Tilt-aftereffect and adaptation of V1 neurons

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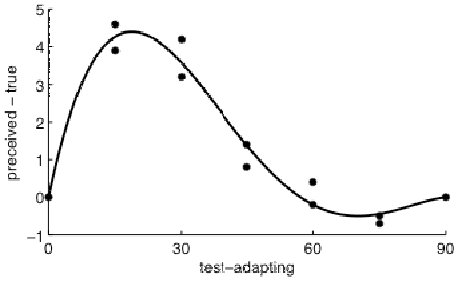
Outline

- The tilt aftereffect (TAE)
- Classical model of neural basis of TAE
- Neural data on V1 neurons challenge the classical model
- A model that reconciles the neural data with TAE
- Discussion

Tilt aftereffect (TAE)

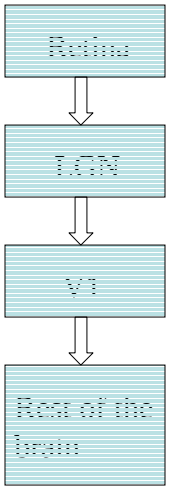
- Adaptation-induced error of orientation perception

(Demo)

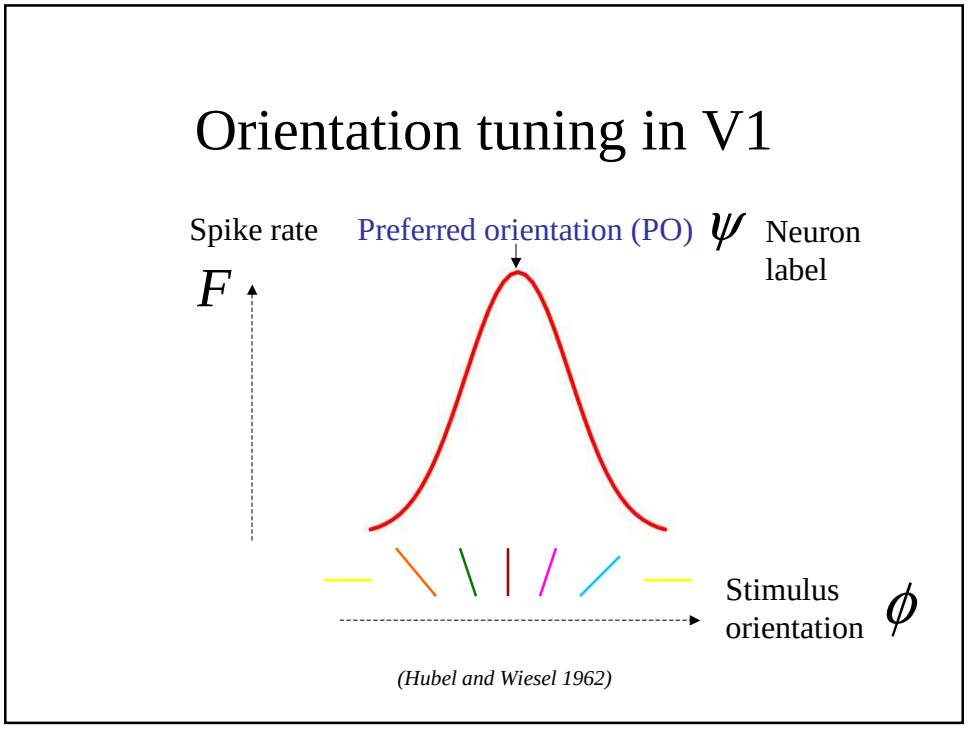


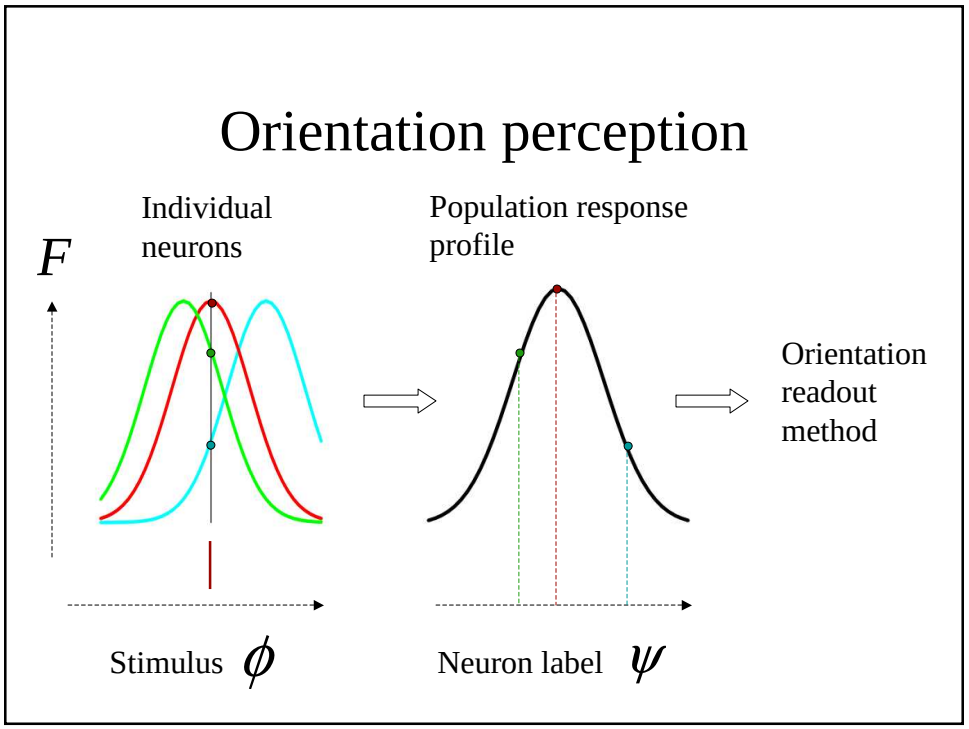
(Gibson and Radner 1937, Mitchell and Muir 1976, Clifford et al. 2000)

Neural basis of TAE



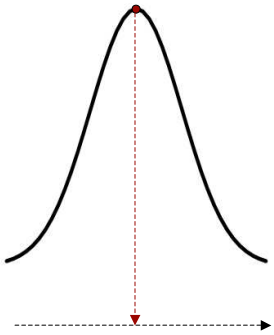
- V1 neurons detect orientations
- The brain perceives orientation information from population responses of V1 neurons
- Adaptation changes V1 response properties, and leads to perceptual error


Orientation tuning in V1
Spike rate
Preferred orientation (PO)
ψ
Neuron label
F
Stimulus orientation
ϕ
(Hubel and Wiesel 1962)


Orientation perception
Individual neurons
Population response profile
F
Orientation readout method
Stimulus ϕ
Neuron label ψ

Winner-take-all (WTA) method

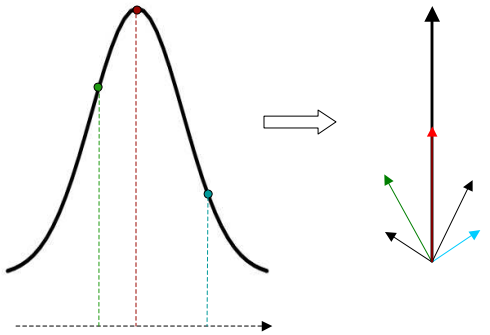
- The label of the neuron that spikes the most is the perceived orientation.



Neuron label ψ

Population vector method

- The perceived orientation is that of the population vector resulted from summation of all vectors contributed by each neuron.

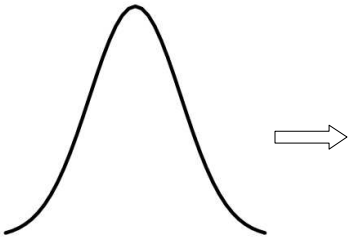


Neuron label ψ

(Georgopoulos et al. 1982; Gilbert and Wiesel 1990; Vogels 1990)

Maximum likelihood method

- Each perceived orientation is associated with a template for the population response profile. The perceived orientation is the label of the template that best match the population response profile of a stimulus.

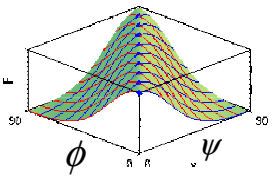


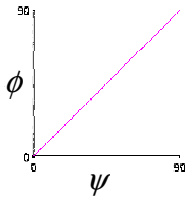
Population profile

Best matching template

(Paradiso 1988; Pouget et al. 2000)

The rate function





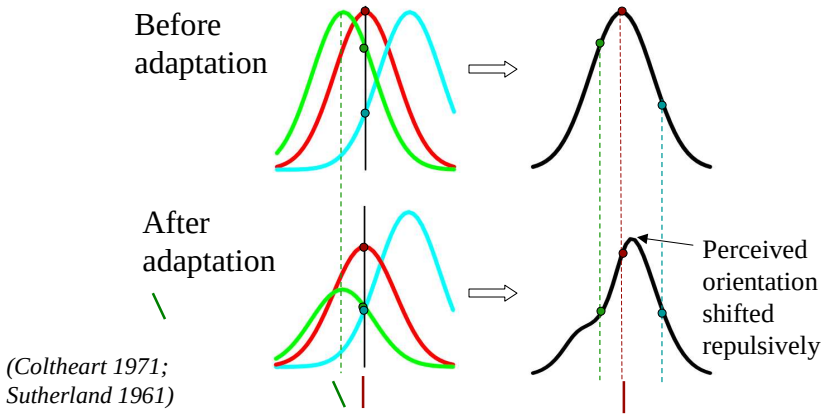
$$F(\psi,\phi)$$

Red: orientation tuning curves

Blue: population response profiles

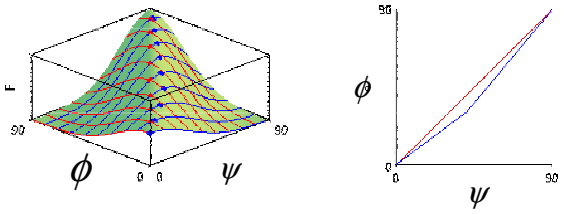
The "fatigue" model of TAE…

- Adaptation leads to reduction of the amplitude of the tuning curve in proportion to the activity level of the neuron to the adapting orientation.



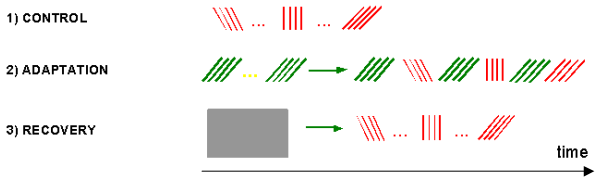
(Coltheart 1971; Sutherland 1961)

…the fatigue model

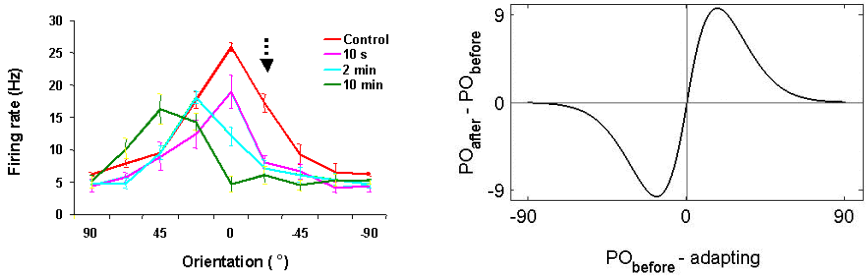


Adapting orientation is assumed to be at 0.

Neurons fatigue, but also shift POs away from adapting orientation

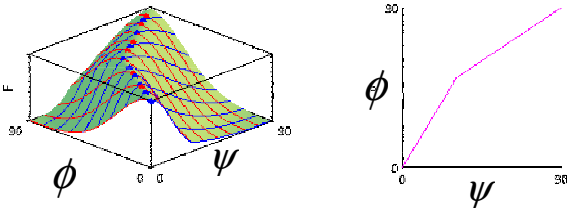


Cat V1 neuron tuning curve



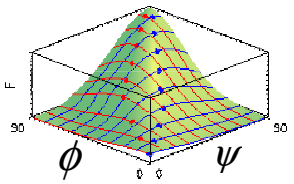
(Dragoi et al., Neuron, 2000)

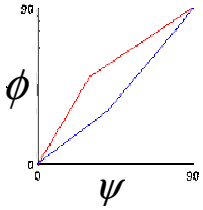
Shifts of POs away from adapting orientation leads to "anti"-TAE



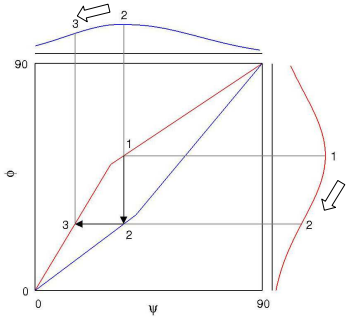
Shifts of POs away from adapting orientation make stimulus appear rotated *toward* to the adapting orientation (opposite to TAE).

Reconciling neural data with TAE : amplitude suppression much be strong enough





From 2 to 3, the firing rate goes down hill on the population curve.



From 1 to 2, the firing rate goes down hill on the tuning curve.

Calculation of the required amount of suppression

Rate function:

$$F(\psi,\phi) = A(\psi)\exp\left(-\frac{(\phi-\phi_n(\psi))^2}{2\sigma(\psi)^2}\right)$$

$\phi_n(\psi)$: preferred orientation of neuron ψ

$\sigma(\psi)$: width parameter of the tuning curve

The perceived orientation for stimulus ϕ is $\psi_p(\phi)$, and is given by the solution of

$$\frac{\partial F(\psi,\phi)}{\partial \psi} = 0$$

…calculation

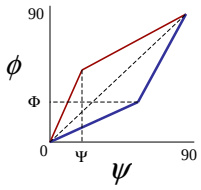
$$\frac{dA(\psi)}{d\psi} = A(\psi)\frac{\phi_n(\psi)-\phi}{\sigma(\psi)^2}\left[\frac{d\phi_n(\psi)}{d\psi} - \frac{\phi_n(\psi)-\phi}{\sigma(\psi)}\frac{d\sigma(\psi)}{d\psi}\right]$$

Solution :

$$A(\psi) = \exp\left[\int_0^{\psi} d\psi' \frac{\left(\phi_n(\psi')-\psi_p^{-1}(\psi')\right)}{\sigma(\psi')^2}\left(\frac{d\phi_n(\psi')}{d\psi'} - \frac{\left(\phi_n(\psi')-\psi_p^{-1}(\psi')\right)}{\sigma(\psi')}\frac{d\sigma(\psi')}{d\psi'}\right)\right]$$

Mathematical relationship between the TAE, the shifts of POs, and the amplitude of the tuning curves

Simplification



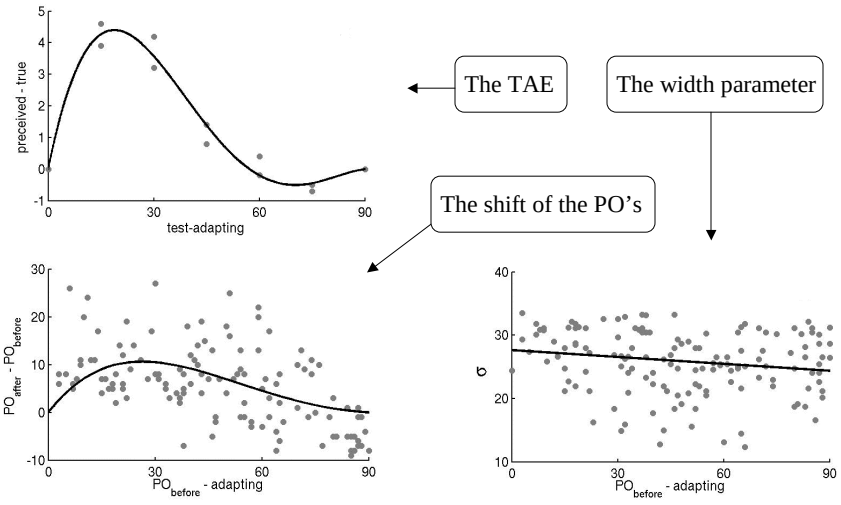
Approximate $\phi_n(\psi)$ (red line)
and $\psi_p(\phi)$ (blue line) with piecewise linear functions.

Ψ : neuron with maximum PO shift
Δ : size of maximum PO shift
Φ : stimulus that causes maximum TAE
δ : size of the maximum TAE

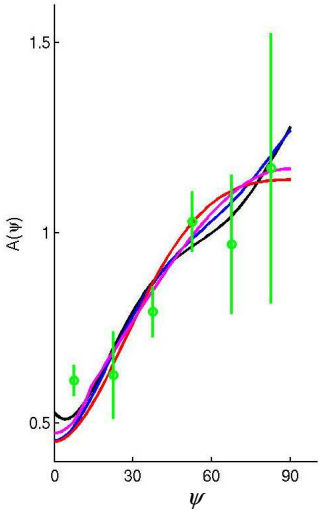
$$A(\psi) \approx \exp\left(\left(\frac{\Delta}{\Psi}+\frac{\delta}{\Phi}\right)\frac{\psi^2}{2\sigma^2}\right),$$

when ψ is close to adapting orientation (at 0)

Experimental data used for predicting the amplitude function



Comparison between the predicted and measured amplitude function



Experimental data

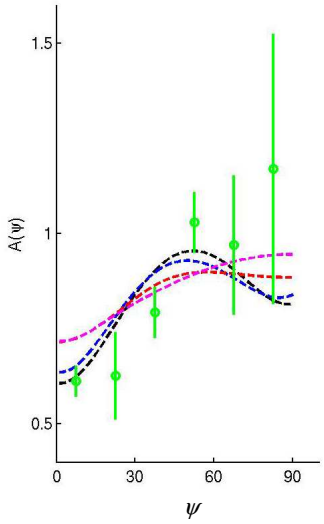
Winner-take-all method

Winner-take-all method (linear approximation)

Population vector method

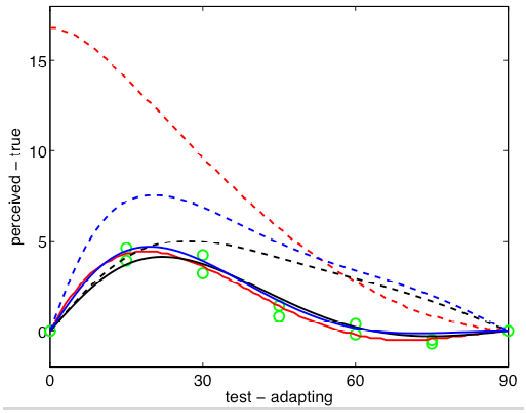
Maximum likelihood method

The fatigue model is inconsistent with data



The theoretical curves are calculated *without the repulsive shifts of the preferred orientation*, as in the fatigue model

The fatigue model predict larger TAE than observed



TAE data

With the PO shifts:

- WTA
- Population vector
- Maximum likelihood

Without the PO shifts:

- WTA
- Population vector
- Maximum likelihood

Using the repulsive PO shifts to reduce TAE

- The repulsive shifts of POs reduce TAE for given amount of amplitude suppression.
- It is possible that by the repulsive shift of POs is the strategy used by the visual system to avoid too much illusion in detecting orientations when adaptation-induced neural fatigue is unavoidable.

Cortical amplification and the depression

- Adaptation in LGN neurons and synapses are not orientation selective. Therefore, an adapting drifting grating of any orientation will adapt all LGN neurons and their synapse to V1.
- The amplitude modulation after adaptation is likely of cortical origin. The factor 2.5 of the tuning curve amplitude modulation may reflect the degree of cortical amplification in producing orientation selectivity.

Conclusion

- A consistent explanation of TAE needs to include not only the fatigue of neurons but also the repulsive shifts of their preferred orientations.
- The repulsive shifts of the preferred orientations are useful for reducing perception deviation in visual system when fatigue is unavoidable.

Collaborators

Valentin Dragoi, University of Houston

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