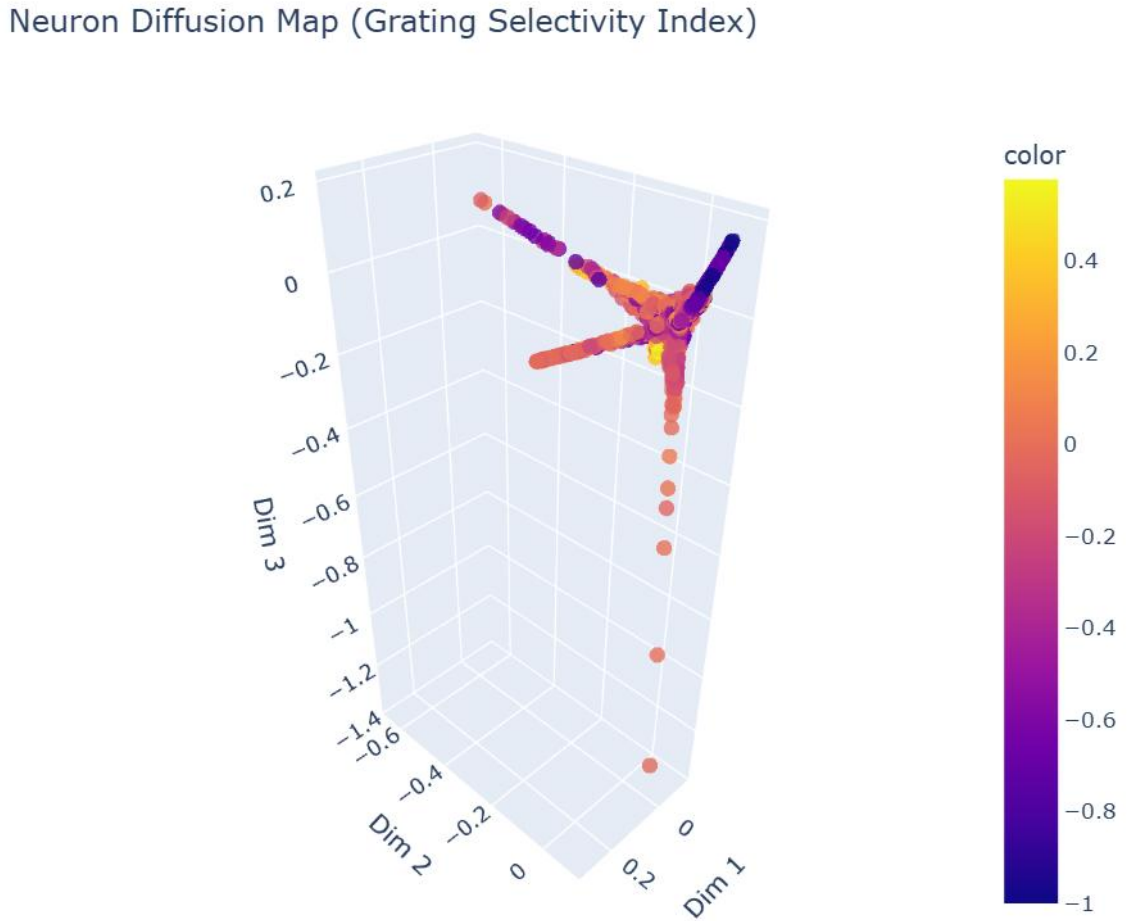
Chirp based RGC results (min-max normalization)



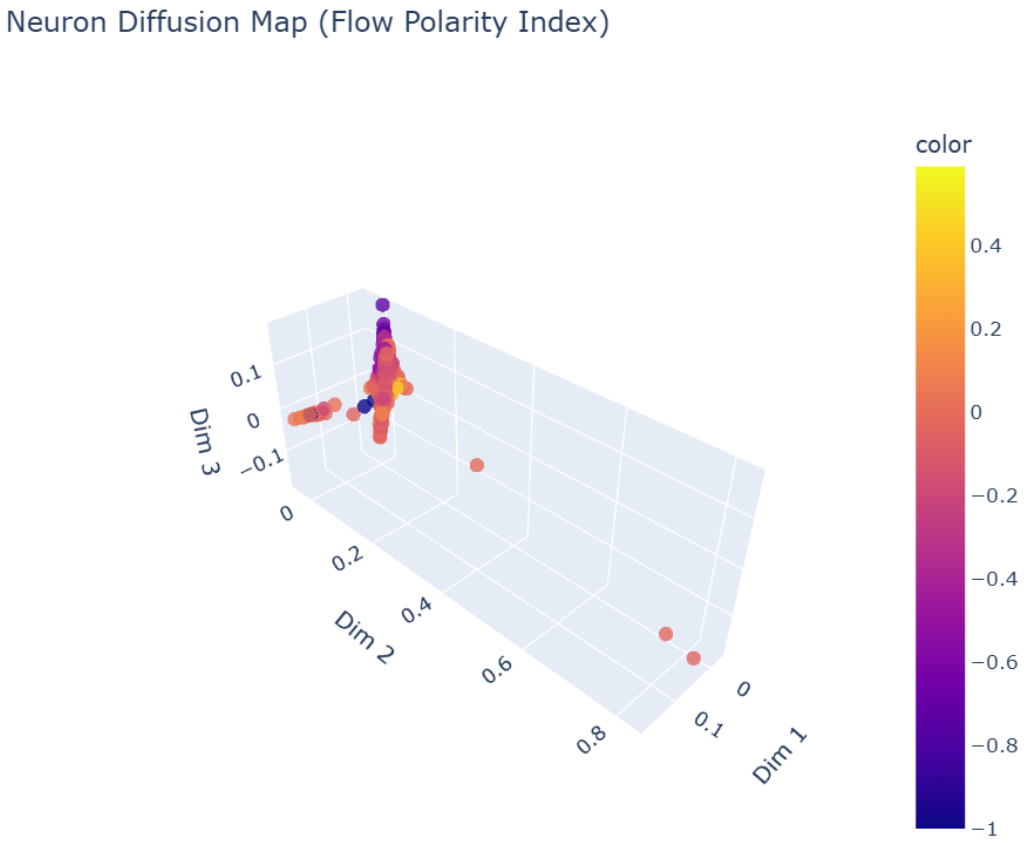
48-stim based RGC results



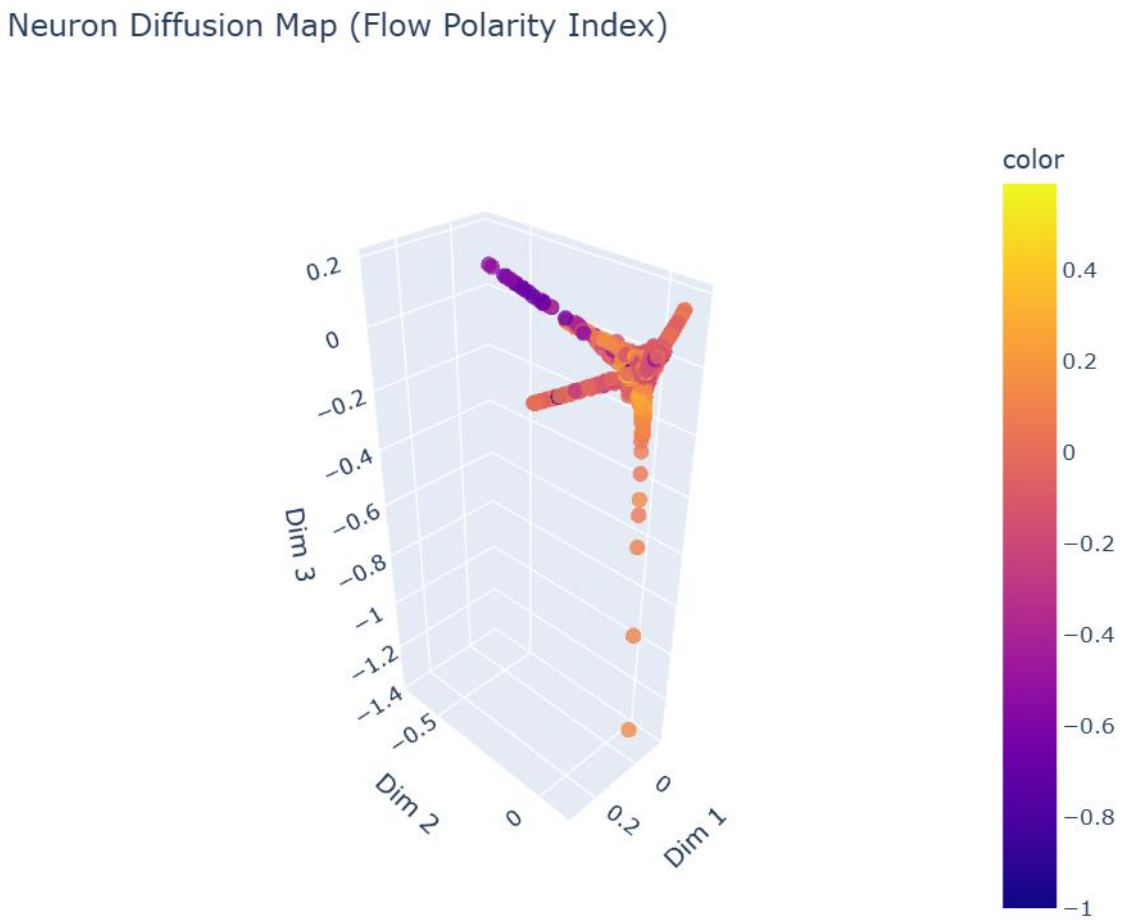
Chirp based RGC results (min-max normalization)



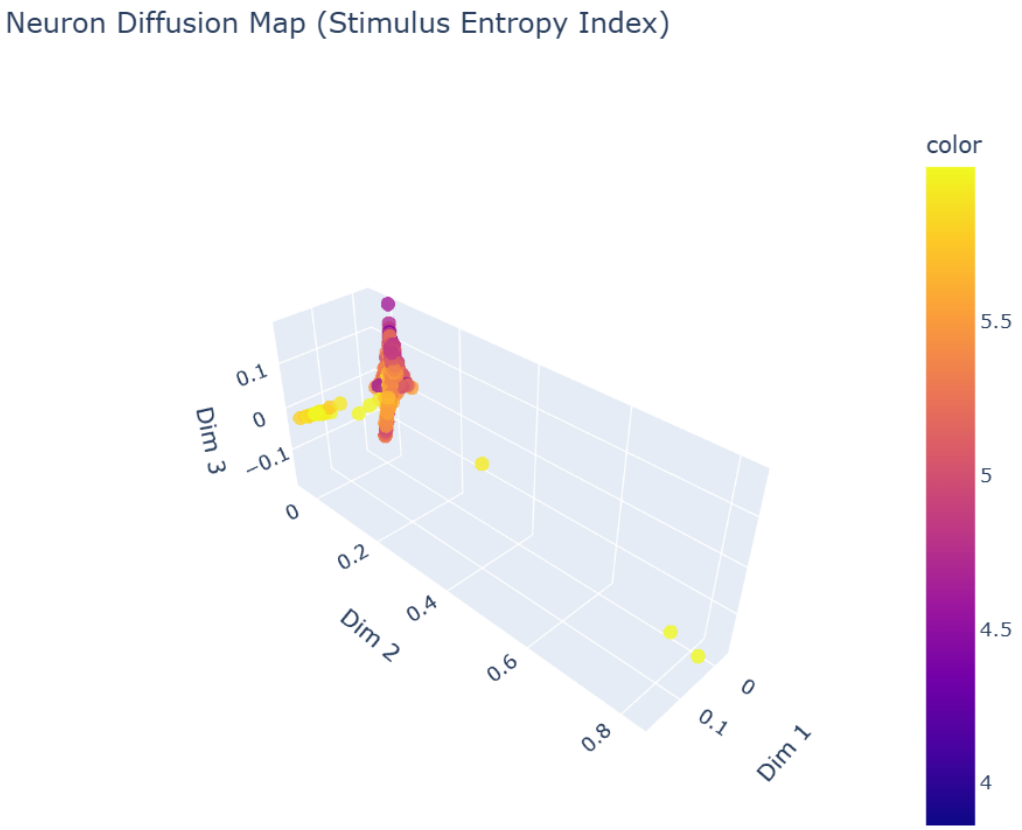
48-stim based RGC results



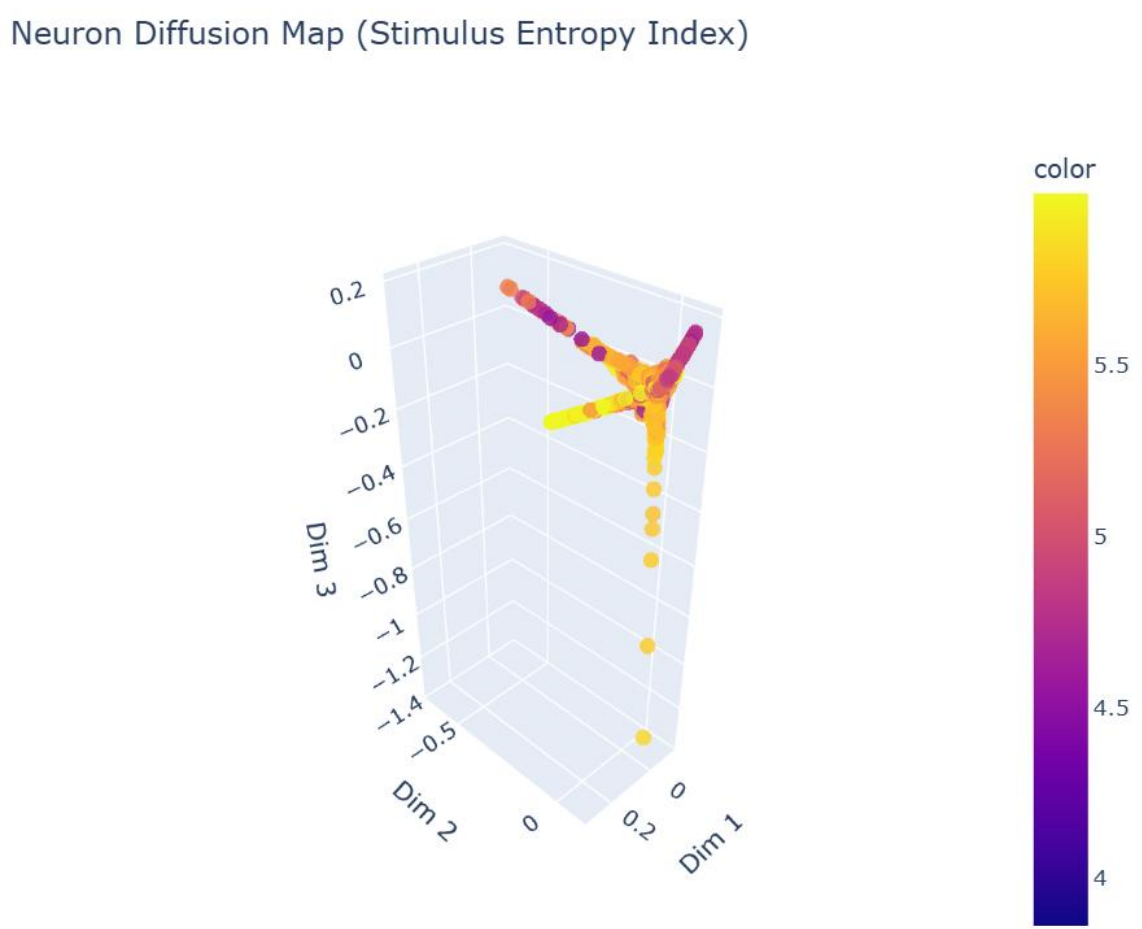
Chirp based RGC results (min-max normalization)



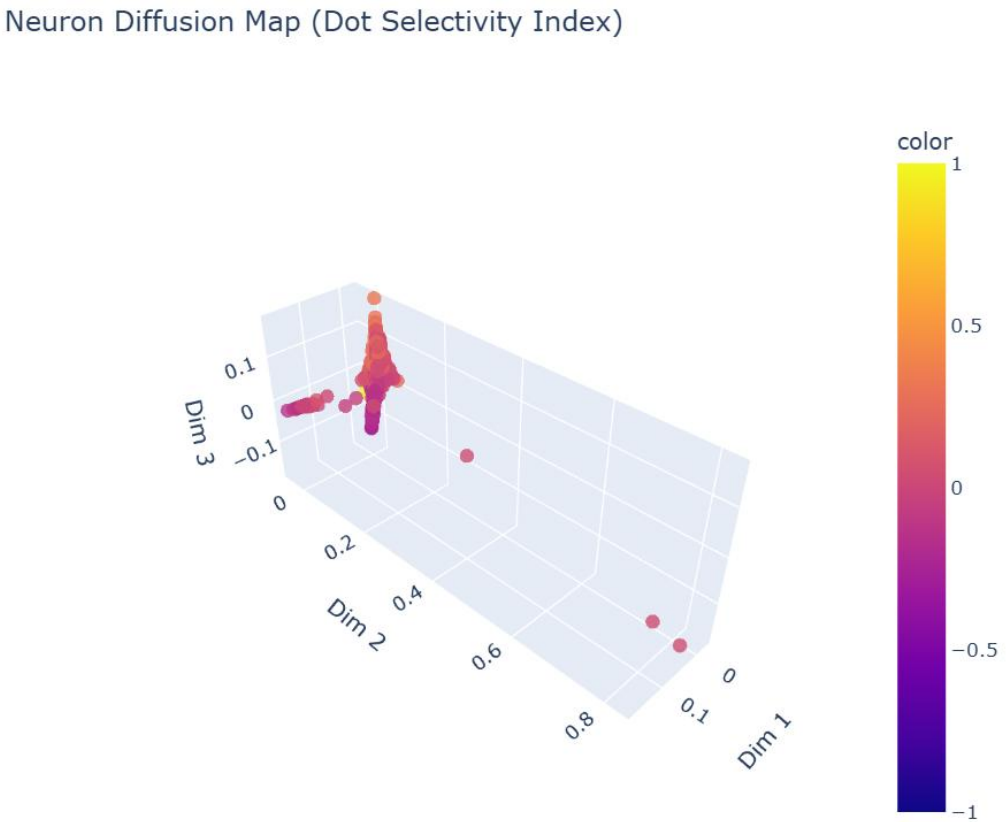
48-stim based RGC results



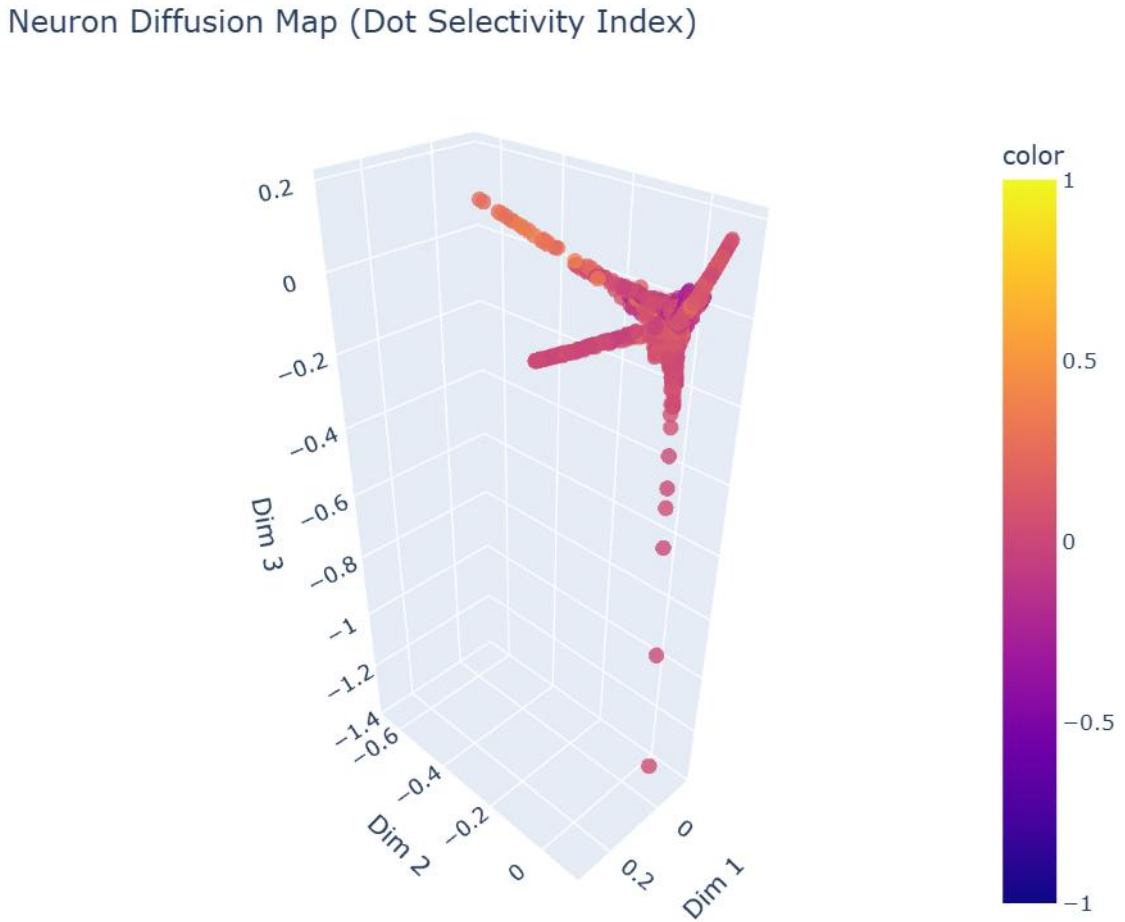
Chirp based RGC results (min-max normalization)

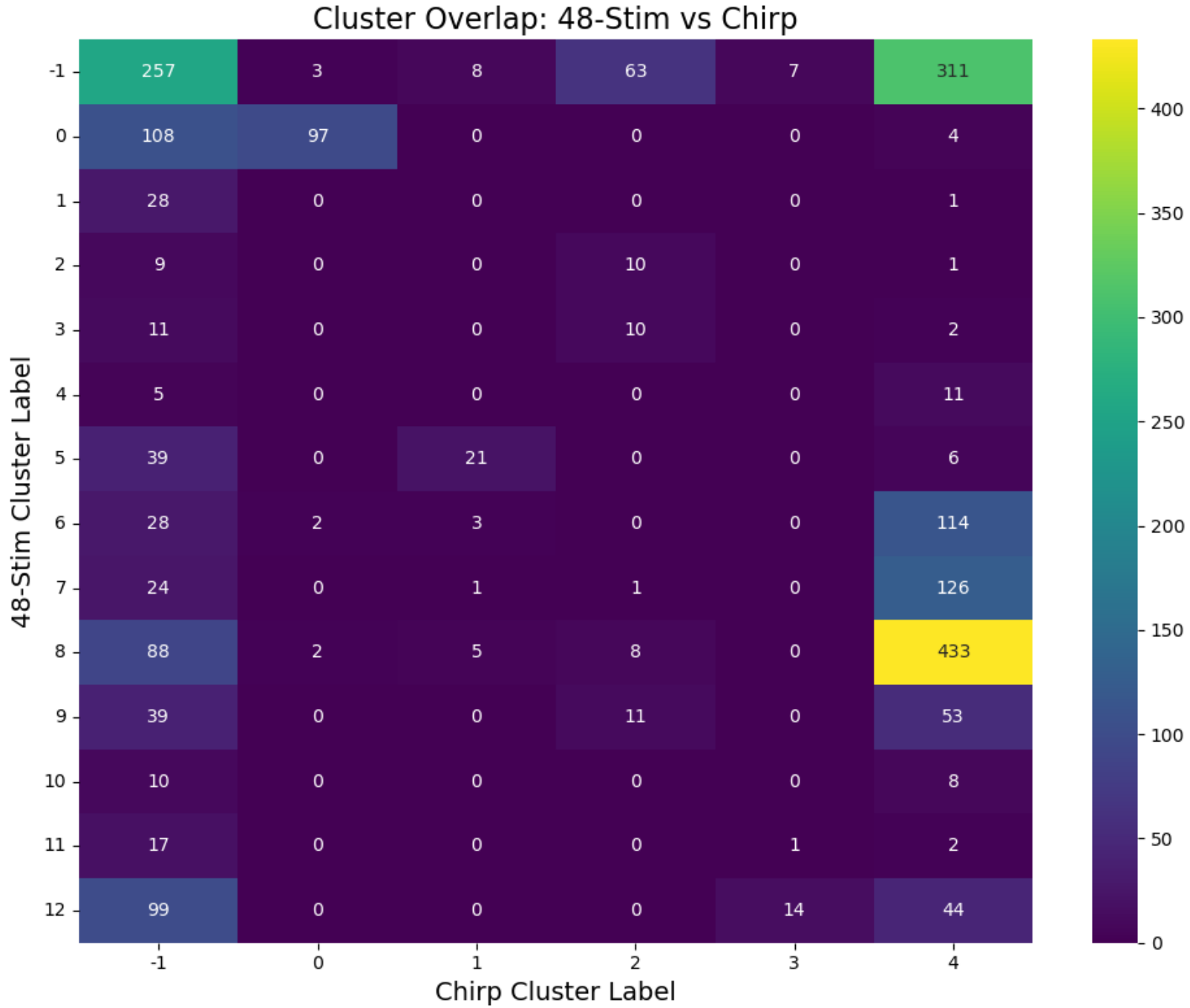


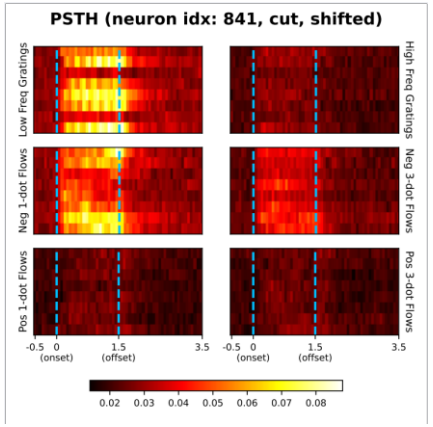
48-stim based RGC results

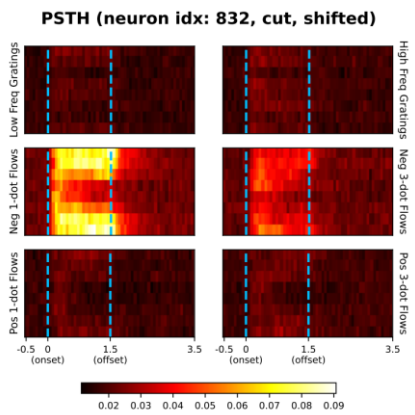


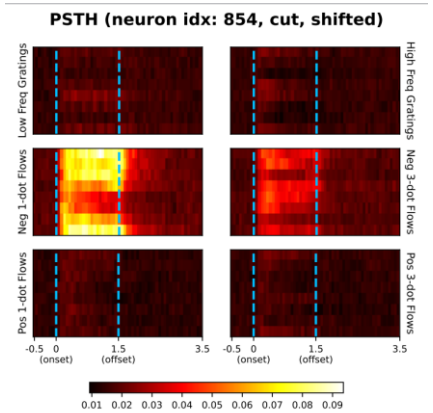
Chirp based RGC results (min-max normalization)

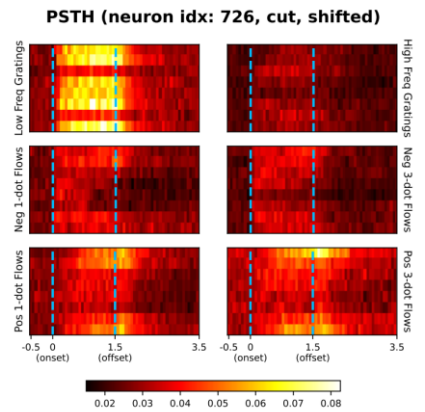


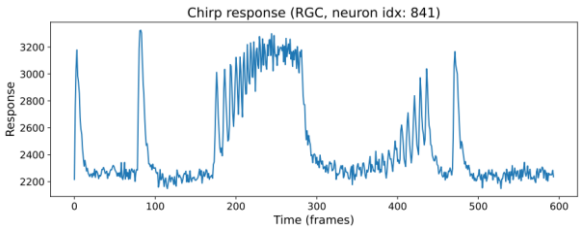

Cluster Overlap: 48-Stim vs Chirp
48-Stim Cluster Label
Chirp Cluster Label
-1 257 3 8 63 7 311
0 108 97 0 0 0 4
1 28 0 0 0 0 1
2 9 0 0 10 0 1
3 11 0 0 10 0 2
4 5 0 0 0 0 11
5 39 0 21 0 0 6
6 28 2 3 0 0 114
7 24 0 1 1 0 126
8 88 2 5 8 0 433
9 39 0 0 11 0 53
10 10 0 0 0 0 8
11 17 0 0 0 1 2
12 99 0 0 0 14 44
-1 0 1 2 3 4
400 350 300 250 200 150 100 50 0

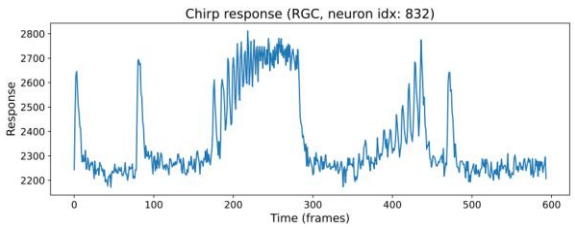

PSTH (neuron idx: 841, cut, shifted)
Low Freq Gratings
Neg 1-dot Flows
Pos 1-dot Flows
High Freq Gratings
Neg 3-dot Flows
Pos 3-dot Flows
(onset)
(offset)

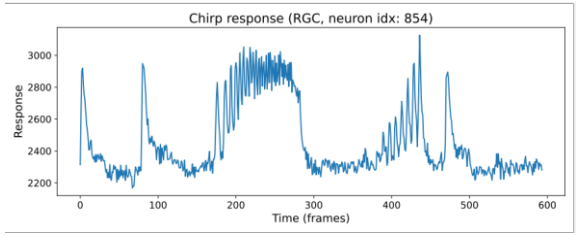

PSTH (neuron idx: 832, cut, shifted)
Low Freq Gratings
Neg 1-dot Flows
Pos 1-dot Flows
High Freq Gratings
Neg 3-dot Flows
Pos 3-dot Flows
(onset)
(offset)

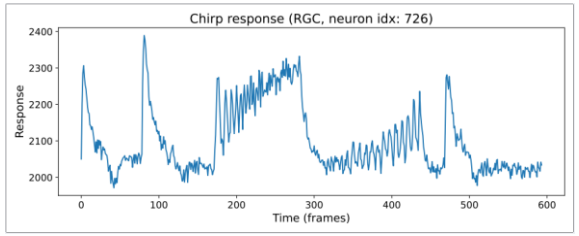

PSTH (neuron idx: 854, cut, shifted)
Low Freq Gratings
Neg 1-dot Flows
Pos 1-dot Flows
High Freq Gratings
Neg 3-dot Flows
Pos 3-dot Flows
(onset)
(offset)

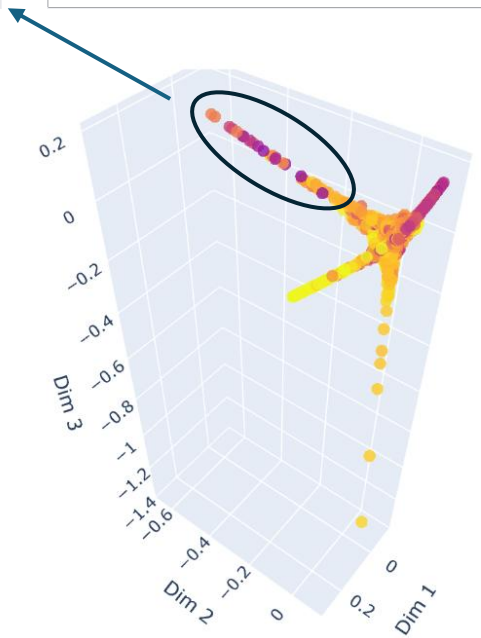

PSTH (neuron idx: 726, cut, shifted)
Low Freq Gratings
Neg 1-dot Flows
Pos 1-dot Flows
High Freq Gratings
Neg 3-dot Flows
Pos 3-dot Flows
(onset)
(offset)

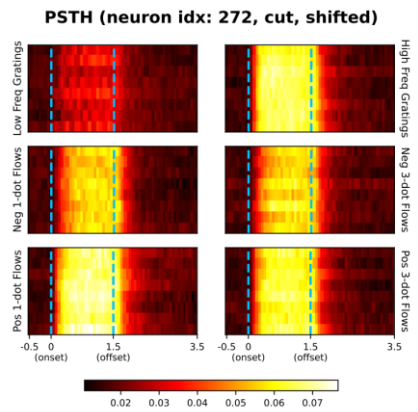

Chirp response (RGC, neuron idx: 841)
Response
Time (frames)

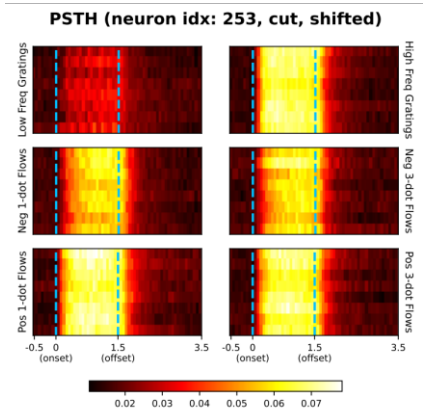

Chirp response (RGC, neuron idx: 832)
Response
Time (frames)

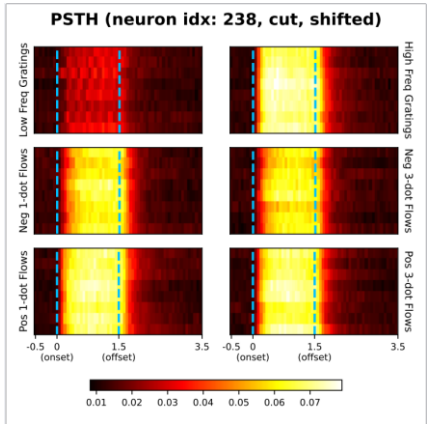

Chirp response (RGC, neuron idx: 854)
Response
Time (frames)

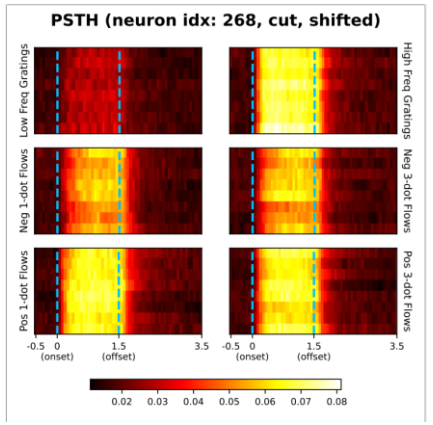

Chirp response (RGC, neuron idx: 726)
Response
Time (frames)

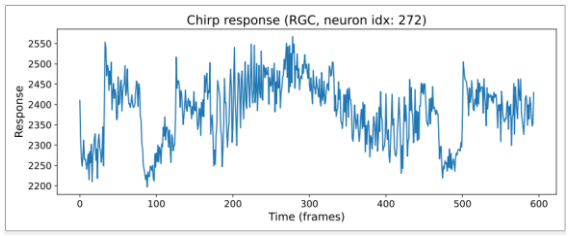

Dim 1
Dim 2
Dim 3

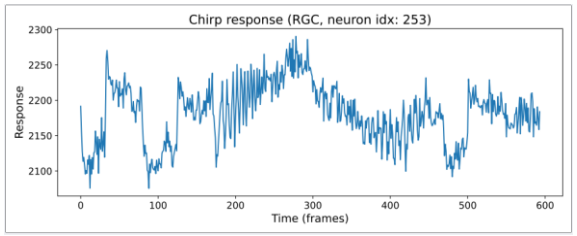

PSTH (neuron idx: 272, cut, shifted)
Low Freq Gratings
Neg 1-dot Flows
Pos 1-dot Flows
High Freq Gratings
Neg 3-dot Flows
Pos 3-dot Flows
(onset)
(offset)

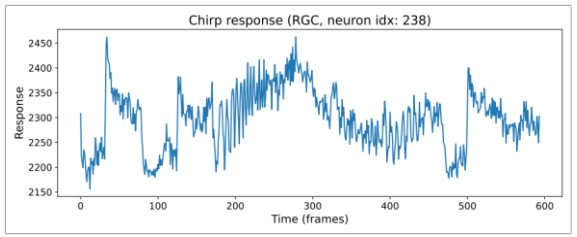

PSTH (neuron idx: 253, cut, shifted)
Low Freq Gratings
Neg 1-dot Flows
Pos 1-dot Flows
High Freq Gratings
Neg 3-dot Flows
Pos 3-dot Flows
(onset)
(offset)

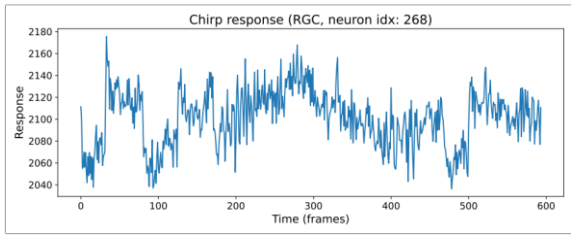

PSTH (neuron idx: 238, cut, shifted)
Low Freq Gratings
Neg 1-dot Flows
Pos 1-dot Flows
High Freq Gratings
Neg 3-dot Flows
Pos 3-dot Flows
(onset)
(offset)

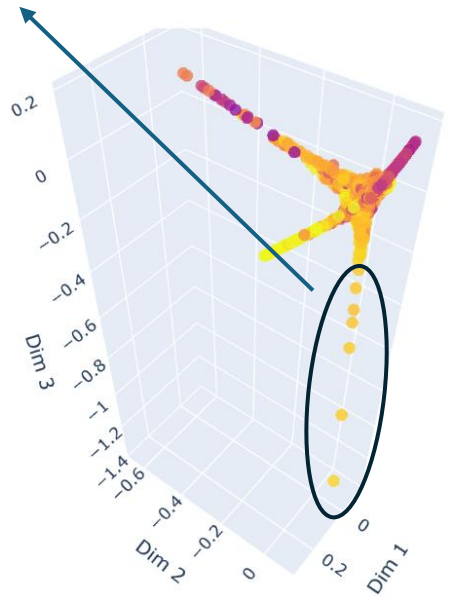

PSTH (neuron idx: 268, cut, shifted)
Low Freq Gratings
Neg 1-dot Flows
Pos 1-dot Flows
High Freq Gratings
Neg 3-dot Flows
Pos 3-dot Flows
(onset)
(offset)


Chirp response (RGC, neuron idx: 272)
Response
Time (frames)


Chirp response (RGC, neuron idx: 253)
Response
Time (frames)


Chirp response (RGC, neuron idx: 238)
Response
Time (frames)


Chirp response (RGC, neuron idx: 268)
Response
Time (frames)


Dim 1
Dim 2
Dim 3

Comparison

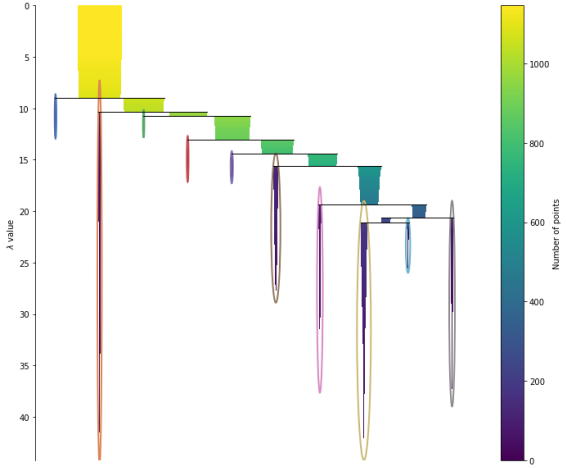
Retina

SC

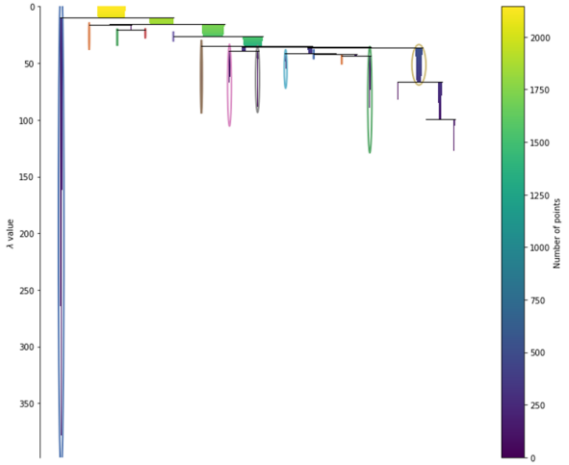
dLGN

V1

Public retina

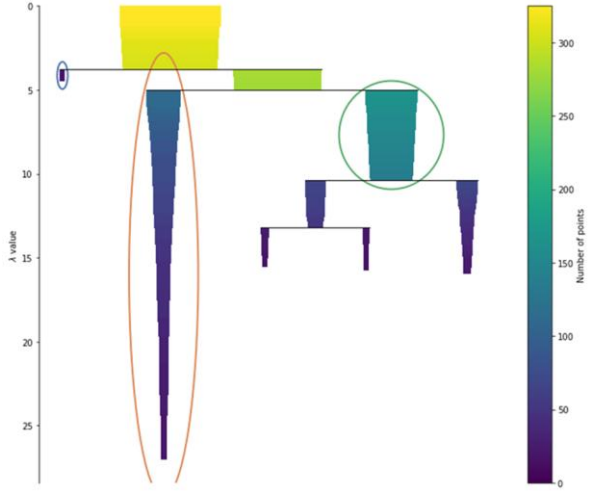


Our RGC



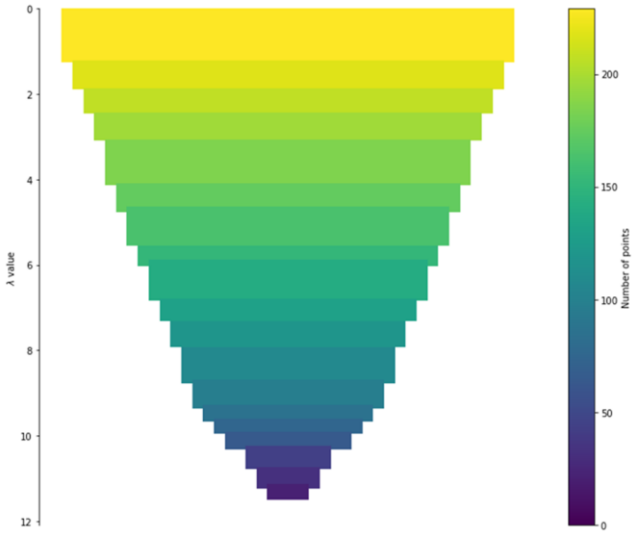
If min_cluster_size=5, 36 clusters.

Our



If min_cluster_size=5, 8 clusters.

Our



Public

If min_cluster_size=5, 2 clusters.