Spectro-Temporal Tuning to Long Duration Stimuli in Primary Auditory Cortex of the Awake Ferret

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Abstract

Many current popular methods that provide a spectral-temporal characterization of auditory neural responses use relatively long stimuli, lasting seconds to minutes. However, neurons in the central part of sensory pathways tend to adapt in their response to stimuli presented over extended periods of time. We have previously shown that auditory cortical neurons display a second order of adaptation, whereby the characteristics of their adaptation to the presentation of repeated long stimuli changes with each presentation; in other words, the rate of cortical adaptation decreases across multiple long stimuli. Methods have been developed which provide a joint spectro-temporal characterization of neural responses in the auditory pathway. In particular, the auditory grating method, known as moving ripple method and its extensions, have proven to be well correlated with the more classic tone pip methods of response area characterization. But the ripple and other related stimuli are periodic, introducing the possibility of adaptation as the receptive field is being measured. Computation of the spectro-temporal receptive field (STRF) using the response to these ripple combinations assumes stationarity in the neural input/output function. We will demonstrate dynamic changes in tuning during the measurement of the STRF over a period of seconds, even in the absence of a relevant behavioral task.

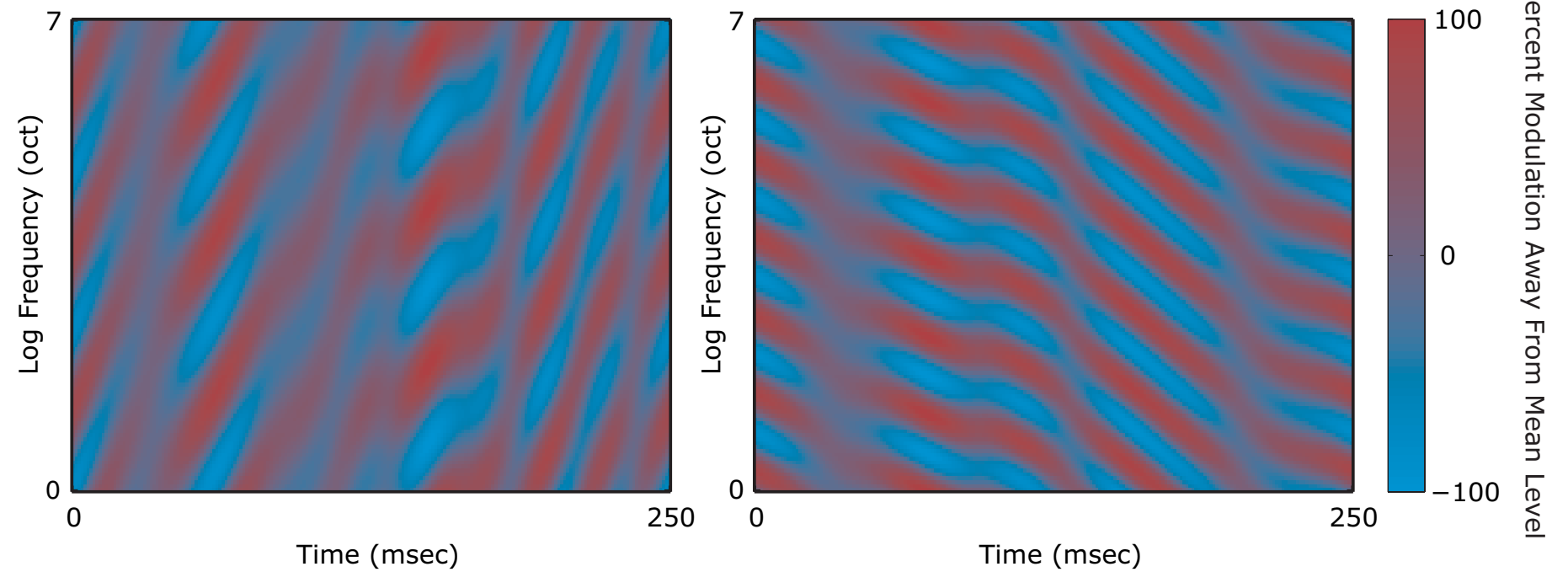
Methods

Ferrets (Mustela putorius furo) were chronically implanted with multi-electrode arrays (Neuralynx, Inc., Tuscon, AZ) with up to eight independently adjustable electrodes (1-5MΩ, MicroProbe Inc., Gaithersburg, MD). Neurophysiological data was obtained with the animal awake and restrained. Sound stimuli were computed in Matlab and synthesized on a TDT RX6 DSP Processor. These stimuli were presented freefield in an acoustically controlled environment from an overhead speaker (Manger Transducers), positioned about 1m above the animal's head.

Early and Late Receptive Fields

A set of six second long Temporally Orthogonal Ripple Combination (TORC) stimuli were presented. Each TORC stimulus was the sum of eight auditory gratings, all with the same spectral density Ω_i, but different angular velocities ω_i. The responses to these spectro-temporal envelopes $s(x,t)$ were used to estimate the STRF. In order to avoid a potential confound from the onset response, the receptive field was computed with responses occuring only 250ms after the onset of the stimulus. In order to examine the stability of the STRF and explore the dynamics of a neuron's tuning while the receptive field is measured, we split the six second analysis window into two. The Early STRF was measured from the first three seconds of response to each stimulus (excluding 250ms onset delay), and the Late STRF from the last three seconds. The features of the two STRFs were determined and compared across a set of indices described in the first panel.

$$s(x,t) = \sum_i \left[1 + \Delta A_i \cdot \cos(\Omega_i x + \omega_i t + \phi_i) \right]$$



Spectro-temporal envelopes of two typical TORC stimuli.
Modulation depth ΔA_i =100%, and the phases ϕ_i are random.

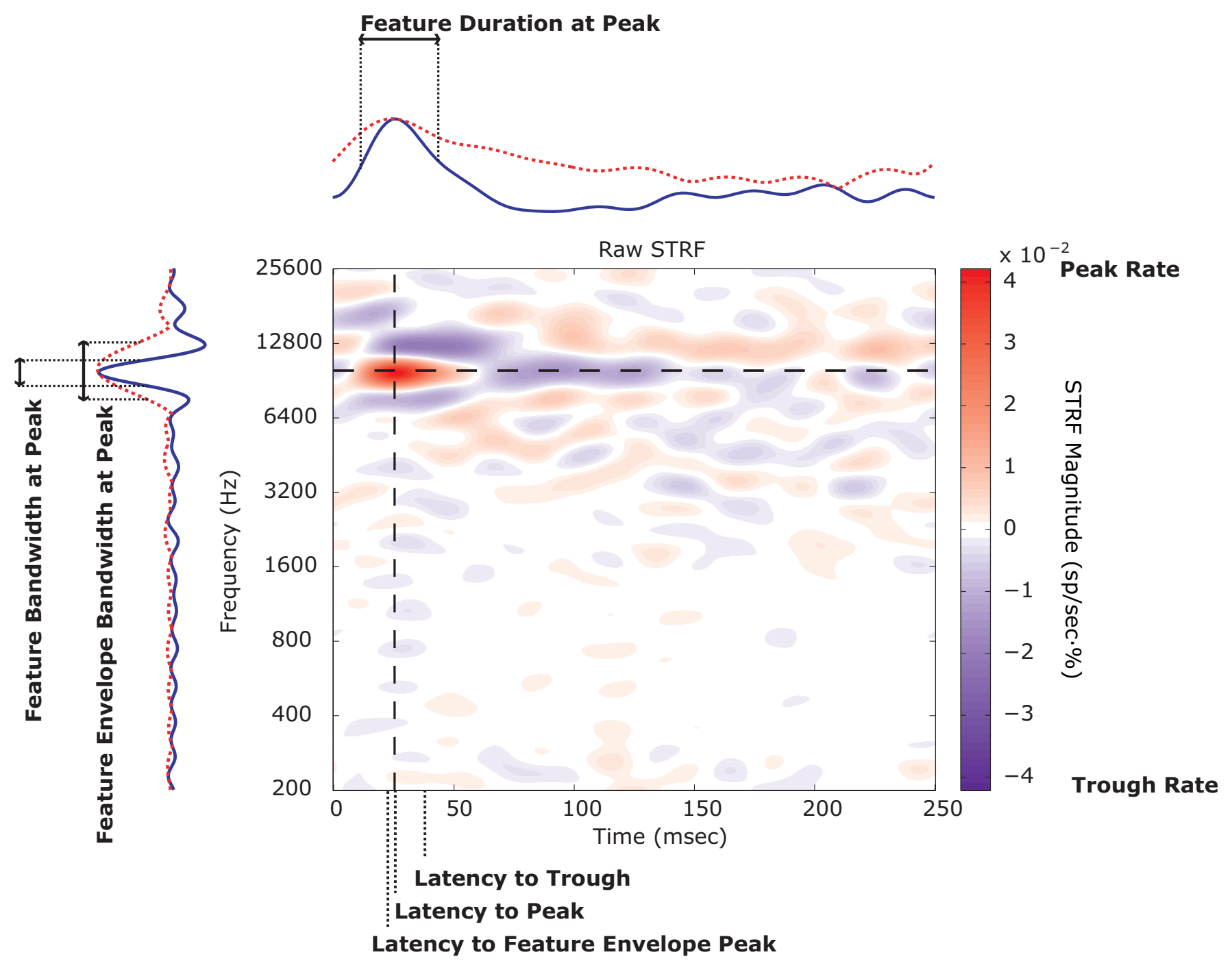
Receptive Field Estimation

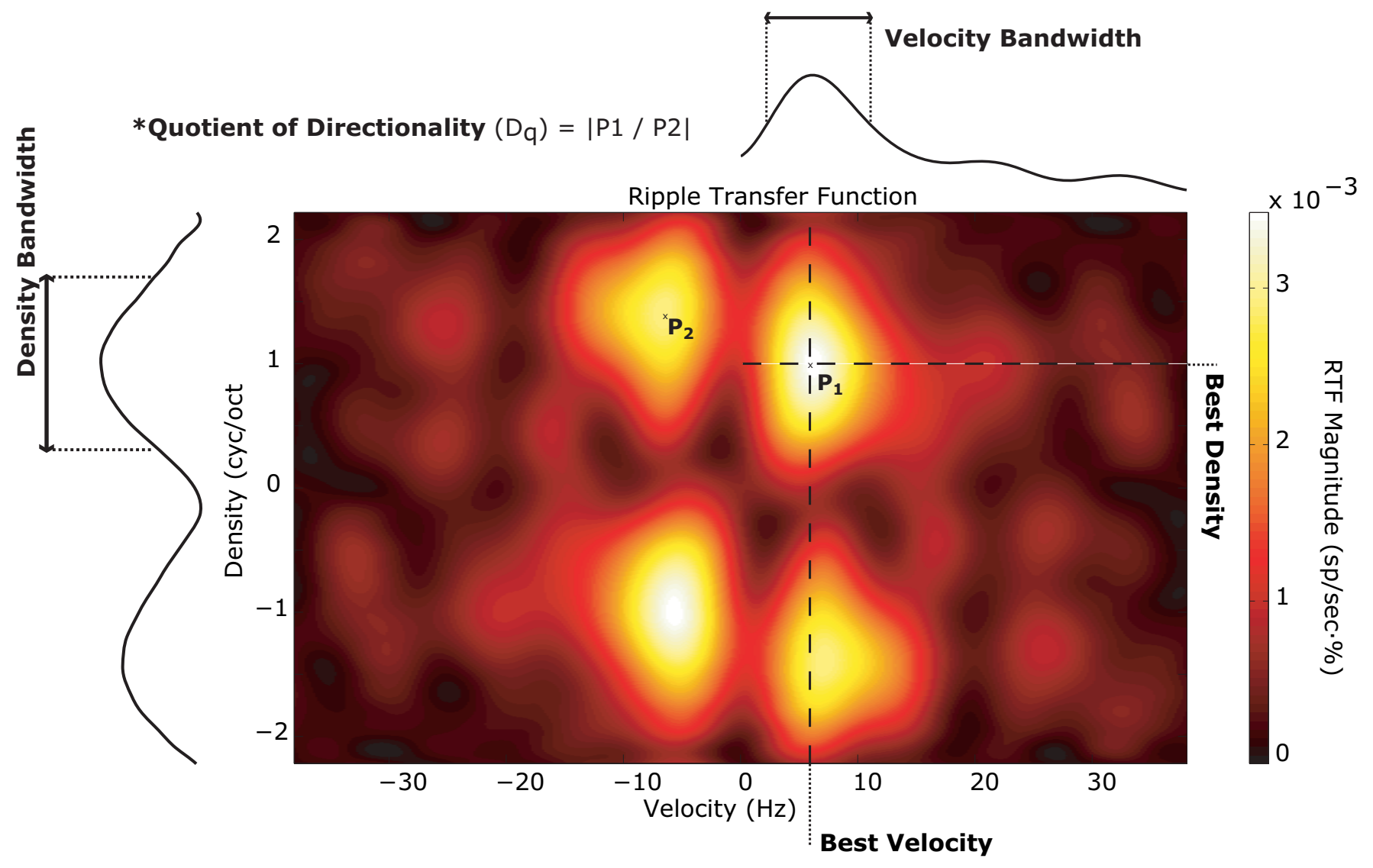
In order to estimate the receptive field of a neuron, we reverse correlate the neural response $r(t)$ with the stimulus $s(x, t)$ that evoked it. Since auditory cortex is thought to encode modulations of sound, the representation of the stimulus used in computing the linear kernel of the response is the envelope of modulation about the mean level of the stimulus. Under the assumptions of the STRF model, frequency bands contribute independently to the neural output and are therefore kept separate in the computations.

$$STRF(x,\tau) = \frac{\int s(x, t-\tau)\cdot r(t)\, dt}{\left[\int s(x, t)\, dt\right]^2}$$

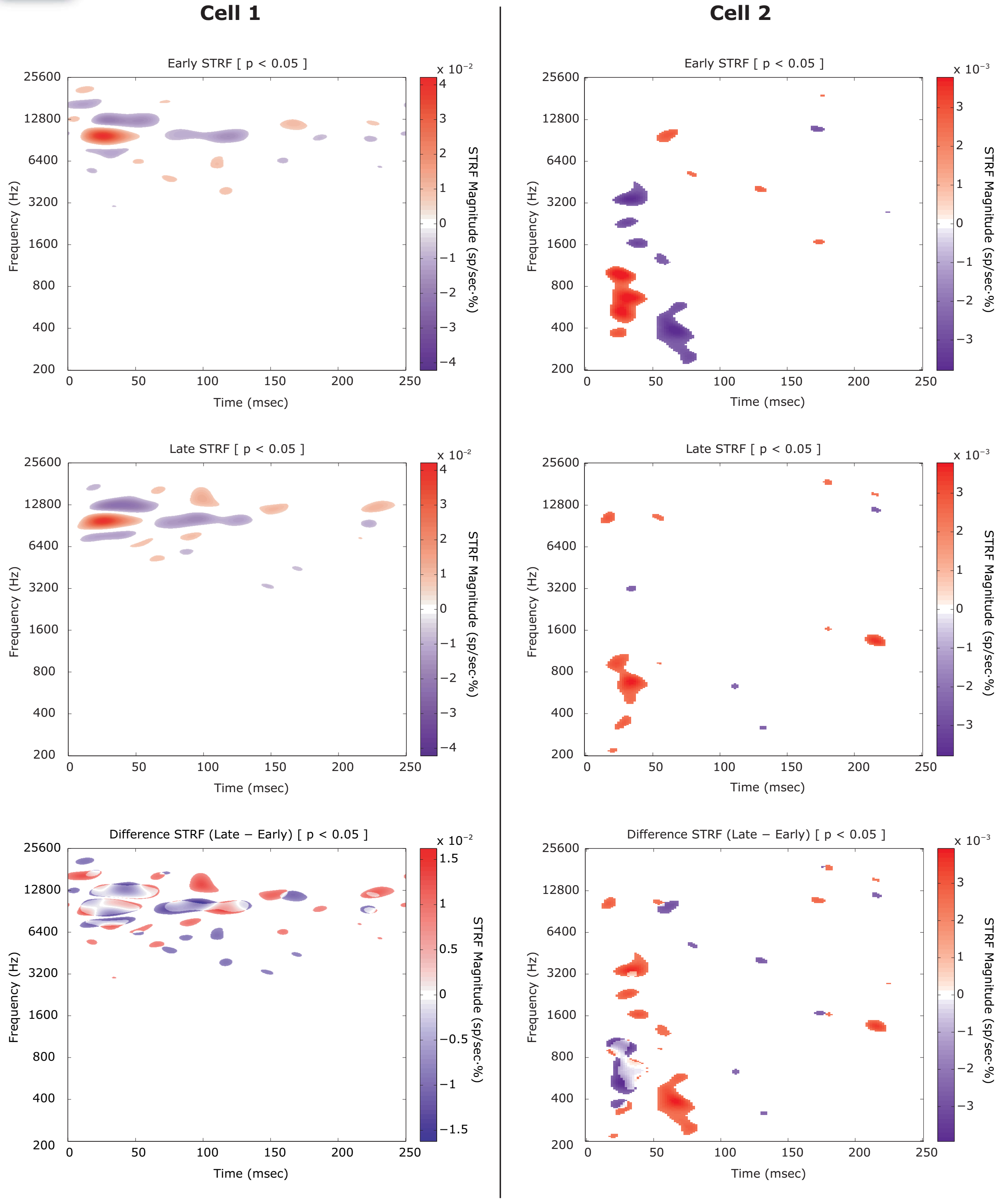
1 Measured Indices

Shown below is a typical receptive field. Temporal (top) and spectral (left) cross sections of the STRF and its envelope are plotted along the margins. Duration and Bandwidth are measured at half maximum of the cross sections. Peak and trough rate are the maximum and minimum values the STRF attains. Latencies were measured at these maximum and minimum values. Below the STRF is its corresponding Ripple Transfer Function (RTF). Temporal (top) and spectral (left) cross sections are plotted along the margins. The peak was defined to have a positive velocity (conjugate symmetry). We define a quotient of directionality as being the magnitude of the peak of the RTF for positive densities and velocities divided by the peak for positive densities and negative velocities.





3 Early and Late STRFs

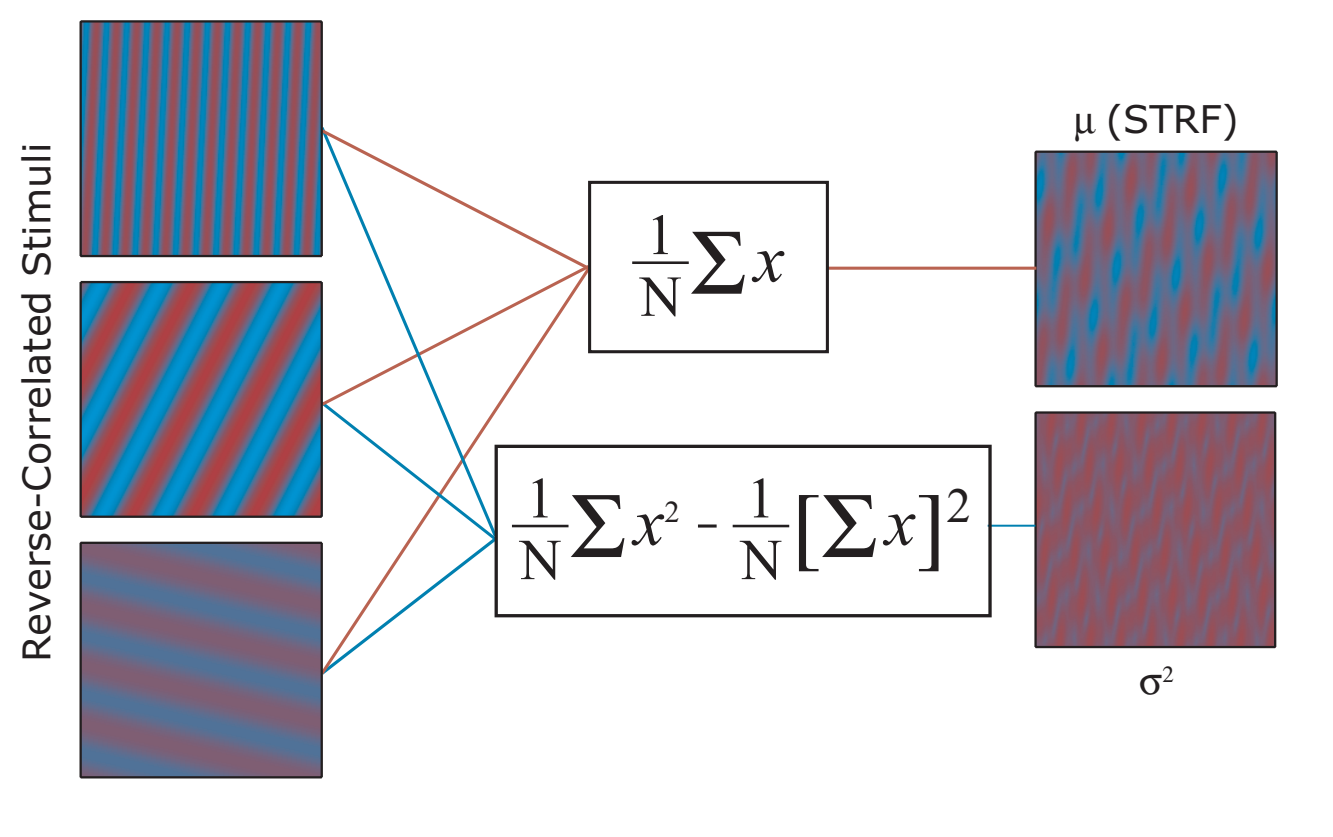


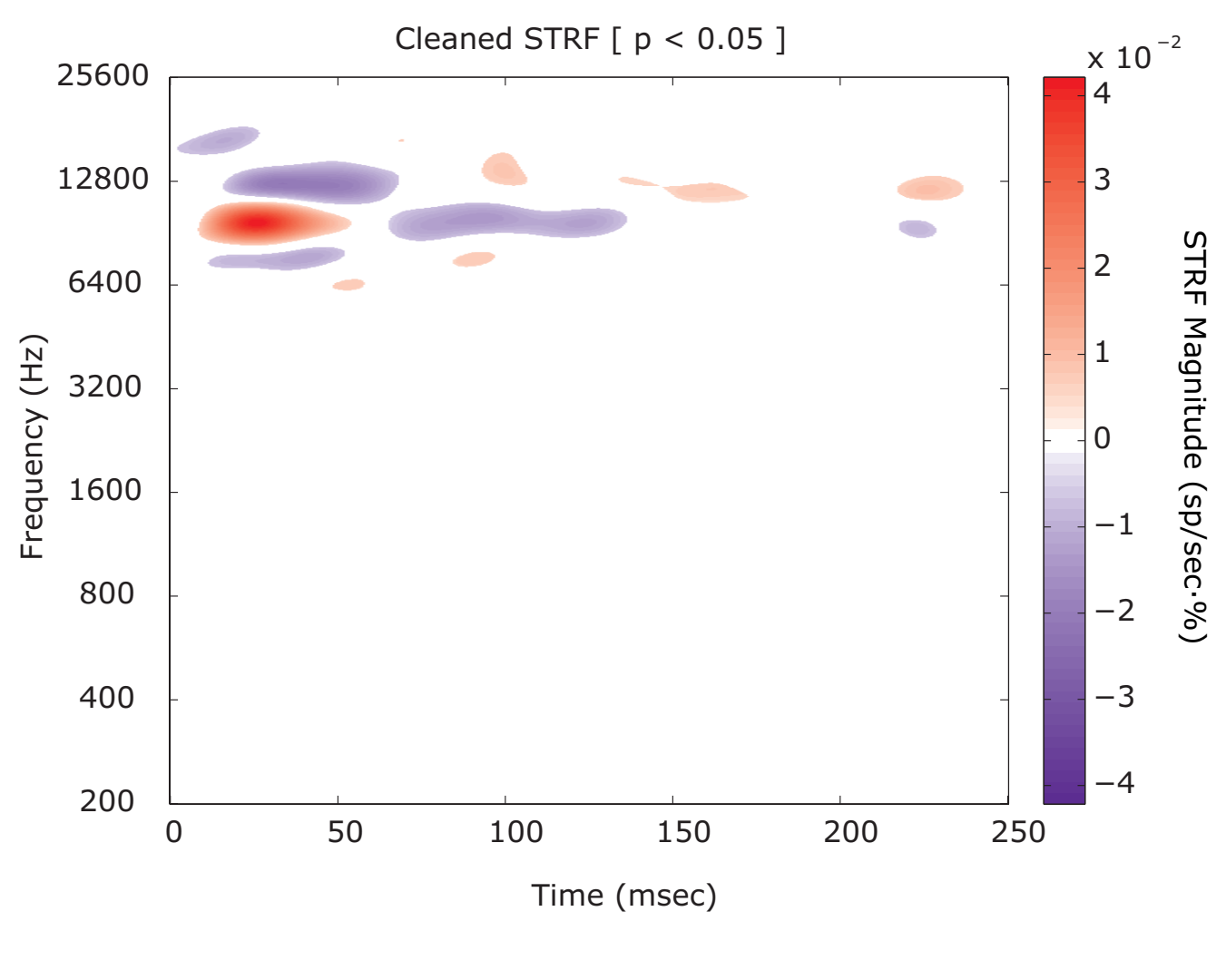
Two representative cells for which early and late receptive fields were compared. The cell at left showed a stable STRF during the presentation of the stimulus. Despite its overall stability, there were slight changes in the response function of the neuron which can be seen in the Difference STRF. Here, the Early STRF is subtracted from the Late. Blue points became more inhibitory (or conversely, less excitatory), and red points became more excitatory (less inhibitory). In the case of the cell at right, the two STRFs differed substantially, with a partial reduction in the size of the excitatory region and a complete elimination of the inhibitory region following it. This can be seen once again in the Difference STRF at points where its absolute magnitude is that of the Early STRF. Units are normalized to spikes per second evoked by one percent modulation away from the mean level of the stimulus.

2 Feature Detection

We characterized the STRF in terms of the important features which govern the neural input/output function. Since we define the receptive field as the reverse correlation on a set of ripple stimuli, the STRF is the sum of a collection of gratings with different densities and velocities. In the linear model, the neuron's output is the sum of a scaled and shifted version of its multiple inputs. Points in the STRF which belong to features will reliably be similar in all constituent gratings. Unreliable points will tend to cancel each other out and not be included in a feature. In much the same manner that we compute the pointwise mean (STRF), we can compute the pointwise standard error of the gratings. The STRF divided by its standard error is a t-distribution which we can threshold to obtain features within a desired confidence interval. Shown at far right are the features detected in the STRF shown in the first panel with a confidence of 95% (p<0.05).

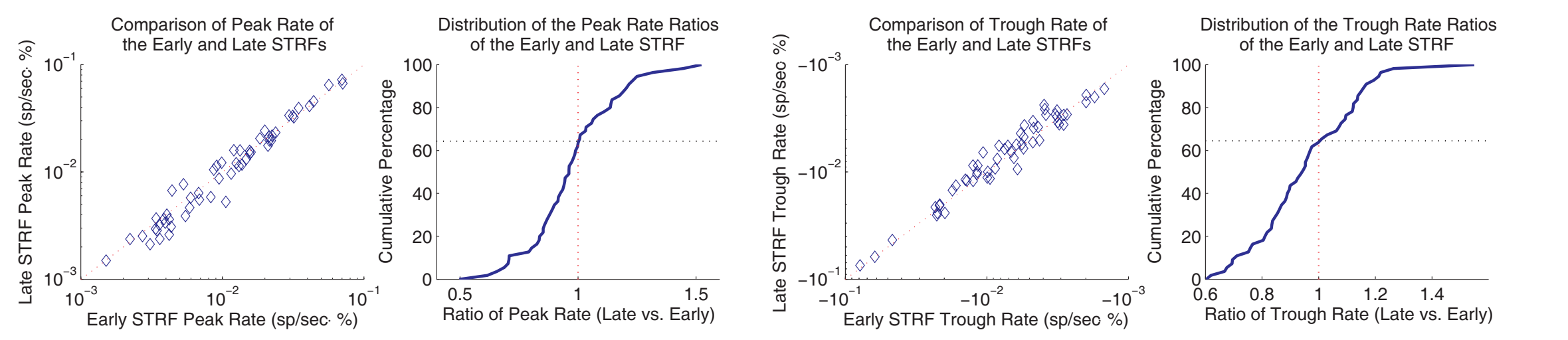
$$t(x,\tau) = \frac{\mu\cdot\sqrt{N}}{\sigma} = \frac{STRF(x,\tau)\cdot\sqrt{N}}{\sigma}$$



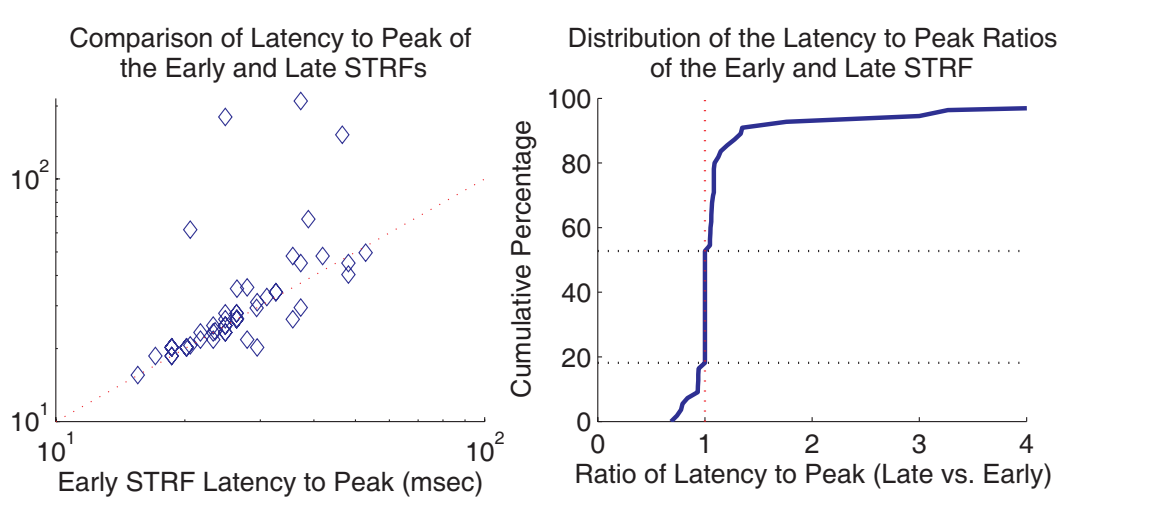


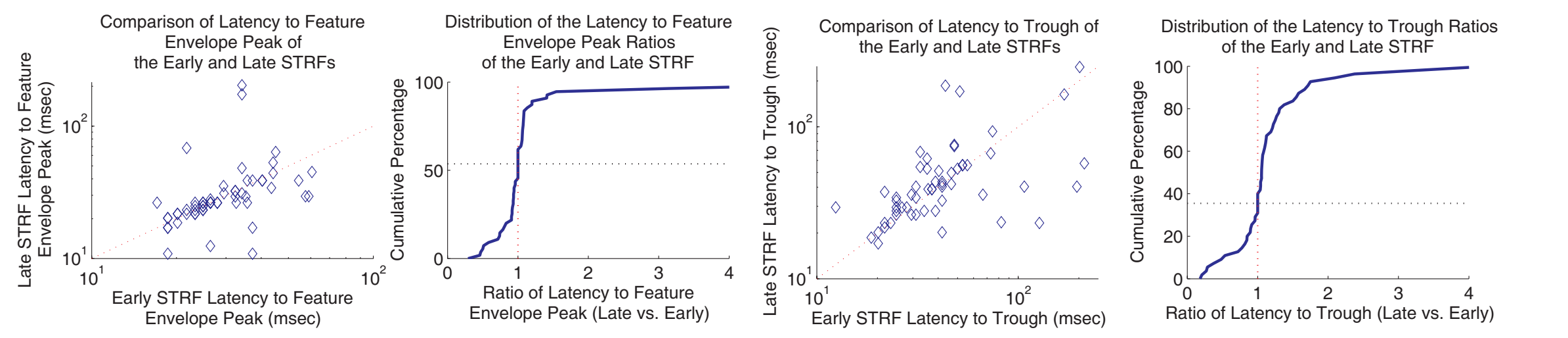
4 Population Analysis of Tuning Dynamics

Rate. Magnitude of peak and trough decreased slightly, but not significantly.

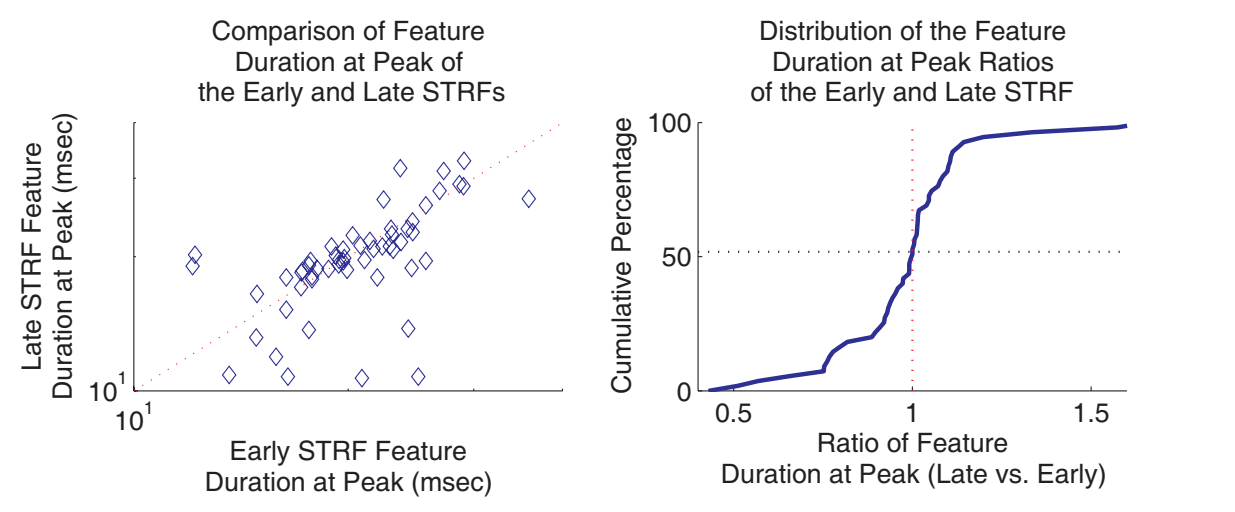


Latency. All three measurements of response latency showed an increasing trend, but only latency to peak was significant (p<0.05, t-test). Latency of the inhibitory trough was noisier (measurement of inhibitory contributions is less reliable than that of excitatory ones).

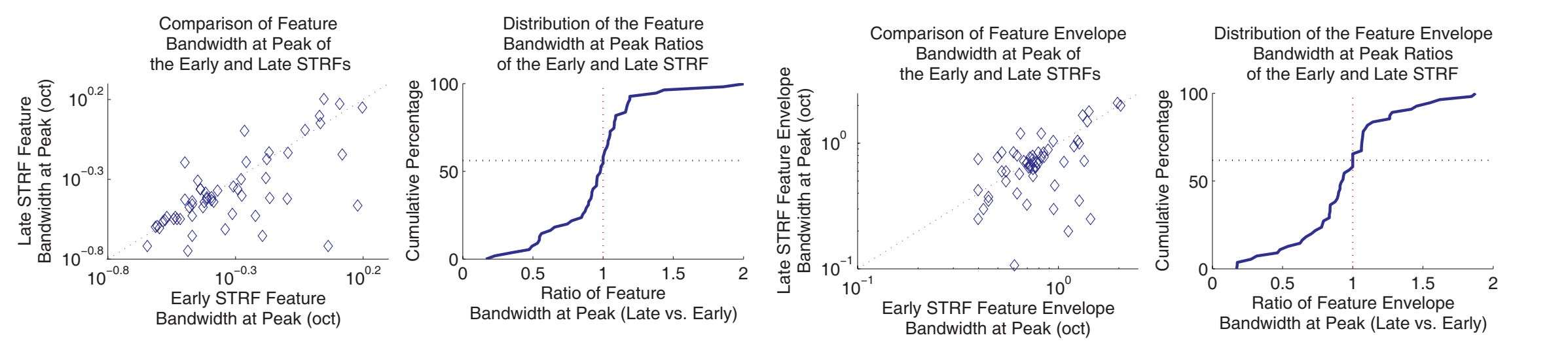




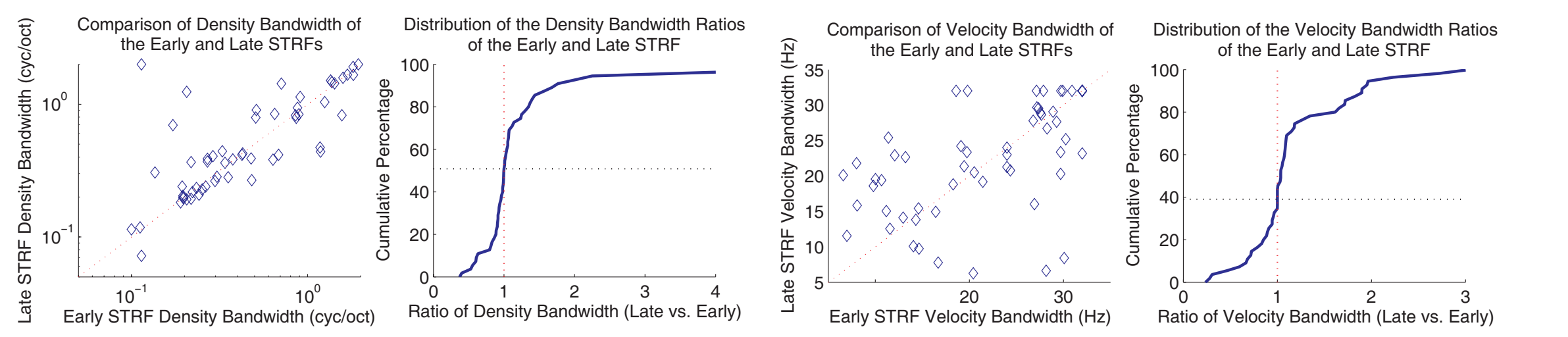
Duration of the excitatory feature in the STRF (measured at half maximum) decreased, but not significantly.



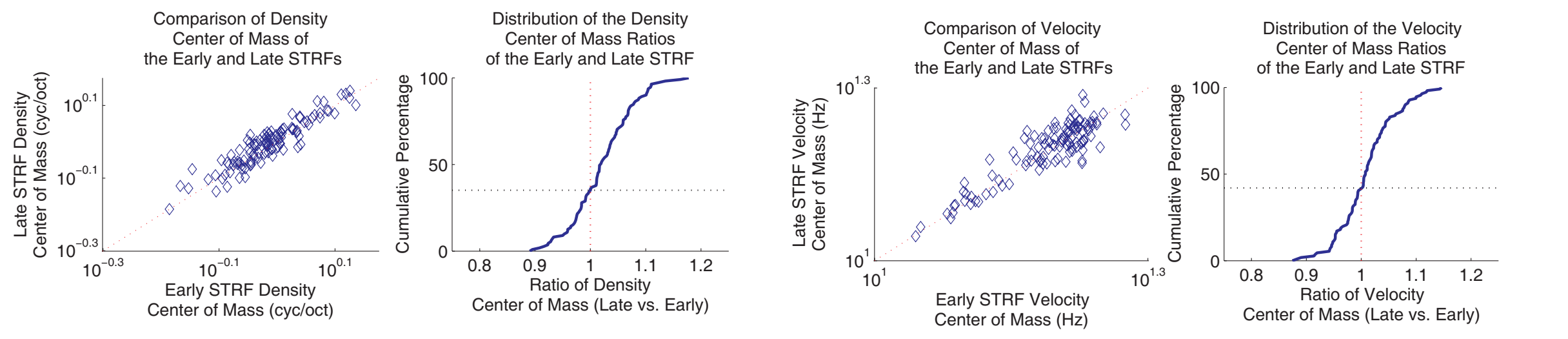
Bandwidth of both the excitatory feature and its envelope decreased, but neither was significant.



Tuning bandwidth at half maximum in ripple space remained fairly constant for density, but sometimes increased. An increase in bandwidth for velocities was more prevalent, and was significant (p<0.05, t-test). These increases in bandwidth correspond to spectral and temporal sharpening of the receptive field, respectively.



Tuning center of mass increased slightly in both density and velocity, but only the increase in density was significant (p<0.05, t-test). This further supports the previous result of spectrotemporal sharpening of the receptive field.



References

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Conclusions

From the time-frequency reverse correlation analysis of dynamic changes in the receptive field, there appear to be slight changes in the structure of the STRF due to presentation of a prolonged stimulus. This was confirmed as well in ripple space, where we found spectrotemporal sharpening of the receptive field.

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