SINGLE-FILTER GAIN CHANGES AND ATTENTIONAL THRESHOLD MODULATION

Laurent Itti, Jochen Braun and Christof Koch
California Institute of Technology, Computation and Neural Systems, Pasadena, California 91125

1. Overview

We previously presented a simple computational model which quantitatively accounts for the attentional modulation of human psychophysical thresholds. In our previous study, we assumed that attention indiscriminately affects all filters in a model visual "hypercolumn", and reported a good account for the observed effects, in which attention strenghtens competition among visual neurons. Here we explore whether more specific attentional feedback, affecting task-dependent filter sub-populations is also plausible.

2. Motivation

Several groups have reported enhanced neuronal activity in visual neurons analysing the part of the visual field which the animal is attending to. Similarly, using psychophysics, we have measured significantly better pattern discrimination performance when attention was fully available for the pattern discrimination task, compared to when it was engaged elsewhere by a concurrent letter discrimination task.

Assuming a single, unified (identical for all psychophysical tasks) and indiscriminate (affecting all filters in our model equally) modulatory effect of attention, we found that the observed psychophysical data could be well explained if attention strengthens competition among visual filters. Strengthening competition entails an increase in the gain of the filters, by a factor 2 to 3, as well as a sharpening of filter tuning for orientation and spatial period, by up to 35% [Itti et al., ARVO'97 & 98; Lee et al, Nature Neuroscience, 1999].

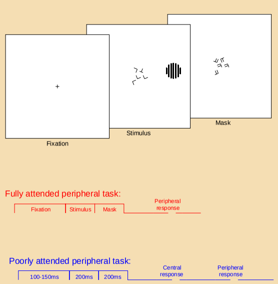
Here we investigate whether a number of simpler manipulations (involving only gain increases with attention), but affecting specific sub-populations of filters rather than all filters, may also predict the observations. In addition, we investigate whether attention could affect only the gain of all filters, but in a task-dependent manner (we have previously ruled out a gain-only, filter- and task-independent manipulation).

Specifically, we investigate whether:

- **Attention could affect the gain of only the filter responding most vigorously (loudest)**
- **Attention could affect the gain of only the filter best-tuned to the target stimulus**
- **Attention could affect the gain of only the filter most informative about the target**
- **Attention could affect the gain of all filters equally, but by different amounts depending on the task.**

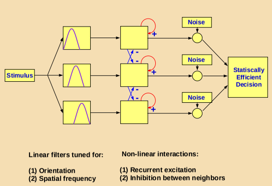
3. Psychophysics of Lee et al.

Spatial vision patterns to be discriminated were presented in the near periphery, along with a letter discrimination task at fixation. In the "Fully Attended" condition, observers only report on the peripheral pattern discrimination, while maintaining central fixation. With exactly identical stimuli, in the "Poorly Attended" condition, observers report on the identity of the central letters (all "T" or four "T" and one "L"; an attention-demanding task), in addition to reporting on the peripheral pattern discrimination.



4. Model

4.1. Model Architecture



Linear filters tuned for:
(1) Orientation
(2) Spatial frequency

Non-linear interactions:
(1) Recurrent excitation
(2) Inhibition between neighbors

4.2. Excitatory and Inhibitory Pooling

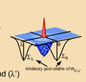
Self excitation and divisive inhibition:

$$R_{\theta,\lambda} = \frac{E^G_{\theta,\lambda}}{S_\lambda + \sum_{\theta',\lambda'} W_{\theta',\lambda'} E^H_{\theta',\lambda'}}$$

$E_{\theta,\lambda}$ is the linear response of filter tuned to (θ,λ)

Excitatory pool is the single unit (θ, λ)

Inhibitory pool is locally weighted around (θ, λ) by Gaussians in orientation (θ') and spatial period (λ')



4.3. Noise Model

Noise variance given by: $V_{\theta,\lambda} = \beta(R_{\theta,\lambda} + \epsilon)$

β: Light noise
ε: Dark noise

β = 1, ε = 0 yields Poisson noise
β = 0 yields constant noise

4.4. Statistically Efficient Decision

Stimulus → Filters, interactions and noise → Statistically efficient estimator T

parameter γ (contrast, orientation, or spatial period)

only partial information about γ preserved in responses $R_{\theta,\lambda}$ (variance $V_{\theta,\lambda}$)

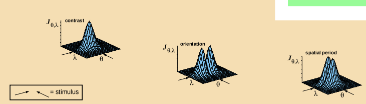
T is an unbiased efficient statistic for γ based on population response $R_{\theta,\lambda}$

mean(T) = γ **var(T) = $1/J_{\theta,\lambda}$**

$$J_{\theta,\lambda} = \frac{1}{V^2_{\theta,\lambda}}\left[\left(\frac{\delta R_{\theta,\lambda}}{\delta\gamma}\right)^2 + 2\left(\frac{\delta V_{\theta,\lambda}}{\delta\gamma}\right)^2\right]$$ **Fisher Information**

$$J_{total} = \sum_{\theta,\lambda} J_{\theta,\lambda}$$

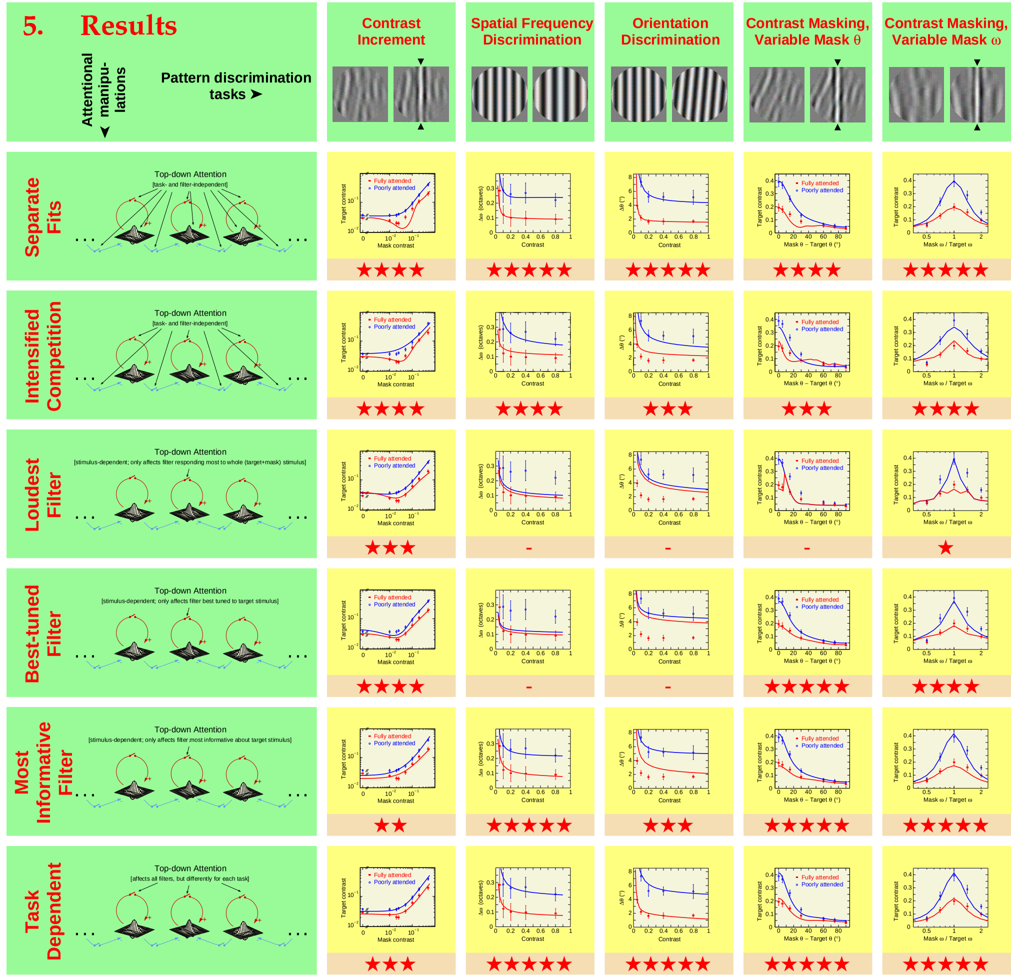
For single unit responses $R_{\theta,\lambda}$, $J_{\theta,\lambda}$ tells us how much information about γ each unit (θ, λ) carries:



Model Fits

The model was simultaneously fit to the data for both attentional conditions. To generate predictions used to evaluate the quality of fit, "fully attended" parameters were used to predict "fully attended" data, and conversely for "poorly attended" data. A downhill simplex with simulated annealing overhead adjusted the model's parameters until the best fit to the data was obtained.

5. Results



Ratings:

Manipulation	Contrast Increment	Spatial Frequency Discrimination	Orientation Discrimination	Contrast Masking, Variable Mask θ	Contrast Masking, Variable Mask ω	Model Parameters	Discussion
Separate Fits	★★★★	★★★★★	★★★★★	★★★★	★★★★★	★★★★★	★★★★★
Intensified Competition	★★★★	★★★★	★★★	★★★	★★★★	★★★★★	★★★★
Loudest Filter	★★★	-	-	-	★	★★	-
Best-tuned Filter	★★★★	-	-	★★★★★	★★★★	★★★★	-
Most Informative Filter	★★	★★★★★	★★★	★★★★★	★★★★★	★	★★★
Task Dependent	★★★	★★★★★	★★★★★	★★★★★	★★★★★	-	-

Model Parameters

γ, δ: Interaction strength
σ_λ, σ_θ: Filter tuning
Σ_λ, Σ_θ: Filter pooling
B, ε: Dark noise
β: Light noise
S: Semisaturation

Separate Fits

Parameters	Fully	Poorly	
γ	3.78	1.85	
δ	3.42	1.80	
σ_θ (°)	9.69	13.19	n.s.
σ_ω (oct)	0.44	0.36	n.s.
Σ_θ (°)	23.01	23.90	n.s.
Σ_ω (oct)	0.81	0.18	n.s.
B/A	0.30	1.10	n.s.
S/A	10.12	8.05	n.s.
β	0.17	0.01	
ϵ/R_{max}	0.03	0.11	n.s.

Intensified Competition

Parameters	Fully	Poorly
γ	3.94	1.40
δ	3.55	1.00
σ_θ (°)	8.92	
σ_ω (oct)	0.41	
Σ_θ (°)	20.80	
Σ_ω (oct)	0.31	
B/A	0.96	
S/A	5.39	
β	0.58	
ϵ/R_{max}	0.02	

Loudest Filter

Parameters	Fully	Poorly
γ	2.22	1.56
δ	1.03	
σ_θ (°)	6.62	
σ_ω (oct)	0.19	
Σ_θ (°)	15.54	
Σ_ω (oct)	1.09	
B/A	0.21	
S/A	12.16	
β	0.65	
ϵ/R_{max}	0.01	

For loudest filter only!

Best-tuned Filter

Parameters	Fully	Poorly
γ	1.40	1.99
δ	1.91	
σ_θ (°)	11.94	
σ_ω (oct)	0.32	
Σ_θ (°)	14.71	
Σ_ω (oct)	7.03	
B/A	0.24	
S/A	3.00	
β	1.5e-9	
ϵ/R_{max}	8635.52	

For best-tuned filter only!

Most Informative Filter

Parameters	Fully	Poorly
γ	1.45	1.05
δ	1.04	
σ_θ (°)	9.70	
σ_ω (oct)	0.31	
Σ_θ (°)	39.15	
Σ_ω (oct)	0.42	
B/A	0.66	
S/A	0.00	
β	3.4e-4	
ϵ/R_{max}	0.01	

For most informative filter only!

Task Dependent

Parameters	Fully	Poorly
γ	1.91 / 3.08 / 2.43	1.50
δ	1.24	
σ_θ (°)	10.63	
σ_ω (oct)	0.36	
Σ_θ (°)	37.63	
Σ_ω (oct)	0.44	
B/A	0.45	
S/A	13.18	
β	0.82	
ϵ/R_{max}	0.14	

For contrast / orientation / period

Discussion

Separate Fits
- very good fit overall
- all parameters biologically plausible
- attention significantly modulates interactions and noise

Intensified Competition
- very good fit overall
- all parameters biologically plausible
- modulation of orientation thresholds slightly under-estimated
- contrast masking with variable mask orientation not perfectly predicted

Loudest Filter
- no modulation of contrast detection threshold
- no modulation of orientation thresholds
- no modulation of period thresholds
- poor prediction of masking
- filter tuning too narrow
- gain modulation too large

Best-tuned Filter
- no modulation of orientation thresholds
- no modulation of period thresholds
- contrast discrimination and masking well fit
- only fit predicting broad pooling in spatial period
- noise parameters unrealistic

Most Informative Filter
- no contrast discrimination "dipper"
- power-law rather than sigmoidal contrast response (S=0)
- modulation of orientation thresholds slightly under-estimated
- noise parameter unrealistic

Task Dependent
- very good fit overall
- gain modulation unrealistically high, especially for orientation discrimination (filter gain when attending to orientation is > 20x poorly attended)

6. Discussion & Conclusion

We found that none of the simpler (gain-only) attentional manipulations could explain the experimental findings as well as our previous manipulation involving task- and filter-independent intensified competition among visual filters.

Two of the four new manipulations studied yielded good quantitative model predictions of the psychophysical data: Affecting the gain of the single filter most informative about the target stimulus, and affecting the gain of all filters in a task-dependent manner. In both cases however, some of the internal model parameters associated with these fits were unrealistic, thus reducing the plausibility of these two hypotheses. In all manipulations studied, we found that the greatest difficulty was in attempting to predict the large observed modulations of orientation and spatial frequency discrimination thresholds without requiring an unrealistically high gain change. These results hence complement our previous finding that both gain increase and sharpening of tuning were necessary to model the observed effects of attention on thresholds.

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