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Dynamic Visual Acuity and Activation Patterns of Spatial Frequency Domains of Primary Visual Cortex

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Abstract

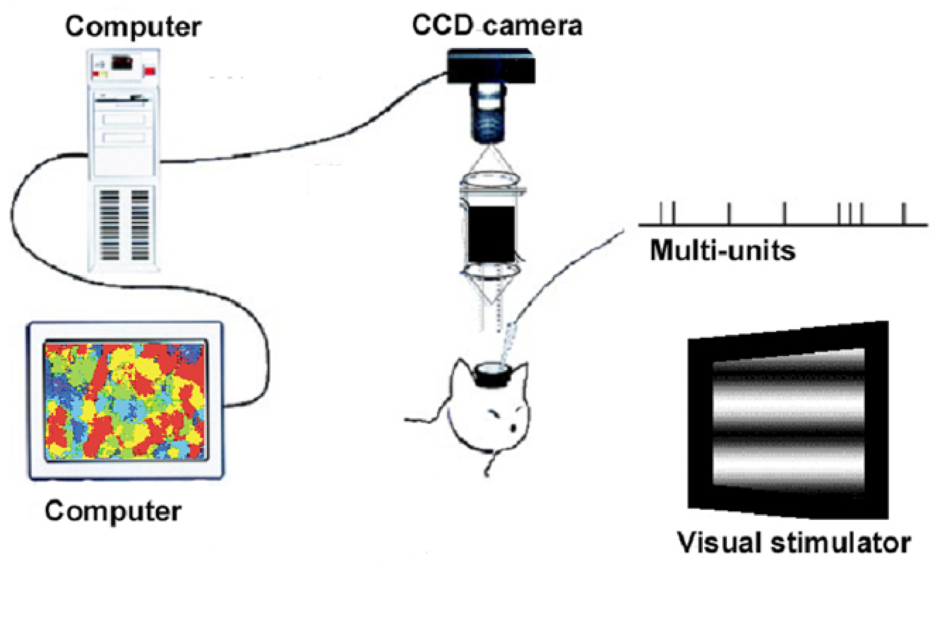
Visual acuity is degraded when an image moves quickly. Retinal and LGN neurons can follow much more rapid changes in contrast than can neurons in V1. This suggests that the spatial and temporal tuning properties of V1 limit dynamic acuity. To test this hypothesis we used optical intrinsic signal imaging to measure responses in cat Area 17 to complex moving images. Stimuli consisted of pairs of gratings, each grating having the same orientation but different spatial frequency (SF). Changes in cortical reflectance were measured in different SF domains in response to stimuli drifting at one of four speeds. Consistent with the hypothesis, activity in high-SF domains decreased as drift speed increased, but activity in low-SF domains was maintained.

To determine if linear filtering properties could account for the changing activity in SF domains, we used optical imaging and extracellular electrophysiology to characterize six spatio-temporal parameters in cat Area 17. These parameters included orientation preference and bandwidth, SF preference and bandwidth, and temporal frequency (TF) preference and bandwidth. Consistent with previous reports, average SF bandwidth is monotonically related to SF preference. TF peak varies as a function of the SF preference of a domain, being somewhat higher in low-SF domains than in high-SF domains, but lower than TF peak in Area 18. Using these parameter values and a non-linear filtering model we could quantitatively predict the shifts in the activation of SF domains as image speed changed. This suggests that dynamic visual acuity is determined in part by the linear filtering properties of primary visual cortex, and by a non-linear mechanism like intra-cortical feedback.

Hypothesis: Neurons in the primary visual cortex limit dynamic acuity.

Dynamic acuity describes how well a person sees detail in a moving image.

Experimental Design: Optical Imaging

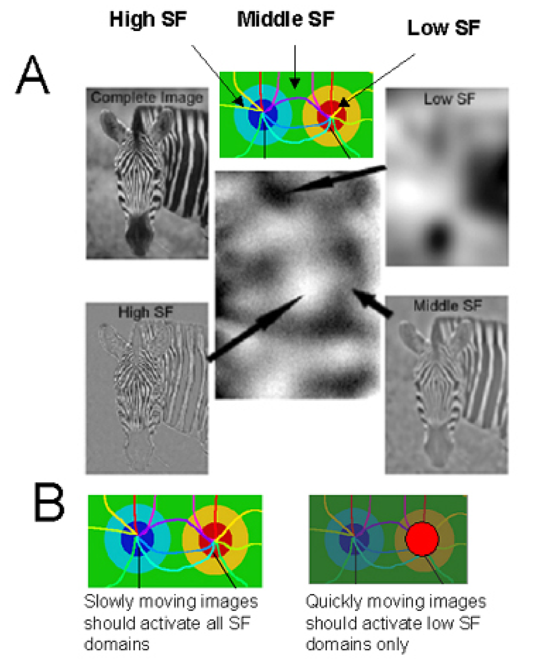


Modified from Tsodyks et al, 1999

Experimental Predictions

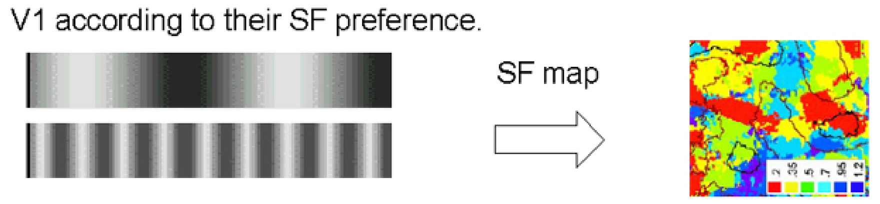
A. Spatial Frequency Domains in V1: Spatial frequencies are continuously represented in V1. Orientation pinwheel centers are found in low and high SF domains.

B. Predicted effect of image speed: slowly moving images should activate both low and high SF domains. Quickly moving images should activate only low SF domains.

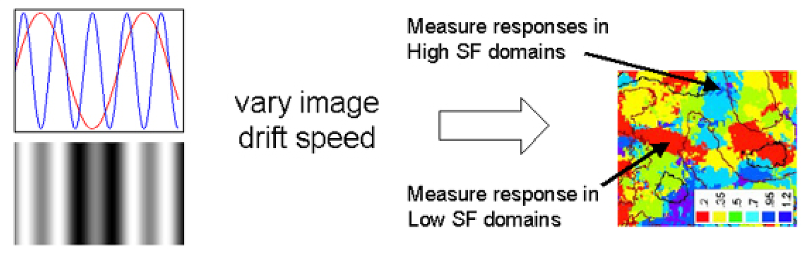


Visual Stimuli

1. Present sine waves of different SF to define functional domains of V1 according to their SF preference.

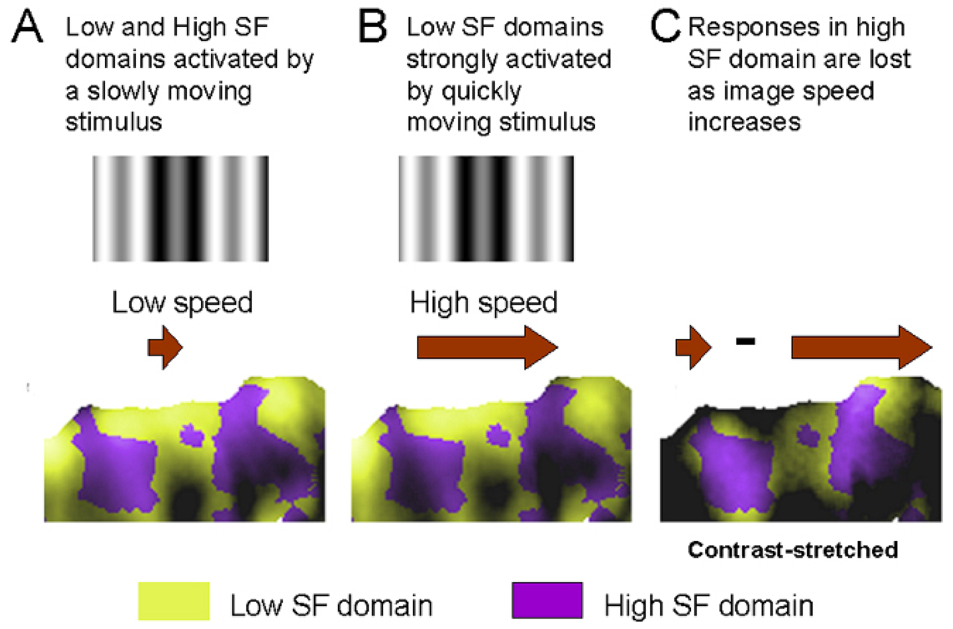


2. Present stimulus made up of two SFs and measure responses in the different domains. How do responses change with image speed?



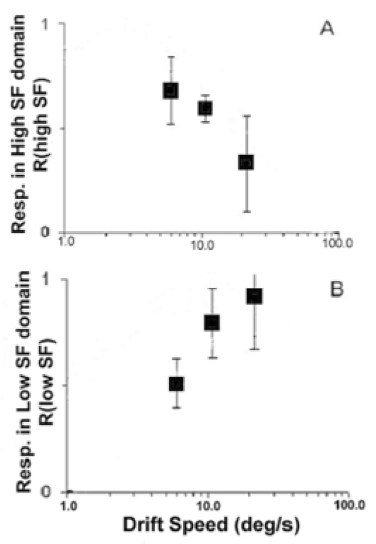
Example SF map from Issa et al. 2000

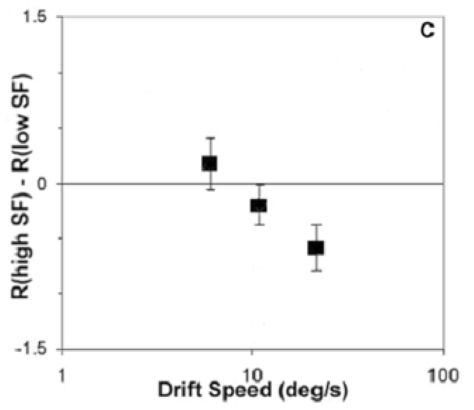
Results



Results

High SF image components have higher temporal frequencies (TF) than low SF components. At high drift speeds, the TF of high SF components fall out of the pass-band of the TF tuning curve.



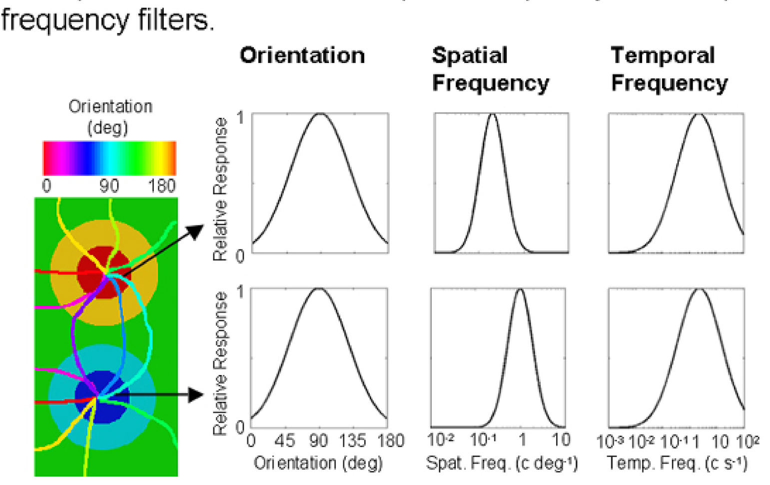


The response of high and low SF domains changes when moving speed increases (Fig. A and Fig. B). The response difference between high and low SF domain drops from positive to negative value (Fig. C). N=3 animals.

A Linear Model

Can a linear model describe the data?

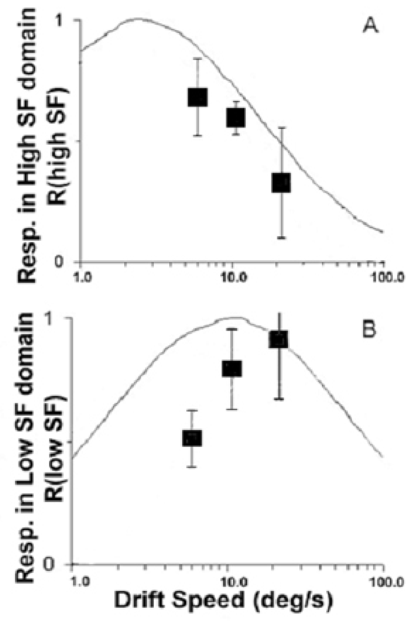
In a linear model, cortical tuning properties are described by three band-pass filters: orientation, spatial frequency and temporal frequency filters.

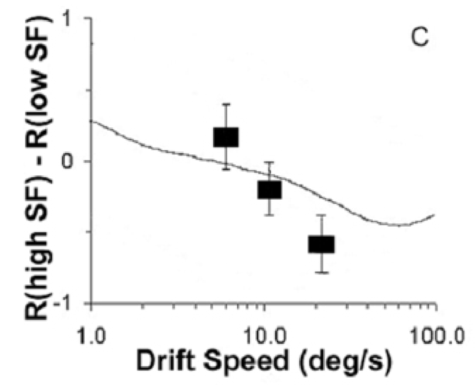


See Baker and Issa 2004, SFN poster 648.7

Comparison to Linear Predictions

The linear model does not describe the data well.

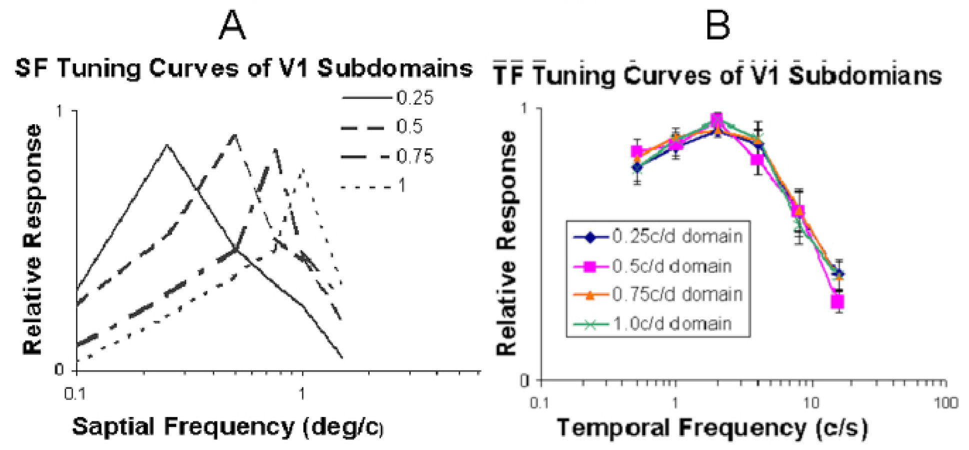




Linear model predictions for responses in A) high SF domains, B) low SF domains. C) The response difference between high and low SF domains. N=3 animals.

Linear Model Parameters

Six parameters are needed to describe orientation, SF and TF tuning curves.



We defined different functional domains in V1 according to their SF preference (tuning curves are shown in Fig. A, N=8 animals). We then measured their TF tuning curves (Fig. B, N=8 animals).

Linear Model Parameters

Orientation Preference	Varies point-by-point Between 0-180°
SF Preference	Varies point-by-point between 0.2 and 1.5 c/° Population average: 0.44± 0.04 c/° (n=8)
TF Preference	2.23 ± 0.41 c/s (n=8)

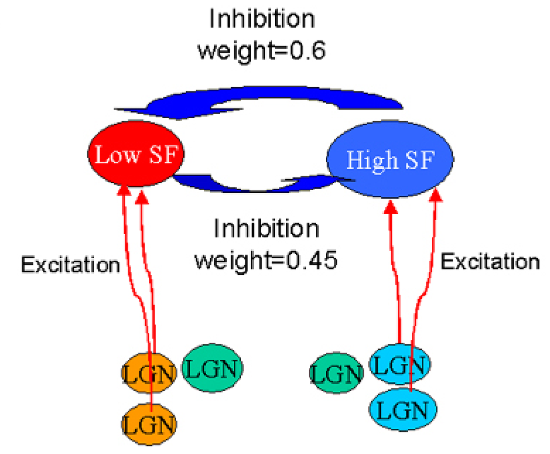
Orientation Bandwidth	40° (Rao *et al.*, 1997)
SF Bandwidth	Individual SF domains: 0.91 ± 0.07 c/° Population average: 1.63 ± 0.20 c/° (n=8)
TF Bandwidth	2.73 ± 0.43 c/s (n=8)

We fit the SF and TF tuning curves with a log-Gaussian function $s(p)=\exp[-(\log_2 P-\log_2 S_p)^2/2\sigma^2]$, with a peak of S_p and a bandwidth of σ. The orientation tuning curve is defined as a wrapped Gaussian, $R(\Phi)=\exp[-(\Phi-\Phi_p)^2/2\sigma_\Omega^2]$, with a peak orientation Φ_p of and a characteristic width of σ_Ω.

Non-Linear Model

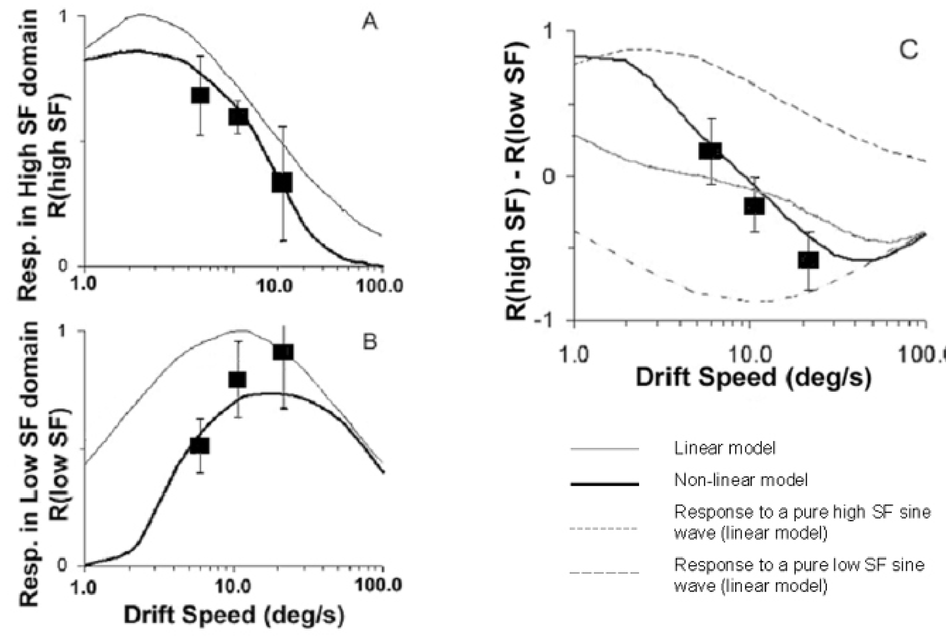
Intra-cortical Inhibition

A non-linear model is needed to explain these data. We apply a model in which intra-cortical inhibition modulates activity in different SF domains. SF domains receive excitatory inputs from LGN and inhibitory inputs from each other.



Intracortical Inhibition

Non-linear model better describes the data.



Summary

- Increasing image speed reduces activation in high spatial frequency domains of primary visual cortex.
- Linear tuning properties do not predict all the responses in different spatial frequency domains.
- We propose a model in which intra-cortical inhibition modulates the effects of image speed on cortical responses.

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