MT neurons have different tuning properties at contrast threshold and above

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Background

A fundamental question in neuroscience concerns the mechanism by which sensory neurons give rise to perceptual experience. One way to understand these mechanisms is to study their visual selectivity (tuning).

Different measures of selectivity are used in physiological and behavioral studies:

- response functions measured, at high contrasts (physiology)
- contrast sensitivity functions, at threshold contrasts (behavior)

In physiology studies, response functions are often used as a proxy for contrast sensitivity functions. Is this a valid approach?

Here we ask whether neurons have similar tuning properties at threshold and supra-threshold contrasts.

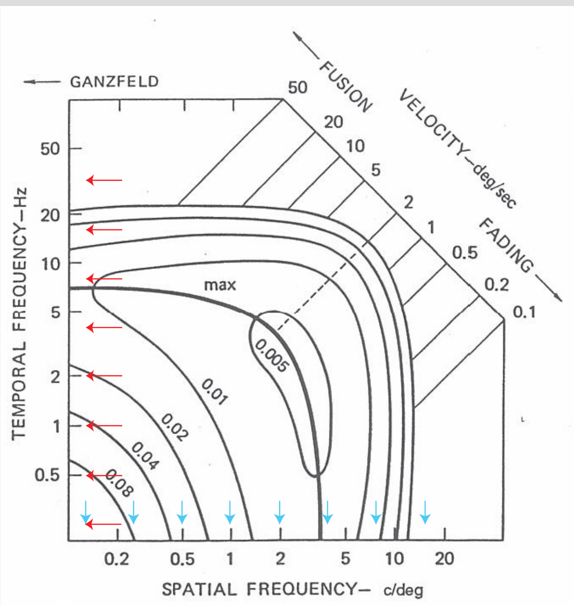
Methods

Experiments were performed on two alert fixating rhesus monkeys (Macaca mulatta).

Neural responses were measured from single cells in the middle temporal area (MT) of the visual cortex.

For 130 cells, we obtained the receptive field center, preferred direction, spatial frequency (SF) and temporal frequency (TF) tuning of the neuron at 100% contrast.

Most neuronal receptive fields were within 6° of the fovea.



RIGHT: Human contrast sensitivity for all visible SF and TF.

Neural responses measured at:

- 5 SF (0.015 to 16 cycles/degree).
- 1-3 TF (0.25 to 32 Hz).
- 5-7 contrasts levels (0.5-100%).

For the population of neurons, stimulus space covered the entire range of spatiotemporal frequencies, as indicated by arrows.

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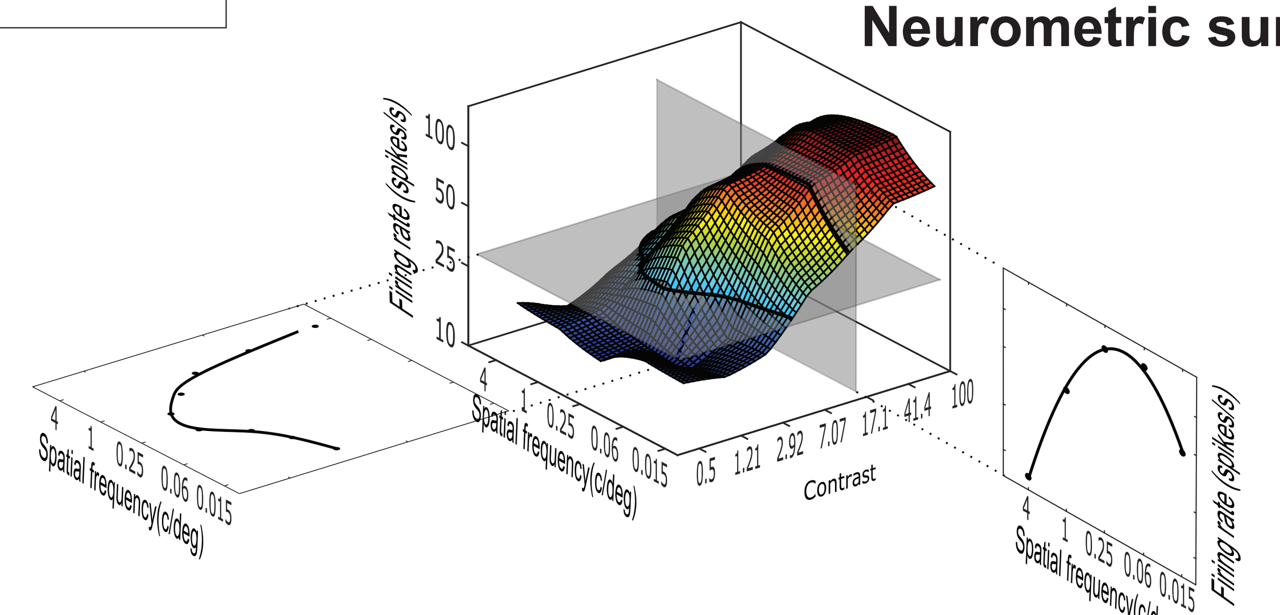
Results

Neurometric surface

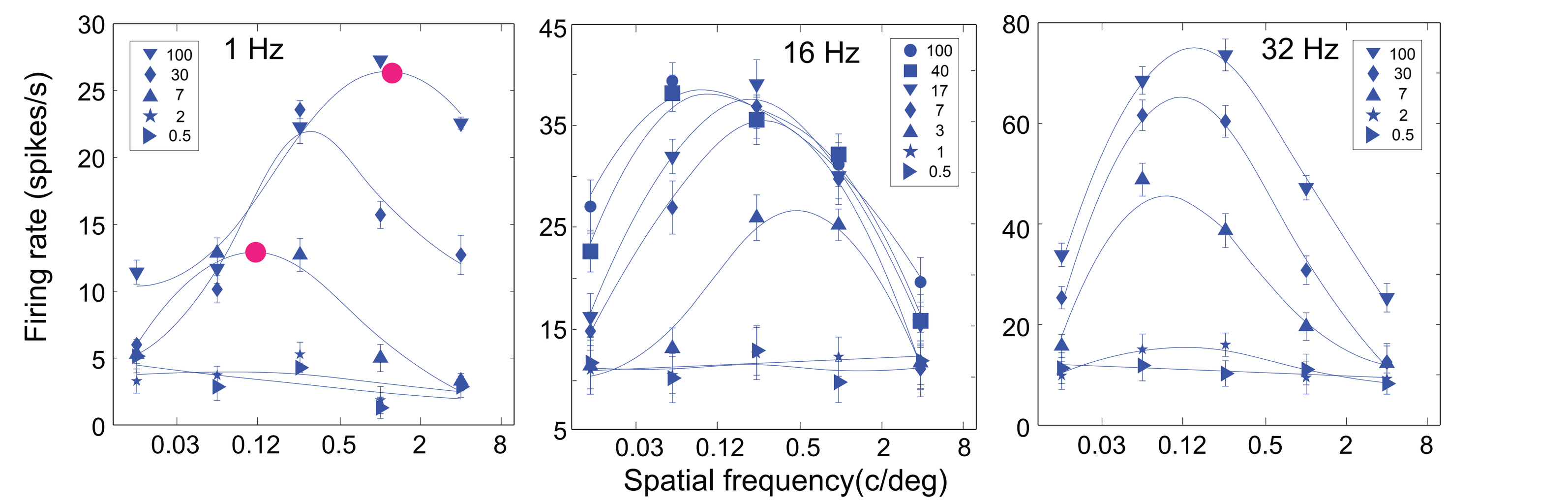


A 3-D plot of neuronal firing rate vs. spatial frequency vs. contrast.

Vertical slice (RIGHT): 'response function', which is the firing rate at a single contrast (17.1%) across SF.

Horizontal slice (LEFT): stimulus contrast that elicited the threshold firing rate (contrast sensitivity function).

SF tuning across contrasts

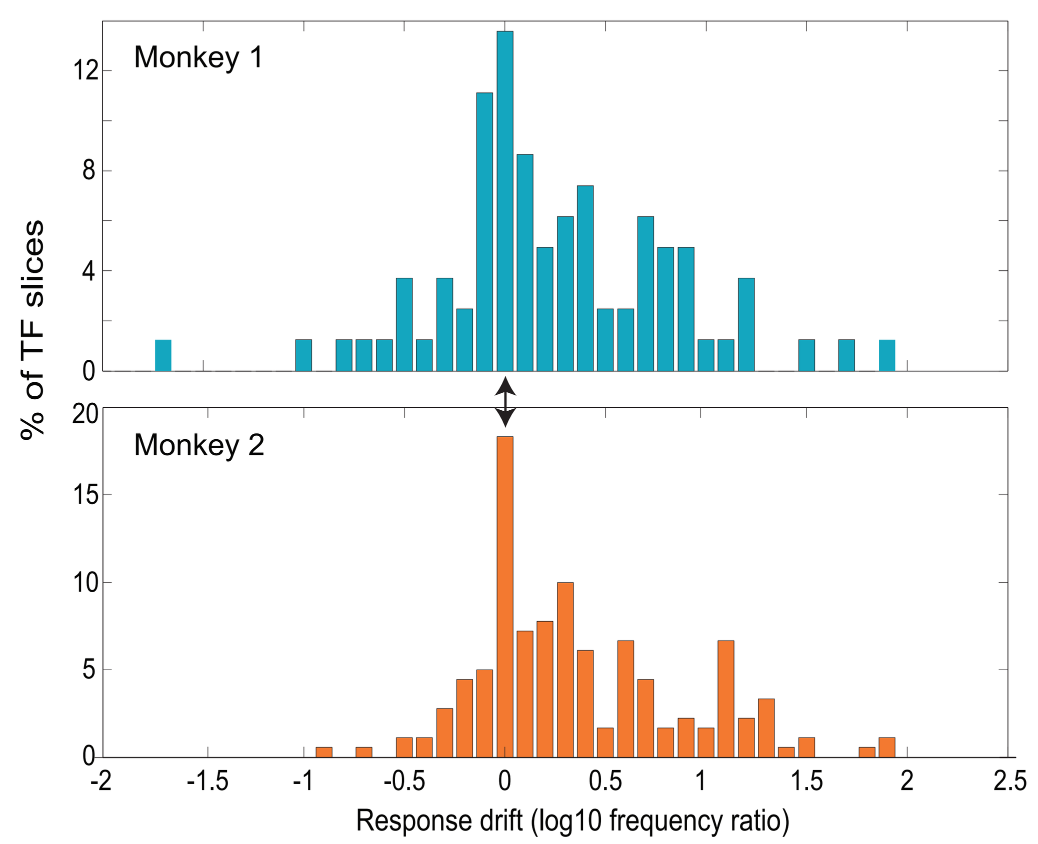


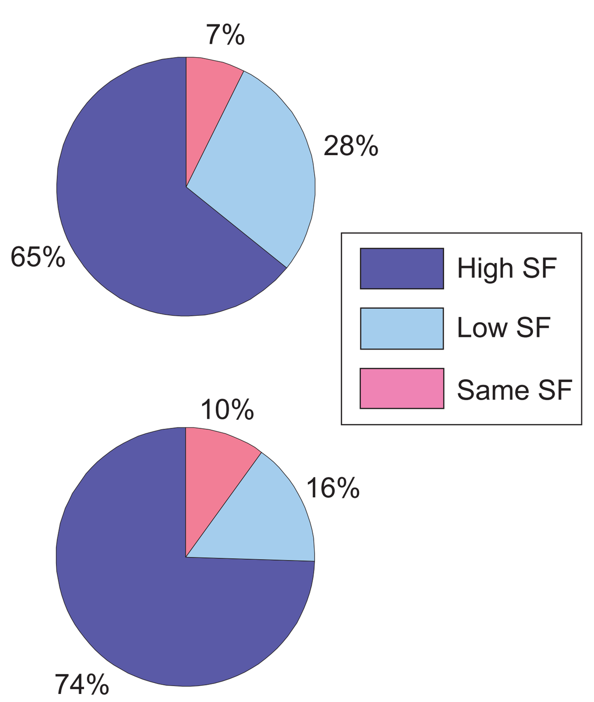
We plotted five response functions that were derived from the neurometric surface at 5-7 contrasts (indicated by legend).

MT neurons showed three patterns of behavior as a function of stimulus contrast:

- drift of peak response toward high spatial frequencies (left panel).
- drift of peak response toward low spatial frequencies (middle panel).
- no change in peak response (right panel).

Drift of peak spatial frequency across cells



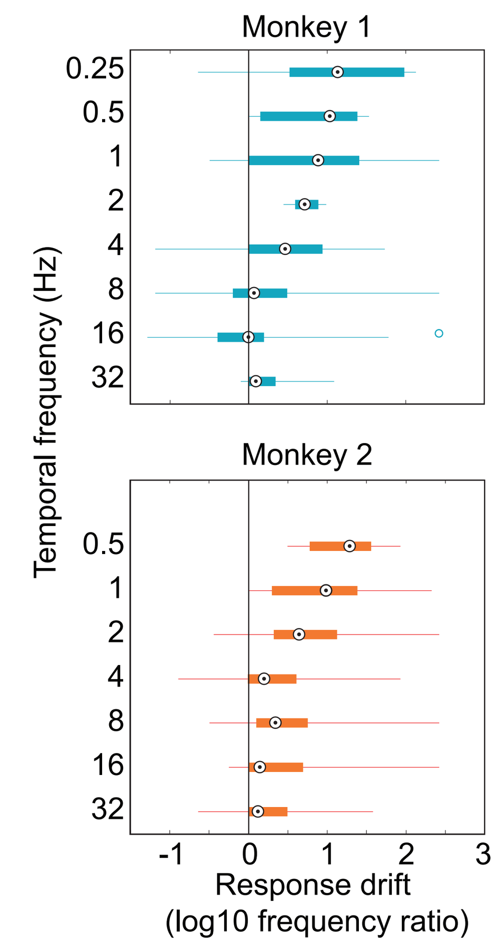


Response drift: log10 ratio of peak SF at high contrast to peak SF at low contrast.

The positive and negative values of drift indicate that peak response respectively increased or decreased as a function of contrast.

Pie-charts: Most TF-slices have a positive drift.

The role of temporal frequency on spatial frequency peak drifts



We found that a majority of cells showed an increase in peak SF with increasing contrast.

Peak SF drift depended on the TF of the stimulus.

Peak SF drifts are the highest for lower TFs, and systematically decrease as TF increases.

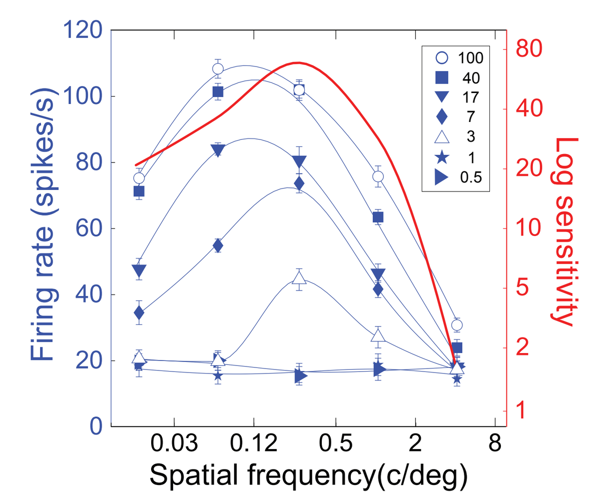
Black circles: median for the data.

Box bottom and top edges: 25th and 75th percentile of the dataset respectively.

Box length: the interquartile range.

Whiskers: minimum and maximum Open circles: outliers (points at a distance >3 times the interquartile range).

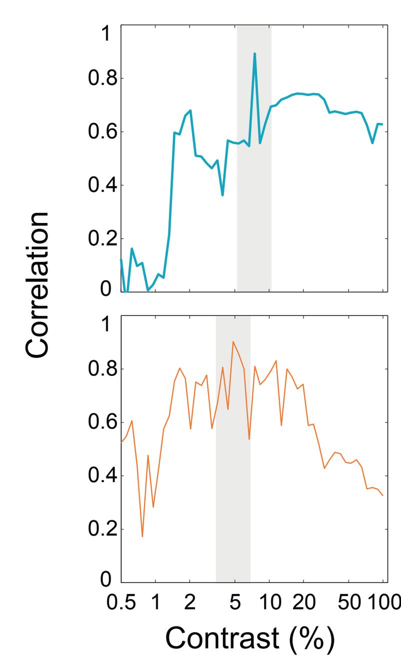
Relationship between response functions and sensitivity

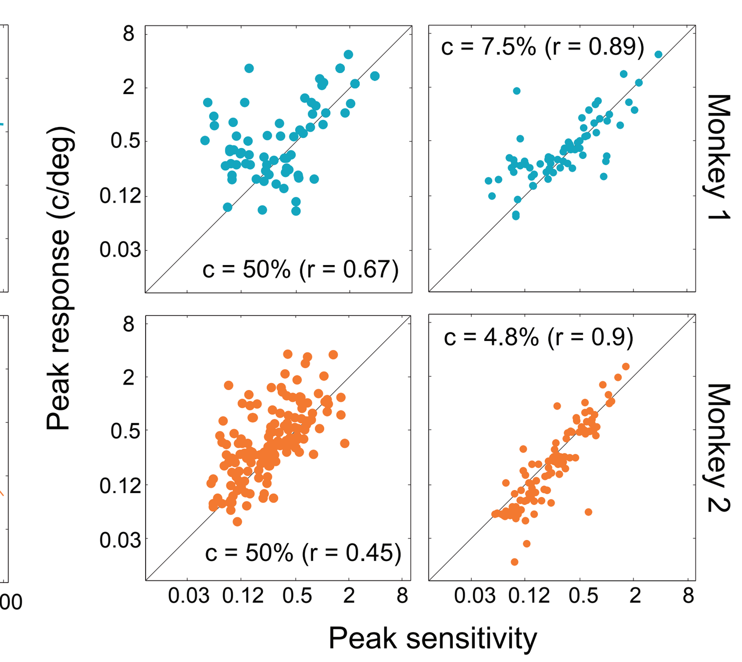


The contrast sensitivity function (red) and response functions (blue) derived from the neurometric surface.

At low contrasts, response peaks match the peak of sensitivity.

At higher contrasts (here above 0.07) response peaks drift to lower spatial frequencies.



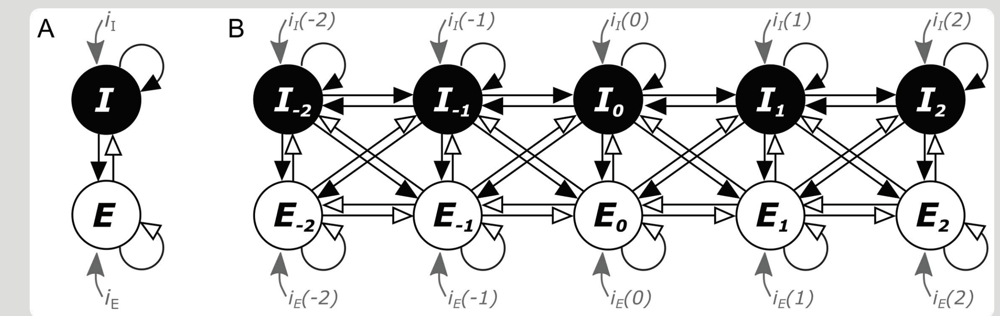


(LEFT) Correlation of peak sensitivity and peak response SFs for all contrasts for all cells. Maximum correlations are found at medium contrasts, 5-15% (gray areas)

(MIDDLE) Sensitivity vs. response peaks for 50% contrast (used in previous studies) at which we found lower correlation (0.67 and 0.45).

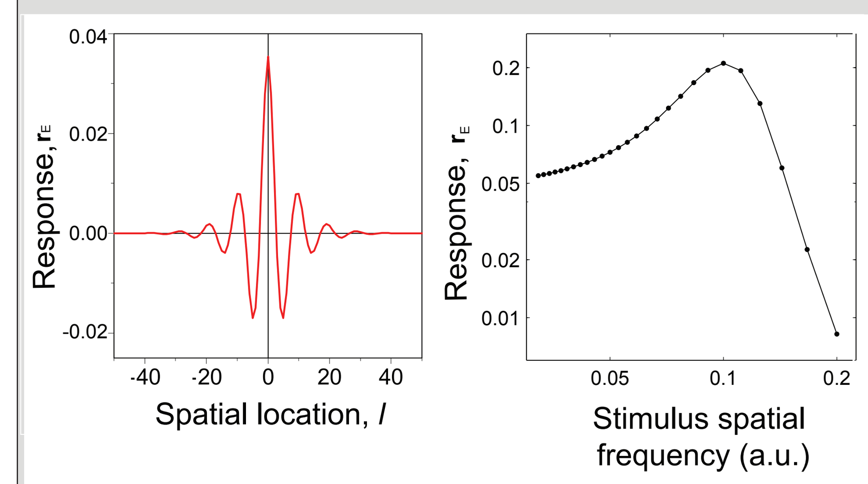
(RIGHT) Sensitivity vs. response peaks for the highest correlations.

Model



A distributed network of canonical inhibition stabilized motifs (A) with nearest-nighbor coupling (B). Each node contains excitatory and inhibitory cells wth reciprocal and recurrent connections.

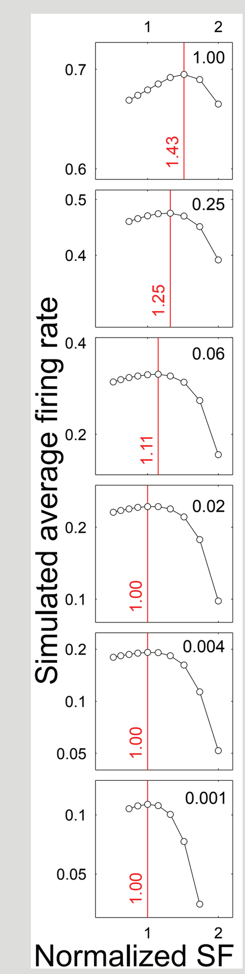
Simulation results



LEFT: Network response to a small low-contrast stimulus applied to a single node of the chain. It generates a neural wave that has the shape of damped oscillation.

The periodic response reflects the arrangement of nodes in the chain and the magnitudes of weights that provide network stabilization.

The wavelength of oscillations generated by the chain is its "intrinsic" wavelength. In the linear regime, properties of such spatial oscillations help to predict system responses to complex stimuli. The waveform generated by a complex stimulus is predicted by linear interference of the waves generated on multiple nodes of the chain. The above RIGHT panel depicts an example of such neural wave interference produced by periodic stimuli characterized by different spatial frequencies.



The model of neural chain with the same parameters as in the previous section was stimulated by a spatially extended stimulus with cosine luminance modulation, similar to one used in our experiments.

Network inputs were selected to represent stimulus contrast varying in the range from 0.001 to 1.00. The results are plotted for six magnitudes of stimulus contrast.

The results reveal that intrinsic tuning of the network is a function of stimulus contrast. At low contrasts, up to 0.02 in these simulations, the maximum response of the chain increased, but the intrinsic frequency (normalized to the low-contrast intrinsic frequency) did not change.

At higher contrasts, above 0.02, increasing the contrast led to an increased maximum response, as before, and also revealed an increased intrinsic frequency of the network.

For the highest contrast of 1.0, the maximum of network activation was found at the stimulus spatial frequency of 1.43, i.e., 43% higher than at low contrasts

Conclusions

Tuning of MT neurons drifts to higher spatial frequencies with contrast. The drift is reduced at higher temporal frequencies.

A model of distributed inhibition-stabilized network predicts such drift of frequency tuning.

Peaks of suprathreshold firing are most similar to peaks of neuronal sensitivity at intermediate contrasts.